The Pigeonpea

Edited by

Y. L. Nene, Susan D. Hall, and V. K. Sheila

C·A·B International

International Crops Research Institute
for the Semi-Arid Tropics

The Pigeonpea

The Pigeonpea

Edited by

Y.L. NENE, SUSAN D. HALL, and V.K. SHEILA

C·A·B International

International Crops Research Institute
for the Semi-Arid Tropics

C·A·B International
Wallingford
Oxon OX10 8DE
UK

Tel: Wallingford (0491) 32111
Telex: 847964 (COMAGG G)
Telecom Gold/Dialcom: 84: CAU001
Fax: (0491) 33508

for

International Crops Research Institute
for the Semi-Arid Tropics (ICRISAT)
Patancheru
Andhra Pradesh 502 324
India

Tel: Hyderabad +91(842) 224016
Telex: 422203 ICRI IN or 4256366 ICRI IN
Cable: CRISAT, Hyderabad
E-mail: Dialcom 157: CG 1505
Fax: +91 (842) 241239

British Library Cataloguing in Publication Data
The pigeonpea.
1. Tropical regions. Pigeonpeas
I. Nene, Y. L II. Hall, Susan D. III. Sheila, V. K
IIII. International crops research institute for the semi-arid tropics
635.65

ISBN 0-85198-657-9

Printed and bound in the UK at the University Press, Cambridge

Contents

Foreword

Pigeonpea is widely grown by small farmers in the semi-arid tropics as a backyard subsistence crop. It is produced commercially in India, Myanmar, Kenya, Malawi, Uganda, and a few countries of Central America (Dominican Republic, Haiti, and Puerto Rico).

Pigeonpea is a profitable and popular crop. It brings good prices in the market. It is a hardy plant that, when intercropped with a cereal, ensures a measure of income stability. People use the dry grain as dhal, the green seed as a vegetable, and the sticks as fuel wood. In addition, it can be cut for forage and it improves poor soils through its deep, strong rooting system, leaf drop at maturity, and addition of nitrogen.

In 1972 the Consultative Group on International Agricultural Research (CGIAR) assigned to the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) the responsibility to serve as a world centre for the improvement of pigeonpea; mainly because it is one of the most important pulse crops of the world, and is a major source of protein to many people who depend largely or wholly on vegetarian diets. In spite of its importance, however, the crop had previously received inadequate attention from research workers. The productivity of local landraces was low and there appeared to be considerable scope for its improvement.

The action of the CGIAR in according global importance to pigeonpea has catalysed research upon the crop, not only by ICRISAT, but by interested national agricultural research institutes as well. There are now more than 11,000 pigeonpea germplasm accessions in the ICRISAT gene bank, basic knowledge about the crop's anatomy and physiology has been obtained, and disease-resistant and pest-tolerant cultivars have been produced.

More recently high-yielding, short-duration varieties and hybrids of pigeonpea with wide adaptation have been made available. They make it possible to take multiple harvests in a wide range of traditional and new locations. It is becoming a more important commercial crop in India, and shifting from a subsistence to a commercial crop in some other countries.

Because considerable new information on pigeonpea has been generated in the last two decades, three ICRISAT scientists led by Dr. Y.L. Nene, Deputy Director General, have produced this book, *The Pigeonpea,* with help from the CAB International. Chapters have been written by scientists at ICRISAT, in Australia, India, Indonesia and the Netherlands. Its 18 chapters cover a wide range of subject matter and it will, I am sure, prove useful to crop scientists all over the world. We hope it will stimulate further interest in this important and physiologically interesting crop. In the decades to come pigeonpea is likely to become a truly world crop through its diversification into non-traditional areas, and the expansion of its uses.

L.D. Swindale
Director General
ICRISAT

22 Jan 1990

Contributors

M. ALI, Principal Investigator and Head (Agronomy), Directorate of Pulses Research, Indian Council of Agricultural Research (ICAR), Kanpur 208 024, India.

Y.S. CHAUHAN, Crop Physiologist, Legumes Program, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Andhra Pradesh 502 324, India.

I.S. DUNDAS, Research Associate, Department of Agronomy, University of Adelaide, Waite Agricultural Research Institute, Glen Osmond, SA 5064, Australia.

D.G. FARIS, Principal Coordinator, Asian Grain Legumes Network, Legumes Program, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Andhra Pradesh 502 324, India.

S.C. GUPTA, Plant Breeder, Legumes Program, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Andhra Pradesh 502 324, India.

SUSAN D. HALL, Research Editor, Information Services, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Andhra Pradesh 502 324, India.

R. JAMBUNATHAN, Principal Biochemist and Program Leader, Grain Quality and Biochemistry Unit, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Andhra Pradesh 502 324, India.

C. JOHANSEN, Principal Agronomist, Legumes Program, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Andhra Pradesh 502 324, India.

J.V.D.K. KUMAR RAO, Crop Physiology, Legumes Program, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Andhra Pradesh 502 324, India.

S.S. LATEEF, Senior Entomologist, Legumes Program, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Andhra Pradesh 502 324, India.

R.J. LAWN, Principal Research Scientist, Commonwealth Scientific and Industrial Research Organization (CSIRO), Division of Tropical Crops and Pastures, The Cunningham Laboratory, 306 Carmody Road, St. Lucia, Queensland 4067, Australia.

LAXMAN SINGH, Principal Agronomist, Eastern African Regional Cereals and Legumes (EARCAL) Network, ICRISAT, C/o OAU/STRC, J.P.31 SAFGRAD, P.O. Box 30786, Nairobi, Kenya.

R.A.E. MÜLLER, Principal Economist, Resource Management Program, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Andhra Pradesh 502 324, India.

Y.L. NENE, Deputy Director General, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Andhra Pradesh 502 324, India.

P. PARTHASARATHY RAO, Senior Research Associate, Resource Management Program, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Andhra Pradesh 502 324, India.

L.J. REDDY, Plant Breeder, Legumes Program, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Andhra Pradesh 502 324, India.

M.V. REDDY, Senior Plant Pathologist, Legumes Program, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Andhra Pradesh 502 324, India.

W. REED, Former Principal Entomologist, Legumes Program, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Andhra Pradesh 502 324, India.

P. REMANANDAN, Botanist, Genetic Resources Unit, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Andhra Pradesh 502 324, India.

K.B. SAXENA, Senior Plant Breeder, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Andhra Pradesh 502 324, India.

D. SHARMA, Grain Legume Breeder, Malang Research Institute for Food Crops (MARIF), P.O. 66, Malang 65101, East Java, Indonesia.

S.B. SHARMA, Nematologist, Legumes Program, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Andhra Pradesh 502 324, India.

V.K. SHEILA, Senior Research Associate, Office of the Deputy Director General, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Andhra Pradesh 502 324, India.

U. SINGH, Biochemist, Grain Quality and Biochemistry Unit, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Andhra Pradesh 502 324, India.

K.V. SUBBA RAO, Senior Research Associate, Resource Management Program, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Andhra Pradesh 502 324, India.

R.J. TROEDSON, Senior Research Officer, Department of Agriculture, University of Queensland, St. Lucia, Queensland 4067, Australia.

L.J.G. van der MAESEN, Professor, Department of Plant Taxonomy, Agricultural University, Wageningen, the Netherlands.

E.S. WALLIS, Group Manager, Bureau of Sugar Experiment Stations, P.O. Box 86, Indooroopilly, Queensland, Australia.

Acknowledgements

The editors thank the following ICRISAT staff members for their help in the compilation and production of this book:
J.B. Wills, Head, Information Services;
G.J. Michael, Sankari Chandrashekar, C.P. Jaiswal, and D.C. Venkaiah for typing;
S.M. Sinha for art direction and A.A. Majid for art work.
A.B. Chitnis, P. Linganna, K. Kabeer Das, and L. Vidyasagar for photographic work;
T.R. Kapoor, K.K. Purkayastha, K. Chandrashekara Rao, and K.S.T.S.V. Prasad for composition.
They also thank The Book Project, Stanton, Worcs, UK for preparing the line diagrams, and B.D. Hall for general support.

Chapter 1

PIGEONPEA: GEOGRAPHY AND IMPORTANCE

Y.L. NENE and V.K. SHEILA

Deputy Director General and Senior Research Associate, Office of the Deputy Director General, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Andhra Pradesh 502 324, India.

INTRODUCTION

Pigeonpea (*Cajanus cajan* (L.) Millspaugh) is one of the major grain legume (pulse) crops of the tropics and subtropics. Endowed with several unique characteristics, it finds an important place in the farming systems adopted by smallholder farmers in a large number of developing countries. Although pigeonpea ranks sixth in area and production in comparison to other grain legumes such as beans, peas, and chickpeas, it is used in more diverse ways than others. Besides its main use as dhal (dry, dehulled, split seed used for cooking), its tender, green seeds are used as a vegetable, crushed dry seeds as animal feed, green leaves as fodder, stems as fuel wood and to make huts, baskets, etc., and the plants are also used to culture the lac-producing insect. Pigeonpea plants are often used as a living fence around small farms. It is grown on mountain slopes to reduce soil erosion. Pigeonpea seed protein content (on average approximately 21%) compares well with that of other important grain legumes.

WORLD DISTRIBUTION

All the evidence gathered to date points to peninsular India as the place where pigeonpea originated. The name "pigeonpea" probably originated in the Americas, where it reached sometime in the 15th Century, because the seeds were found to be favoured by pigeons (Pundir *et al.*, 1989). It is now widely grown in the Indian subcontinent which accounts for almost 90% of the world's crop. Other regions where pigeonpea is grown are Southeast Asia, Africa, and the Americas. There is substantial area of pigeonpea in Kenya, Uganda, and Malawi in eastern Africa, and in the Dominican Republic and Puerto Rico in Central America. In most other countries pigeonpea is grown in small areas and as a backyard crop. Table 1.1 includes available information on pigeonpea area and production in different countries, but it is often felt that the information on area and

Table 1.1. World production of pigeonpea.

Country	Area ('000 ha)	Production (t)	Year	References
ASIA and OCEANIA				
Australia	5	na[1]	1985/86	Meekin *et al.*, 1988
Bangladesh	2.460	1 700	1985/86	ICRISAT, 1990
India	2 973	2 230 000	1979-84	ICRISAT, 1990
Myanmar (Burma)	83	52 000	1985/86	Wallis *et al.*, 1988
Nepal	18	9 000	1987/88	ICRISAT, 1990
Pakistan	2	1 000	1972	Sharma and Green, 1975
Thailand	1	na	1988	ICRISAT, 1990
AFRICA				
Kenya	164	na	1981	Omanga and Matata, 1987
Malawi	35	20 000	1972	Sharma and Green, 1975
Tanzania	22	11 000	1972	Sharma and Green, 1975
Uganda	63	22 000	1985	Nalyongo and Emeetai-Areke, 1987
AMERICAS				
Antigua	0.008	5	1978	Brathwaite, 1981
Barbados	0.003	1	1978	Brathwaite, 1981
Dominican Republic	13.941	14 545	1978	Brathwaite, 1981
Grenada	0.607	36	1978	Brathwaite, 1981
Guadeloupe	0.200	60	1978	Brathwaite, 1981
Guyana	0.016	7	1978	Brathwaite, 1981
Haiti	6.667	4 000	1978	Brathwaite, 1981
Jamaica	2.800	1 510	1978	Brathwaite, 1981
Panama	2.703	3 436	1978	Brathwaite, 1981
Puerto Rico	3	4 000	1972	Sharma and Green, 1975
St. Kitts/ Nevis/Anguilla	0.004	3	1978	Brathwaite, 1981
St. Lucia	0.052	16	1978	Brathwaite, 1981
St. Vincent	0.056	50	1978	Brathwaite, 1981
Trinidad and Tobago	0.178	150	1978	Brathwaite, 1981
Venezuela	11	6 000	1972	Sharma and Green, 1975

[1] na = data not available.

production of pigeonpea is inadequate because the substantial proportion of pigeonpea grown as a backyard crop is not included in the statistics. Other pigeonpea-growing countries include:

Asia and Oceania	Afghanistan, Bhutan, Caroline Islands, Christmas Islands, Fiji, French Polynesia, Hong Kong, Indonesia, Japan, Kampuchea, Laos, Malaysia, Mariana Islands, New Caledonia, Papua New Guinea, the Peoples Republic of China, The Philippines, Pitcairn Island, Sri Lanka, Taiwan, Tonga, USSR, Vietnam;
Africa	Angola, Benin, Burkina Faso, Burundi, Cameroon, Congo-Brazzaville, Côte d'Ivoire, Egypt, Ethiopia, the Gambia, Ghana, Guinea-Bissau, Liberia, Madagascar, Madeira, Mali, Mauritius, Mozambique, Nigeria, Rwanda, São Tome, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, St. Helena, Sudan, Swaziland, Togo, Zaire, Zambia, Zimbabwe;
The Americas	Argentina, Bahamas, Belize, Bermuda Islands, Bolivia, Brazil, Colombia, Costa Rica, Cuba, Dominica, El Salvador, Equador, French Antilles, French Guyana, Guatemala, Honduras, Martinique, Mexico, Montserrat, Netherlands Antilles, Paraguay, Peru, St. Croix, St. Thomas, Suriname, Turks and Caicos Islands, USA; (Nene *et al.*, 1989; Nyabyenda, 1987; van der Maesen, 1983, 1986).

Pigeonpea is grown in almost all the states of India, but the major concentration is in the state of Uttar Pradesh in northern India and the states of Gujarat (eastern), Maharashtra (eastern), and Karnataka (north-east) in western India, and Madhya Pradesh (western) in central India (Figure 1.1).

PIGEONPEA AS A SOIL AMELIORANT

Pigeonpea is known to provide several benefits to the soil in which it is grown. Being a legume it fixes nitrogen. The leaf fall at maturity not only adds to the organic matter in the soil, but also provides additional nitrogen. In one experiment where maize followed pigeonpea, the residual nitrogen was estimated to be approximately 40 kg ha^{-1} (Kumar Rao *et al.*, 1981).

Pigeonpea is outstanding in the depth and lateral spread of its root system, which incidentally enables it to tolerate drought. Its root system is reported to break the plough pans, thus improving soil structure. No wonder that pigeonpea is often called a "biological plough". Pigeonpea plants can adapt to a wide range of soil types from gravelly stones to heavy clay loams of close texture and high moisture content, provided there is no standing water on the soil surface. Farmers in India often grow pigeonpea on poor soils where they have problems in growing other crops. Pigeonpea can tolerate salinity and alkalinity, but not excessive acidity; i.e., pH below 5.0.

The deep root system allows for optimum moisture and nutrient utilization. Pigeonpea seems to have special mechanisms to extract phosphorus from some soils (e.g., black Vertisols) to meet its needs. Extensive ground cover by pigeonpea prevents soil erosion by wind and water, encourages filtration, minimizes sedimentation, and smothers weeds. Pigeonpea is often grown on mountain slopes (e.g., in the Dominican Republic) to utilize their poor soils and to reduce soil erosion (Figure 1.2).

Growing pigeonpea continuously may have adverse effects on succeeding pigeonpea crops - an allelopathic effect which could be due to a build up of pathogenic microflora and microfauna, or to toxic products released during the decomposition of leaf litter and roots.

SIGNIFICANCE IN CROPPING SYSTEMS

Pigeonpea is a perennial, but is most often cultivated as an annual (Figure 1.3). Traditional landraces and cultivars of pigeonpea are harvested after 180-280 days, though the plants may be left in the

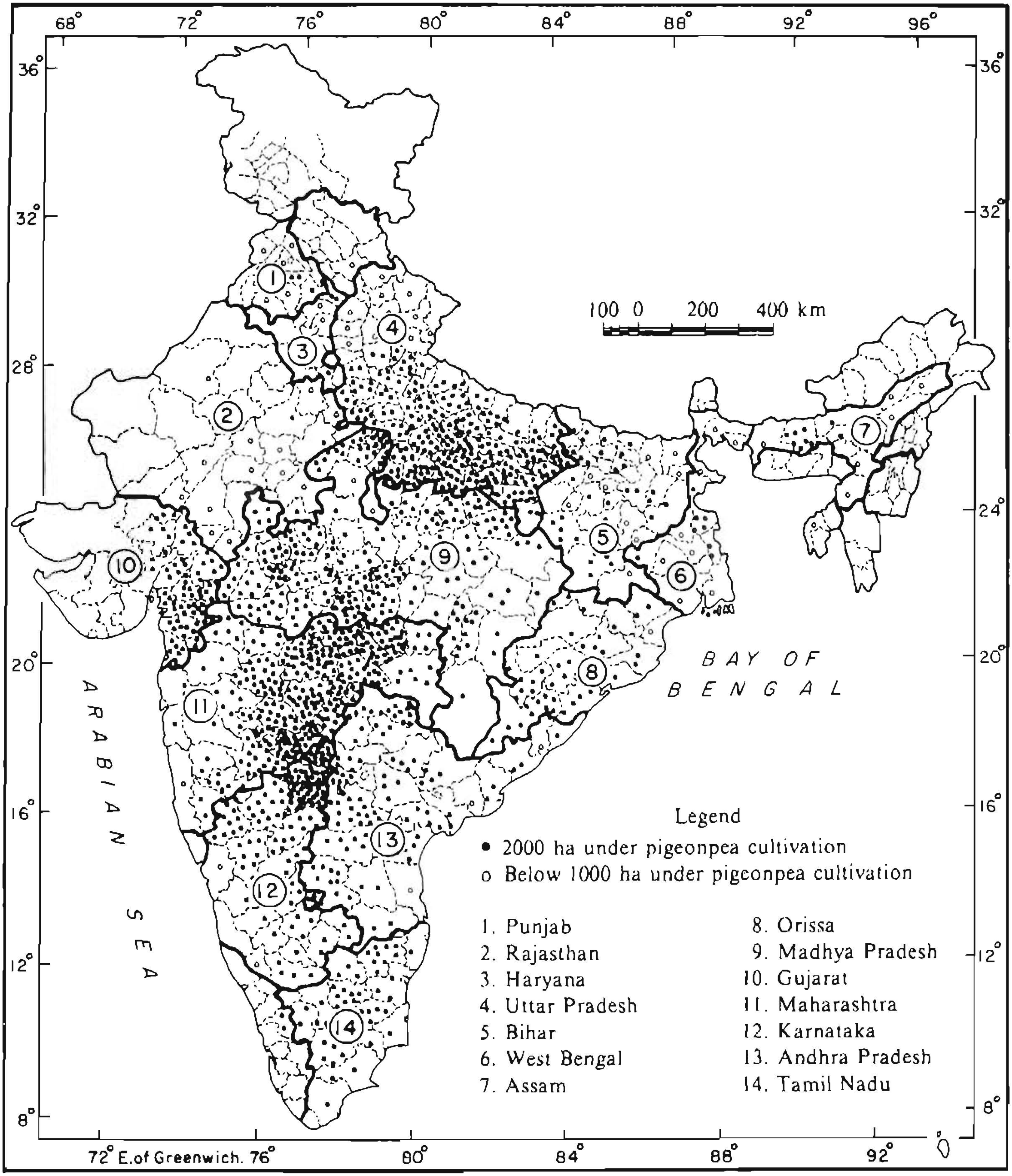


Figure 1.1. Distribution of pigeonpea in India (1979/80).

Source: Data from Government of India (Ministry of Agriculture), 1981.

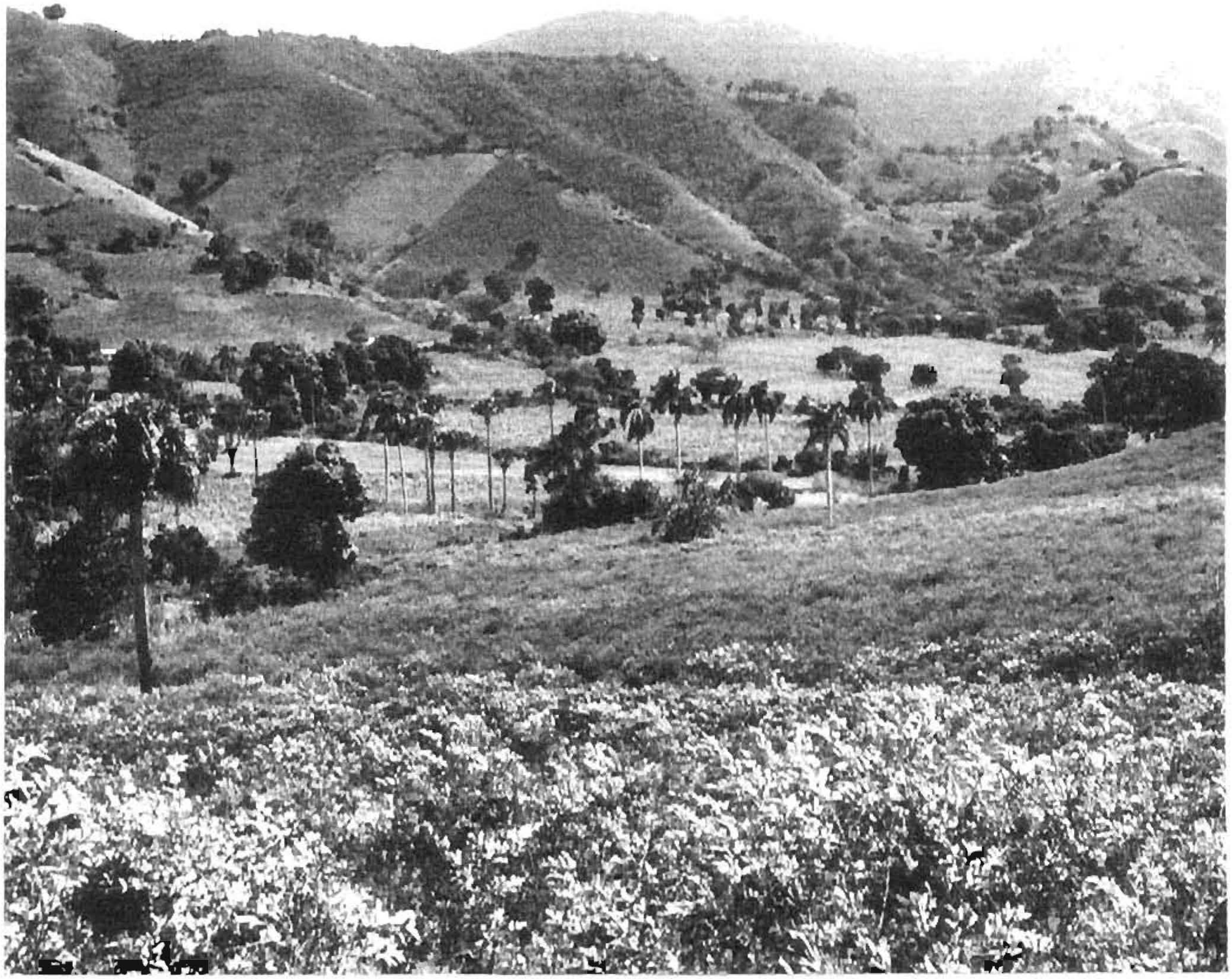


Figure 1.2. Pigeonpea growing on mountain slopes in the Dominican Republic.

field to regrow and provide browsing for animals. In many parts of Africa and Central America where pigeonpea is grown as a backyard crop, its perennial habit enables the production of multiple harvests. The short-duration cultivars (100-140 days) (Figure 1.4) are also used in multiple harvest systems in parts of India.

Because of their long duration, the landraces and traditional cultivars are almost always grown as intercrops or in mixed cropping systems with shorter-duration crops. The latter are harvested at their maturity; the fields are then left for pigeonpeas to grow on residual moisture and complete their lifespan with the first flush of mature pods. The new short-duration cultivars are grown as sole crops. Also grown as sole crops are the traditional cultivars sown 90-120 days later than normal, thereby giving the crop a short period in which to mature; however, this system is only possible in areas where winters are mild. In rainfed situations pigeonpea provides more stability of productivity over environments and seasons than the cereals with which it is intercropped (Singh and Subba Reddy, 1988).

Figure 1.3. A traditional, tall pigeonpea crop growing at ICRISAT Center, India.
Photo: ICRISAT.

Figure 1.4. Dwarf, short-duration pigeonpea breeding lines, University of Queensland, Australia, 1980.

Photo: ICRISAT.

On the Indian subcontinent pigeonpea is commonly intercropped with cereals (e.g., sorghum, pearl and other millets, maize, upland rice), other legumes (e.g., groundnut, soybean, mungbean, cowpea), or castor, cotton, sesame, sunflower, etc. In Africa it is commonly intercropped with maize, sorghum, cowpea, and cassava. In Central and South America the usual intercrop is maize. Pigeonpea/sorghum is one of the most widely adopted intercrop combinations on the Indian subcontinent and in Africa (Figure 1.5). It should also be noted here that intercropping sorghum and pigeonpea leads to significant reduction in the incidence of fusarium wilt of pigeonpea (Natarajan *et al.*, 1985).

Waterlogging, frost in winters, and highly acid soils adversely affect pigeonpea crops. There are many areas of eastern, central, and southern India and of Nepal where winters are mild and rainfall during the winter months is not excessive. Local landraces and traditional cultivars of pigeonpea are often grown successfully as sole crops in such situations to exploit the residual moisture in the soil. The short-duration pigeonpeas recently introduced in India now make it possible to grow a sole crop of pigeonpea before the major postrainy-season crop of wheat is sown, something that was not possible earlier with traditional, long-duration pigeonpeas.

Figure 1.5. A pigeonpea/sorghum intercrop, ICRISAT Center, 1980.
Photo: ICRISAT.

USES

As mentioned earlier, pigeonpea is used in a wide variety of ways. Its main use in the Indian subcontinent is as human food. The dry seed (Figure 1.6) is dehulled and the split cotyledons, that are called dhal (Figure 1.6), are cooked to make a thick soup primarily for mixing with rice. This is the way generations of Indian people on the subcontinent have used pigeonpea for over 2000 years. Indian immigrants no matter where and when they moved, still retain their preference for pigeonpea dhal over dhals made from other grain legumes. In Africa and Central America whole dry seeds without the seed coat are cooked alone without the seed coat, or together with meat. Sometimes sprouted seeds are consumed, and the flour or split seeds are used for making soups. Split dry seed can be stored for longer periods than the dry whole seeds.

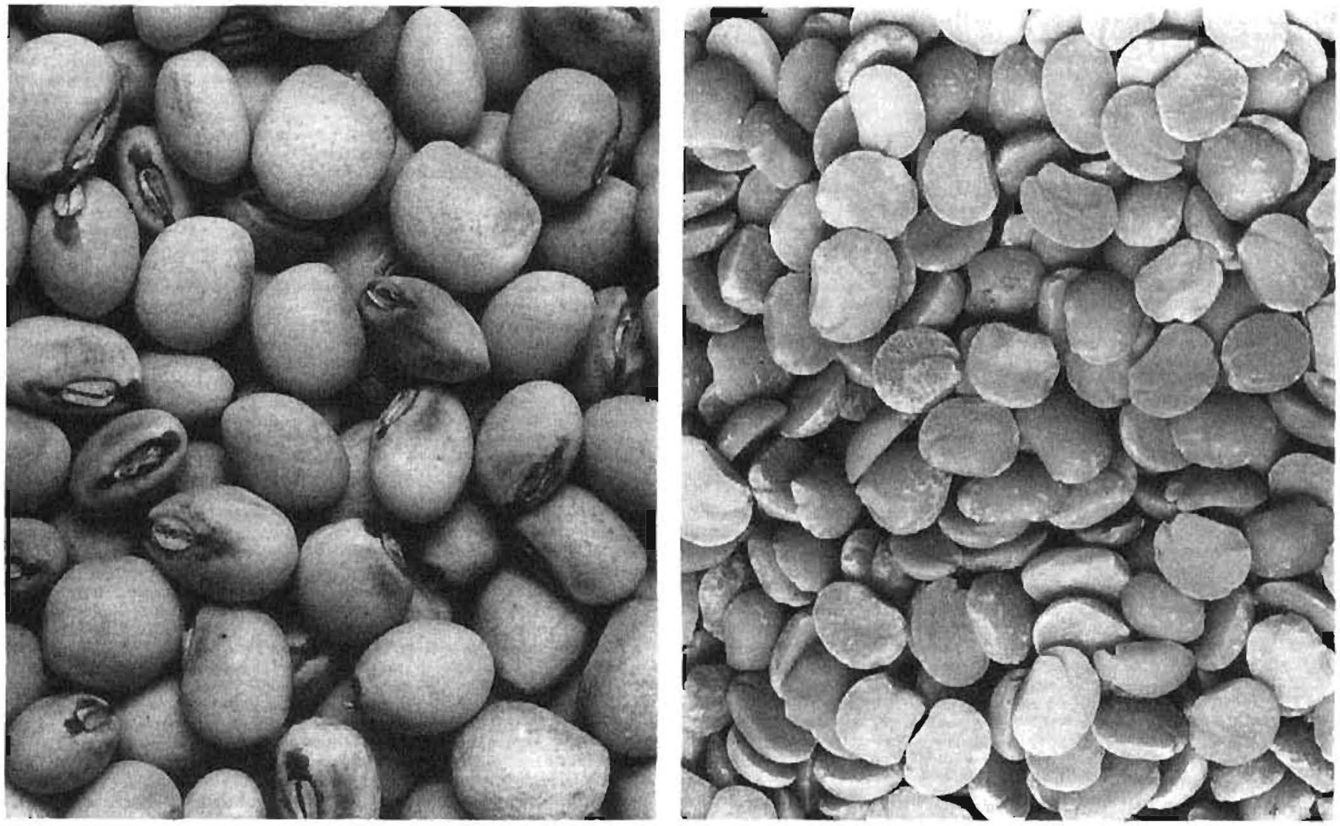


Figure 1.6. Pigeonpea seeds (left), and dhal (right) made from decorticated, split, dried seeds. Photo: ICRISAT.

Pigeonpea is a popular backyard or kitchen-garden crop, primarily grown for its green seeds or tender green pods (Figure 1.7). While green seeds are cooked as a vegetable, like garden peas, in Africa, Central America, and the states of Gujarat and Karnataka in India, tender pods (about 3-cm long) are cooked whole in Brazil, Thailand, and the eastern islands of Indonesia. Green pigeonpeas are processed for canning and freezing in Central America and India for export to North America.

The seed husks and pod walls are commonly fed to cattle, and green leaves are used as cattle fodder. After the pods are harvested (Figure 1.8), plants are often left in the field for cattle to graze the new green leaves such plants produce.

Pigeonpea is used as a green manure crop in some countries, the tall perennial plants sometimes serve as windbreak hedges, and occasionally pigeonpeas are used as shade for tree crops or vanilla (Duke, 1981). In parts of India and Central America, pigeonpea is grown as a perennial to mark field boundaries.

Pigeonpea dry stems are an important household fuel wood in many countries (Figure 1.9). Ten tonnes of dry sticks per hectare can be routinely obtained. These sticks are also used to make field fences, huts, and baskets.

In the state of Assam in eastern India and in Thailand pigeonpea crops grown for 2 to 3 years, serve as an important host for the scale insect that produces lac. Pigeonpea leaves are also used to feed silkworms.

Morton (1976) lists many folk medicinal uses for pigeonpea. Dry roots, leaves, flowers, and seeds are used in different countries to treat a wide range of ailments of the skin, liver, lungs, and kidney.

Figure 1.7. Vegetable pigeonpeas showing pods and fresh seeds.
Photo: ICRISAT.

FUTURE OF PIGEONPEA

As we have discussed earlier pigeonpea, unlike other food legumes, can simultaneously satisfy needs for food, feed, and fuel. It has an ameliorative effect on the soils in which it grows. It is a very hardy crop, growing well in marginal soils and fitting extremely well into diverse intercropping situations. Recent breeding efforts have lead to the development of disease-resistant, long-duration cultivars that were previously not available. The new relatively dwarf, short-duration cultivars and hybrids now allow cultivation of pigeonpea at latitudes up to 45° on both sides of the Equator, in contrast to the adaptation of traditional landraces and cultivars to latitudes between 32°N and S. Thus the future of pigeonpea as a world crop seems bright. The next few years should see a substantial increase in pigeonpea production on the Indian subcontinent and in eastern Africa, with some countries perhaps reaching the point of self-sufficiency. However, if pigeonpea is to extend to non-traditional areas, markets will have to be created to make its cultivation remunerative.

At present green pigeonpea seed is used as a vegetable in Central America, Africa, and a few states in India. There is, however, tremendous scope for increase in pigeonpea vegetable production in countries of the Indian subcontinent, Southeast Asia, and Africa. Recent efforts to produce pigeonpea hybrids especially for better and sweeter green seed should contribute towards

Figure 1.8. Pigeonpea pods of a grain cultivar.
Photo: ICRISAT.

popularizing pigeonpea as a vegetable. Canning and freezing green pigeonpea seed is mainly done in Central America and this industry could very well expand to other areas. Even tender green pods as used in Indonesia, and sprouted pigeonpea seed can be canned and marketed.

The use of pigeonpea as animal feed is bound to increase in many regions of the world. Pigeonpea grain has been found useful in the rations of pigs and poultry, and can be substituted for currently used soybean to some extent. Fortunately pigeonpea genotypes with high seed protein (29%) have been produced by scientists at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), and these should prove useful in situations where the grain is to be used in animal rations. Pigeonpea leaves provide excellent fodder to grazing animals, particularly in seasons when green fodder is scarce in the semi-arid tropics.

Of late pigeonpea is being considered a potential crop for marginal lands on the plains as well as on hilly slopes, not only to ameliorate soils, but also to prevent soil erosion. Pigeonpea could be useful for the hilly lands which occupy 30% of tropical Asia, and for marginal lands in Australia and the Americas. The potential of pigeonpea as a cover crop in the new rubber plantations of Thailand and Indonesia has been demonstrated (Wallis *et al.*, 1988). Recent ICRISAT studies indicate that pigeonpea has excellent potential for use in agroforestry systems. With the increasing shortage of fuel wood in villages, pigeonpea sticks are likely to be in demand for fuel, and many smallholder farmers will be tempted to grow more pigeonpea.

It will be absolutely necessary to increase research and technology development in pigeonpea utilization. Recent work indicates that pigeonpea starch can be used to make noodles that compare

Figure 1.9. A cartload of pigeonpea stalks that are used as fuel wood, Tadanapalli village, India.
Photo: ICRISAT.

well with those presently made from mung bean starch. Likewise fermented foods such as tempe, normally made from soybean, can be successfully made from pigeonpea. Another possible product is instant dhal made from pre-cooked split pigeonpea seed. This should prove very popular in both traditional and non-traditional pigeonpea-consuming areas. Cowpea is more popular in Africa than pigeonpea, possibly because whole cowpea seed takes less time to cook than whole pigeonpea seed. If pigeonpea lines with white seed that cook faster than traditional types are developed, pigeonpea could become a viable substitute for cowpea and could then also offer its other unique advantages to farmers in Africa. In Venezuela a local soft drink/mild liquor called "chicha" which is usually prepared from rice, can also be prepared from pigeonpeas, and is considered very tasty. This could be one more possibility of utilizing pigeonpeas.

Recent studies in Bangladesh indicate the possibility of using pigeonpea to produce paper pulp (Razzaque *et al.*, 1986; Akhtaruzzaman *et al.*, 1986) and such a use should certainly increase the demand for pigeonpeas in non-traditional areas.

Here therefore is a crop that is available for use in many diverse ways; but much depends upon the interest and innovativeness of research workers as to whether pigeonpea remains a regional crop, or becomes a truly world crop.

Acknowledgement

The assistance of Mr K.S. Prasad, Assistant Cartographer, ICRISAT in the preparation of Figure 1.1 is appreciated.

REFERENCES

Akhtaruzzaman, A.F.M., Siddique, A.B. and Chowdhury, A.R. (1986) Potentiality of pigeonpea (arhar) plant for pulping. *Bano Biggyan Patrika* 15(1-2), 31-36.

Brathwaite, C.W.D. (1981) Diseases of pigeonpea in the Caribbean area. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 129-136.

Duke, J.A. (1981) *Handbook of Legumes of World Economic Importance.* Plenum Press, New York and London, pp. 33-37.

Government of India (Ministry of Agriculture) (1981) District-wise estimates of area and production of gram and tur, 1979-80 (final). *Agricultural Situation in India* 36, 442-449.

ICRISAT (1990) *Agroclimatology of Asian Grain Legume Growing Areas. Research Bulletin no.14.* Patancheru, A.P., India: ICRISAT.

Kumar Rao, J.V.D.K., Dart, P.J. Matsumoto, T. and Day, J.M. (1981) Nitrogen fixation by pigeonpea. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 190-199.

Meekin, S., Troedson, R.J., Byth, D.E. and Wallis, E.S. (1988) Release of Quantum in Queensland, Australia. *International Pigeonpea Newsletter* 7, 6-8.

Morton, J.F. (1976) The pigeonpea (*Cajanus cajan* Millsp.), a high protein tropical bush legume. *HortScience* 11(1), 11-19.

Nalyongo, P.W. and Emeetai-Areke, T.E. (1987) Groundnut and pigeonpea production and improvement in Uganda. In: *Research on Grain Legumes in Eastern and Central Africa. Summary Proceedings of the Consultative Group Meeting for Eastern and Central African Regional Research on Grain Legumes (Groundnut, Chickpea, and Pigeonpea), 8-10 December 1986, International Livestock Centre for Africa (ILCA), Addis Ababa, Ethiopia.* Patancheru, A.P., India: ICRISAT, pp. 71-80.

Natarajan, M., Kannaiyan, J., Willey, R.W. and Nene Y.L. (1985) Studies on the effects of cropping system on fusarium wilt of pigeonpea. *Field Crops Research* 10, 333-346.

Nene, Y.L., Sheila, V.K. and Sharma, S.B. (1989) *A World List of Chickpea (Cicer arietinum L.) and Pigeonpea (Cajanus cajan(L.) Millsp.) Pathogens. Legumes Pathology Progress Report-7.* Patancheru, A.P., India: ICRISAT, 23 pp.

Nyabyenda, P. (1987) Grain legume production in Rwanda. In: *Research on Grain Legumes in Eastern and Central Africa. Summary Proceedings of the Consultative Group Meeting for Eastern and Central African Regional Research on Grain Legumes (Groundnut, Chickpea, and Pigeonpea), 8-10 December 1986, International Livestock Centre for Africa (ILCA), Addis Ababa, Ethiopia.* Patancheru, A.P., India: ICRISAT, pp. 57-58.

Omanga, P.A. and Matata, J.B.W. (1987) Grain legume production in Kenya. In: *Research on Grain Legumes in Eastern and Central Africa. Summary Proceedings of the Consultative Group Meeting for Eastern and Central African Regional Research on Grain Legumes (Groundnut, Chickpea, and Pigeonpea), 8-10 December 1986, International Livestock Centre for Africa (ILCA), Addis Ababa, Ethiopia.* Patancheru, A.P., India: ICRISAT, pp. 51-56.

Pundir, R.P.S., Remanandan, P. and Sastry, D.V.S.S.R. (1989) Status of the world collection of pigeonpea germplasm at ICRISAT. In: *Collaboration on Genetic Resources. Summary Proceedings of a Joint ICRISAT/NBPGR (ICAR) Workshop on Germplasm Exploration and Evaluation in India, 14-15 November 1988, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 31-34.

Razzaque, M.A., Das, S.C., Shaheen Akhter and Sayeed, M. (1986) Economic and chemurgic prospects of *Cajanus cajan*. *Bano Biggyan Patrika* 15(1-2), 16-20.

Sharma, D. and Green, J.M. (1975) Perspective of pigeonpea and ICRISAT's breeding program. In: *International Workshop on Grain Legumes, 13-16 January 1975, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 19-29.

Singh, R.P. and Subba Reddy, G. (1988) Identifying crops and cropping systems with greater production stability in water-deficit environments. In: Bidinger, F.R. and Johansen, C. (eds), *Drought Research Priorities for the Dryland Tropics.* Patancheru, A.P., India: ICRISAT, pp. 77-85.

van der Maesen, L.J.G. (1983) *World Distribution of Pigeonpea. Information Bulletin no. 14.* Patancheru, A.P., India: ICRISAT, 40 pp.

van der Maesen, L.J.G. (1986) *Cajanus DC. and Atylosia W.&A. (Leguminosae). Agricultural University Wageningen Papers 85-4 (1985).* Agricultural University, Wageningen, the Netherlands, 225 pp.

Wallis, E.S., Woolcock, R.F. and Byth, D.E. (1988) *Potential for Pigeonpea in Thailand, Indonesia and Burma. CGPRT no. 15.* Bogor, Indonesia: CGPRT Centre, 74 pp.

Chapter 2

PIGEONPEA: ORIGIN, HISTORY, EVOLUTION, AND TAXONOMY

L.J.G. van der MAESEN

Professor, Department of Plant Taxonomy, Agricultural University, Wageningen, the Netherlands.

INTRODUCTION

The pigeonpea, *Cajanus cajan* (L.) Millspaugh, has been distributed to most tropical countries, but is of major importance in India and eastern Africa. Despite a lack of very ancient remains, some contrasting opinions about its origin exist. It may be satisfactorily concluded that pigeonpea originated in India and spread quite early. A secondary centre of diversity of the species is found in eastern Africa. Ancient Sanskrit sources might still clarify the early travels of the pigeonpea. The recent taxonomy as revised by van der Maesen (1986) does not yet need an update, and is presented here in abridged form.

The genus *Cajanus* as accepted in the broad sense, including the former genus *Atylosia*, also has two areas of diversity. Seventeen species occur in the Indian subcontinent, and another 13 species are almost all endemics of Australia. The Australian species must have developed from *ancestral complexes separated from the Asian group of species when Australia separated from mainland Asia after the Pleistocene.*

ORIGIN

Pigeonpea originated in India, as is made likely by the presence of several wild relatives, (including the nearest one), the large diversity of the crop gene pool, ample linguistic evidence, a few archaeological remains, and the wide usage in daily cuisine.

De (1974) and Vernon Royes (1976) prepared reviews that include discussion of the pigeonpea's origin. The latter considered the dispute settled in favour of Indian origin. Further considerations also clarified this (van der Maesen, 1980). Several authors considered eastern Africa as the "centre of origin", since pigeonpea seems to occur wild in Africa. While reports of wild plants in India are scarce, the intensity of grazing animals in India easily explains this difference. The scarce but often cited archaeological evidence of one seed in an ancient Egyptian tomb, and the wild occurrence in Africa made many authors (Purseglove, 1968; Rachie and Roberts, 1974) favour an African origin. The range of diversity of the crop in India is much larger, and this made Vavilov (1951) list the pigeonpea as of Indian origin.

Africa harbours only one close wild relative of pigeonpea, *C. kerstingii* Harms, the other wild relative is the widespread *C. scarabaeoides* (L.) Thouars which apparently arrived in Africa relatively recently, since its distribution is limited to coastal areas (van der Maesen, 1979). India and Myanmar (formerly Burma) account for 16 related wild species, one of which, *Cajanus cajanifolius* (Haines) van der Maesen, could be considered as a progenitor. *Cajanus volubilis* (Blanco) Blanco, a species related to *C. crassus* (Prain ex King) van der Maesen, is restricted to some islands of Indonesia and the Philippines.

Australia, with 15 wild species of which 13 are endemic is another centre of diversity. Any direct role of this area in the origin of pigeonpea has to be ruled out since the island continent separated from Asia in the Upper Cretaceous, while contacts in the Pleistocene era via the Indonesian archipelago were limited. *Cajanus* progenitors must then have evolved along different lines in Australia and Asia, as almost no species is common between these continents. In drier parts of the southeast Asian islands a few species occur, including one only found in the Philippines and Indonesia. *Cajanus* spp., barring an occasional pigeonpea, are not found in the humid tropics.

ARCHAEOLOGICAL REMAINS

Many references point to the presence of pigeonpea seeds (as *Cajanus indicus*=*C. cajan*) in an Egyptian tomb of the 12th Dynasty (2200-2400 BC) at Dra Abu Negga (Thebes) (Schweinfurth, 1884), but this concerns only a single seed in a grave offering of several agricultural seeds, such as faba beans (*Vicia faba* L.), and dried grape skins. The seed, which has not been inspected recently, is probably in the Cairo Museum. Schweinfurth saw the seed in the museum then at Boulak, in a glass case containing the mentioned funeral offerings. Pigeonpea seeds are not so conspicuous as some other pulses, so scrutiny for more evidence is required. The pigeonpea seed did not differ from those of plants with yellow flowers then grown in Egypt. At present pigeonpea is still grown as a minor hedge crop by some farmers along the Upper Nile. Grain legumes are not common in grave offerings, as they were considered unclean by the priestly class. Recently some archaeological remains of small-sized pigeonpea from Bhokardan in Maharashtra, India (Kajale, 1974) were dated from the 2nd Century BC to the 3rd Century AD, and hence do not support a very ancient use in India. A lack of further documented finds makes conclusions on this basis alone impossible. The absence of a very distinctive seed shape does not facilitate identification of pigeonpea seeds from carbonized materials. Certainly with time more remains are likely to come to light.

WRITTEN HISTORY AND THE PIGEONPEA'S VERNACULARS

The name pigeonpea was first reported from plants used in Barbados where the seeds were once considered very useful as pigeon feed (Plukenet, 1692). The name has been translated into Dutch, French, German, Russian, and Spanish as one of the vernaculars in those languages.

The vernacular names of pigeonpea, of which about 350 have been recorded, including slight orthographic variants (van der Maesen, 1986) do not allow us to draw conclusions as to whether pigeonpea was first used in India or in Africa. Ancient written sources for African languages are absent, and pigeonpea has not been identified from Egyptian hieroglyphs. The African names are quite old, although their age cannot be ascertained. It seems logical that they influenced pigeonpea vernaculars in the Americas, but more details are needed.

In India, many Sanskrit names have their modern equivalents: Adhaki or Adhuku became Arhar, the Dravidian Tuvarai or Tuvari, used in Sanskrit since 300-400 AD, became Tur (De, 1974). Further searches in ancient manuscripts may reveal more about the earliest history and philology of pigeonpea (K.L. Mehra, personal communication). The crop has many ancient names in Indian languages, and several Sanskrit names have their modern equivalents.

The names of pigeonpea in the American hemisphere are derived from African and European tongues: an interesting subject for a linguist. The Portuguese "Guandu" and Spanish "Gandul" may have been derived from the Indian Telugu word "Kandulu" (van der Maesen, 1986), or have African roots, such as the Gabonese Fioffe "Oando", alternative suggestions are that Guandu or Gandul is a corruption of Cajan, that is the name pigeonpea took from the Malay Kacang (Vernon Royes, 1976). The names Angola pea (pois d' Angole), Congo pea, Kachang Bali, Ads Sudani, Cajan des Indes, Puerto Rican pea, Indischer Bohnenstrauch, and Lentille du Soudan all point to purported origins. Most of the names in European languages, like the name pigeonpea itself, were not framed earlier than during the 16th Century.

TAXONOMY OF *CAJANUS* AND *ATYLOSIA*

Pigeonpea, *Cajanus cajan* (L.) Millspaugh, is the only cultivated food crop of the Cajaninae subtribe of the economically most important leguminous tribe Phaseoleae, which contains the many bean species consumed by man (e.g., *Phaseolus, Vigna, Cajanus, Lablab, Macrotyloma*). Within the tribe Phaseoleae (twining, prostrate or erect herbs or subshrubs, usually pinnately trifoliolate leaves, with stipels and stipules, flowers in panicles or pseudoracemes, calyx with 4-5 teeth, corolla papilionaceous, stamens 9 fused and 1 free, pods 2-valved), the subtribe Cajaninae is well distinguished by the presence of vesicular glands on the leaves (usually more on the undersurface of the leaves), calyx, and pods. Eleven genera remain in the Cajaninae, the larger ones are *Rhynchosia* Lour. (130 spp.) and *Eriosema* (DC.) G. Don (200 spp.), other genera are *Dunbaria* W. and A. and *Flemingia* Roxb. ex Aiton. The Cajaninae are a very natural group. The cultivated pigeonpea stands alone as a crop species in the subtribe, of which most species belong outside the pigeonpea gene pool, or at the most in its tertiary gene pool, while several *Cajanus* species can be placed in the secondary gene pool (Table 2.1). Harlan and de Wet's subspecies classification (1971) is not followed, but their concept of gene pools is most useful. Lackey (1977, 1978, 1981) reviewed the Phaseoleae as a group and realigned Bentham's classical classification (Bentham, 1837; Bentham and Hooker, 1865) taking into account the genera described since the last century. Baudet's (1978) classification differs from that of Lackey in minor detail.

Table 2.1. Gene pools of pigeonpea.

Primary gene pool	Cultivar collections
Secondary gene pool	*Cajanus acutifolius*, *C. albicans*, *C. cajanifolius*, *C. lanceolatus*, *C. latisepalus*, *C. lineatus*, *C. reticulatus*, *C. scarabaeoides* var. *scarabaeoides*, *C. sericeus*, *C. trinervius*
Tertiary gene pool	*C. goensis*, *C. heynei*, *C. kerstingii* (?), *C. mollis*, *C. platycarpus*, *C. rugosus*, *C. volubilis*, other *Cajanus* spp.(?), other Cajaninae (e.g., *Rhynchosia*, *Dunbaria*, *Eriosema*)

The taxonomy of *Cajanus* DC. has recently been revised (van der Maesen, 1986). Its nearest relatives, earlier commonly classified in *Atylosia* W. and A., do not differ sufficiently from *Cajanus* to warrant generic status. Morphological, cytological, chemical, and hybridization data support this merger, even if the needed taxonomic changes are inconvenient.

Morphology

The only remaining key character, the presence of a seed strophiole in *Atylosia*, which is absent in *Cajanus*, is actually of little taxonomic importance. It is based on only two genes, a dominant one, and one with inhibitory action (Reddy *et al.*, 1981). Several pigeonpea accessions (approximately 200 out of about 10 000) possess a small strophiole, and a few have a conspicuous strophiole. Many hybrids of *Cajanus* × *Atylosia* are fertile, and do not deserve to be called intergeneric (McComb, 1975; see also De, 1974; Smartt, 1980). Since 1957 (Kumar *et al.*, 1958) there have been several reports of successful crosses between *Cajanus* and *Atylosia* spp. and several breeders (e.g., ICRISAT, 1986) utilize wild *Atylosia* species in their crossing programmes.

Cytogenetics

The cytological evidence supporting congenericity of *Cajanus* and *Atylosia* is considerable. High degrees of homology between chromosomes, among species which hybridize, have been reported (Deodikar and Thakar, 1956; Roy and De, 1965; Sikdar and De, 1967; Reddy, 1973, 1981a, b, c; Pundir, 1981; Dundas *et al.*, 1983, and I.S. Dundas, University of Adelaide, personal communication). Somatic karyotype and pachytene analysis have both offered useful methods to compare pigeonpea chromosomes with those of the related species.

There is no discrepancy between the chromosome number reports: all authors found $2n=22$ for *Cajanus (sensu lato)* spp and some *Rhynchosia* spp (van der Maesen, 1986).

Chemotaxonomy

The chemical constituents of *Cajanus* spp have not been investigated in a consolidated manner, the major reason being unavailability of research material. Lackey (1977) found all the Cajaninae he investigated, including seven species of *Cajanus*, lacking in canavanine, a compound mainly found in seeds of Papilionoideae. Harborne *et al.* (1971) summarized some chemical constituents, but it is difficult to draw taxonomical or evolutionary conclusions based on this rather inadequate information.

Seed protein electrophoresis might provide data that could be used to visualize evolutionary pathways. Remarkable similarities between pigeonpea and wild species again confirm congenericity (Ladizinsky and Hamel, 1980; Singh *et al.*, 1981; Pundir, 1981). The pattern of *C. cajanifolius* differed much more from the *C. cajan* pattern than the variation between *C. cajan* cultivars. *Cajanus platycarpus* and *C. volubilis*, both species with which pigeonpea does not produce hybrids, have patterns less homologous than other species, while *Rhynchosia rothii* was even more distinct. Krishna and Reddy (1982) studied the esterase isozyme pattern of seven *Cajanus* species, showing a closer homology between pigeonpea and *C. cajanifolius* than when compared with other species. Ladizinsky and Hamel (1980) suggested a polyphyletic origin of pigeonpea from several wild *(Atylosia)* species as each band in the *Atylosia* species had a homologue in the standard profile of pigeonpea, or in one of its variants.

Cajanus as here recognized now has 32 species. Some closely affiliated *Atylosia* species were considered conspecific and lowered to the rank of varieties (Table 2.2).

A sectional division of the genus groups the species into six sections. Section *Cajanus* contains pigeonpea, and its closest relative, *C. cajanifolius*. Crossing barriers between these two species are not insurmountable. Sections *Atylia* Benth. and *Fruticosa* van der Maesen contain the remaining erect species, sections *Cantharospermum* (W. and A.) Benth. and *Volubilis* van der Maesen cover the climbing species, while Section *Rhynchosoides* Benth. has three trailing species resembling some *Rhynchosia* spp, such as *R. aurea* DC. (Table 2.3). A comprehensive citation of specimens examined is presented by van der Maesen (1983, 1986).

The genus *Cajanus* is distributed in the old world, with 18 species in Asia, 15 in Australia, and one in Africa. All but two Australian species are endemic, the Indian subcontinent and Myanmar harbour eight endemic species, with the other species occuring over larger areas. Apart from the pigeonpea only one species, *Cajanus scarabaeoides* (L.) du Petit-Thouars is common and widespread throughout South and Southeast Asia, the Pacific Islands, and northern Australia. It has an endemic variety, var. *pedunculatus* (Reynolds and Pedley) van der Maesen, in Australia. Table 2.2 lists the species currently recognized, their most recent valid synonym, and their distribution. Pedley (1981) depicted the distribution of the Australian species. Detailed distribution data are compiled in the revision by van der Maesen (1986). Myanmar, Yunnan-China, and northern Australia are the areas where the greatest diversity of wild species can be found.

Habitat

Some species occur in grassy habitats (*Cajanus platycarpus*, *C. scarabaeoides*), although most are confined to open tropical semi-deciduous and wet forests, especially the fringes along open spaces. Overgrazing of the palatable legume species obviously restricts *Cajanus* to more or less protected habitats. All species of *Cajanus* grow at altitudes between 0 and 1500 m, except for *C. trinervius*, *C. rugosus*, *C. mollis*, and *C. grandiflorus*, which are high-altitude species more common above 800 to 2000 m. *Cajanus mollis* is mainly found above 700-800m. *Cajanus trinervius* occurs above 850 m, and has recently been found only above 1000 m in Sri Lanka and 2000 m in India.

Several species are rare. Even when searched for, *C. villosus* and *C. elongatus* in northeastern India have so far eluded collection for germplasm purposes. The most recent Indian specimens available in the herbarium date from 1895 for *C. villosus*, and from 1957 for *C. elongatus*. Two other species not recently found in India are *C. grandiflorus*, and *C. niveus* from Myanmar, which might also occur in Assam. Habitat destruction in accessible places is an obvious reason for retreat and perhaps extinction.

Table 2.2. Species recognized in the genus *Cajanus*, their basionyms or most widely known synonyms, and their distribution.

	Species	Basionym or most common synonym	Distribution
1	*Cajanus acutifolius* (F. v. Muell.) van der Maesen	*Rhynchosia acutifolia* F.v. Muell. ex Benth.	Australia
2	*Cajanus albicans* (W. & A.) van der Maesen	*Atylosia albicans* (W. & A.) Benth.	S. India, Sri Lanka
3	*Cajanus aromaticus* van der Maesen	-	Australia
4	*Cajanus cajan* (L.) Millsp.	*Cajanus indicus* Spreng.	Pantropic
5	*Cajanus cajanifolius* (Haines) van der Maesen	*Atylosia cajanifolia* Haines	SE. India
6	*Cajanus cinereus* (F. v. Muell.) F. v. Muell.	*Atylosia cinerea* F. v. Muell. ex Benth.	Australia
7	*Cajanus confertiflorus* F.v.Muell.	*Atylosia pluriflora* F.v. Muell. ex Benth.	Australia
8	*Cajanus crassicaulis* van der Maesen	-	Australia
9	*Cajanus crassus* (Prain ex King) van der Maesen	*Atylosia crassa* Prain ex King	S., SE. Asia
10	*Cajanus elongatus* (Benth.) van der Maesen	*Atylosia elongata* Benth.	NE. India, Vietnam
11	*Cajanus goensis* Dalz.	*Atylosia barbata* (Benth.) Bak.	India, SE. Asia
12	*Cajanus grandiflorus* (Benth. ex Bak.) van der Maesen	*Atylosia grandiflora* Benth. ex Bak.	NE. India, S. China
13	*Cajanus heynei* (W. & A.) van der Maesen	*Dunbaria heynei* W. & A.	SW. India, Sri Lanka
14	*Cajanus kerstingii* Harms	-	W. Africa
15	*Cajanus lanceolatus* (W.V. Fitzg.) van der Maesen	*Atylosia lanceolata* W.V. Fitzg.	Australia
16	*Cajanus lanuginosus* van der Maesen	-	Australia
17	*Cajanus latisepalus* (Reynolds & Pedley) van der Maesen	*Atylosia latisepala* Reynolds & Pedley	Australia
18	*Cajanus lineatus* (W. & A.) van der Maesen	*Atylosia lineata* W. & A.	S. India, Sri Lanka
19	*Cajanus mareebensis* (Reynolds & Pedley) van der Maesen	*Atylosia mareebensis* Reynolds & Pedley	Australia
20	*Cajanus marmoratus* (R. Br. ex Benth.) F. v. Muell.	*Atylosia marmorata* R. Br. ex Benth.	Australia
21	*Cajanus mollis* (Benth.) van der Maesen	*Atylosia mollis* Benth.	Himalaya foothills
22	*Cajanus niveus* (Benth.) van der Maesen	*Atylosia nivea* Benth.	Myanmar, S. China
23	*Cajanus platycarpus* (Benth.) van der Maesen	*Atylosia platycarpa* Benth.	Indian subcontinent, **Java**
24	*Cajanus pubescens* (Ewart & Morrison) van der Maesen	*Atylosia pubescens* (Ewart & Morrison) Reynolds & Pedley	Australia
	var. *mollis* Reynolds & Pedley	var. *mollis* Reynolds and Pedley	Queensland
	var. *pubescens*		Australia
25	*Cajanus reticulatus* (Dryander) F. v. Muell.		
	var. *grandifolius* (F. v. Muell.) van der Maesen	*Atylosia grandifolia* (F.v. Muell.) Benth.	Australia, New Guinea
	var. *reticulatus*	*Atylosia reticulata* (Dryander) Benth.	Australia
	var. *maritimus* (Reynolds & Pedley) van der Maesen	-	Australia
26	*Cajanus rugosus* (W. & A.) van der Maesen	*Atylosia rugosa* W. & A.	S. India, Sri Lanka
27	*Cajanus scarabaeoides* (L.) Thouars	*Atylosia scarabaeoides* (L.) Benth.	
	var. *pedunculatus* (Reynolds & Pedley) van der Maesen	var. *pedunculata* Reynolds & Pedley	Australia
	var. *scarabaeoides*	*Atylosia scarabaeoides* (L.) Benth.	S., SE. Asia, Pacific, coastal Africa
28	*Cajanus sericeus* (Benth. ex Bak.) van der Maesen	*Atylosia sericea* Benth. ex Bak.	S. India
29	*Cajanus trinervius* (DC.) van der Maesen	*Atylosia candollei* W. & A.	S. India, Sri Lanka
30	*Cajanus villosus* (Benth. ex Bak.) van der Maesen	*Atylosia villosa* Benth. ex Bak.	NE. India
31	*Cajanus viscidus* van der Maesen	-	Australia
32	*Cajanus volubilis* (Blanco) Blanco	*Cytisus volubilis* Blanco	Philippines, Indonesia

Table 2.3. Sections of the genus *Cajanus* (*sensu lato*).

	Major characters					
Section	Habit	Leaves	Hairs	Corolla	Strophiole	Species
1 *Atylosia* Benth.	Erect	Obovate to rounded	±Dense	Persistent	Divided	7
2 *Cajanus*	Erect	Elliptic-acuminate	Sparse	Caducous	Vestigial or divided	2
3 *Fruticosa* van der Maesen	Erect	Lanceolate to rounded	Absent to dense	Caducous	Divided	9
4 *Cantharospermum* (W. & A.) Benth.	Climbing, creeping	Obovate, apex acute to rounded	Sparse to ± dense	Caducous	Divided	5
5 *Volubilis* van der Maesen	Climbing	Rhomboid to rounded	± Dense	Persistent	Divided	6
6 *Rhynchosoides* Benth.	Trailing	Elongate to rounded	Sparse	Caducous	Horseshoe	3

KEY TO THE ASIAN AND AFRICAN SPECIES OF *CAJANUS*

(van der Maesen, 1986)

1 a Erect shrubs 2
b Climbing or creeping plants 8
2 a Widely cultivated for seed, sometimes an escape to the wild; ripe seeds without strophiole or with small vestigial strophiole .... **4. *C. cajan***
b Occurring wild; ripe seeds with conspicuous strophiole 3
3 a Leaflets elliptic-acuminate 4
b Leaflets obovate, tip rounded or acute 6
4 a Leaflets with acute tip, indumentum greyish short 5
b Leaflets thick, with rounded tip, indumentum golden brown, copious, long on leaf margin (S. India, Sri Lanka, hill tops) .... **29. *C. trinervius***
5 a Leaflets short-elliptic; pod wall thick, sutures 1 mm wide, tipped by ca 10-mm style (W. Africa) .... **14. *C. kerstingii***
b Leaflet as long-elliptic; pod wall thin, sutures inconspicuous, tipped by ca 2-mm style (E. Central India) .... **5. *C. cajanifolius***
6 a Leaves pinnately trifoliolate, leaflets rounded-obovate, whitish below; pods 4-6 seeded (Myanmar) .... **22. *C. niveus***
b Leaves digitately trifoliate, leaflets obovate-oblong, glaucous-green below 7
7 a Leaflets broad, with acute to rounded tip, stipules short, 2-3 mm (India, W. Ghats).. .... **18. *C. lineatus***
b Leaflets narrow, with rounded tip, stipules long, above 5 mm (India, W. Ghats, E. Ghats).. .... **28. *C. sericeus***
8 a Annual creeper in grass, pods flat, broad, papery .... **23. *C. platycarpus***
b Perennial creepers or twiners, pods narrower, more rounded and thicker 9
9 a Leaves pinnately trifoliolate 10
b Leaves (sub)digitately trifoliolate 16
10 a Leaflets membranaceous, thinly puberulous, pods with long caducous hairs 11
b Leaflets thick, more or less short indumentum 12
11 a Calyx with few conspicuous bulbous-based hairs (Philippines) .... **32. *C. volubilis***
b Calyx with fine hairs (India, Sri Lanka) .... **13. *C. heynei***
12 a Leaflets small, elliptic or obovate-obtuse, twiner in grasses (Asia, Africa, Australia) .... **27. *C. scarabaeoides***
b Leaflets larger, obovate-acuminate, climber in shrubs and trees 13
13 a Flowers large, ca 25-30 mm (NE. India, China) corolla persistent, calyx with bulbous-based hairs .... **12. *C. grandiflorus***
b Flowers generally smaller, less than 15-28 mm long, calyx hairs not bulbous-based .. 14
14 a Indumentum fine, spreading, green, bracts very hairy; corolla not persistent (India, SE. Asia) .... **11. *C. goensis***
b Indumentum short, dense and grey or golden brown below, bracts short-puberulous; corolla persistent 15
15 a Leaflets semi-coriaceous, densely grey-hairy below, end leaflets longer than broad; pods 8-10 seeded; flowering after the monsoon (Himalaya foothills above 800 m) . **21. *C. mollis***
b Leaflets coriaceous, brown-pubescent below, end leaflets broader than long; pods 3-5 seeded; flowering the first months of the year (India, below 800 m, SE. Asia)... .... **9. *C. crassus***
16 a Leaflets obovate-rounded (S. India, Sri Lanka) 17
b Leaflets obovate-acuminate (NE. India) 18
17 a Strong climber in trees, leaflets silvery below; pods (3-) 5-6 seeded .... **2. *C. albicans***
b Twiner in grasses, leaflets reticulate, densely grey-hairy below, pods (2-)3-4 seeded) .... **26. *C. rugosus***

18 a Slender herbaceous twiner in grasses, woody rootstock; pods small 2-2.5 × 0.5-0.8 cm, reticulate, 3-4 seeded, glabrescent .... **10. *C. elongatus***
b More robust twiner; pods larger 2-3.5 × 0.8-1.1 cm, not reticulate, 5-6 seeded, densely pubescent with long brown hairs .... **30. *C. villosus***

KEY TO THE AUSTRALIAN SPECIES OF *CAJANUS*

(van der Maesen, 1986)

1 a Shrubs, erect or with straggling branches 2
b Prostrately creeping plants, branches twining at the ends 13
2 a Cultivated, in Australia rather a new crop, or as an escape to the wild; ripe seeds without strophiole or with small vestigial strophiole .... **4. *C. cajan***
b Occurring wild, ripe seeds with conspicuous strophiole 3
3 a Leaflets narrow-lanceolate, 3 (or 1) per leaf .... **15. *C. lanceolatus***
b Leaflets rhomboid, ovate, obovate or rounded, 3 per leaf 4
4 a Leaves digitately trifoliolate .... **7. *C. confertiflorus***
b Leaves pinnately trifoliolate 5
5 a Leaflets thin-coriaceous to membranaceous, pubescence very short, apex acute 6
b Leaflets thick-coriaceous, pubescent, apex more obtuse 8
6 a Shrub with straggling branches, leaves viscid .... **31. *C. viscidus***
b Shrub erect, leaves glandular but not sticky 7
7 a Leaflets elongate to rounded-ovate, apex acute, almost non-aromatic; pods (1-)2-4 seeded .... **1. *C. acutifolius***
b Leaflets broadly ovate, apex, acute aromatic; pods (6-)8-10 seeded .... **3. *C. aromaticus***
8 a Stems very thick also towards the apex, whitish-pubescent; leaves very thick..9
b Stems thin also towards the apex, pubescence grey or brown; leaves reticulate, not so thick 10
9 a Indumentum white, very dense, covering stems and leaves; inflorescences much longer (up to 14 cm) than the leaves (up to 7 cm) .... **8. *C. crassicaulis***
b Leaves woolly, green with yellow-brown veins, young stems and peduncles visible through the white hairs; inflorescence as long as the leaves (up to 8-9 cm) .... **16. *C. lanuginosus***
10 a Calyx teeth lanceolate or acuminate 11
b Calyx teeth broad-acuminate .... **17. *C. latisepalus***
11 a Leaflets often large, rhomboid to rounded, to 12.5 cm long, tip acute to rounded, pubescence relatively thin, hairs long, on new leaves and branches dense and conspicuously golden brown, more rarely grey; calyx teeth linear-lanceolate, curved in open flower .... **25. *C. reticulatus***
b Leaflets smaller, to 5 (-7) cm long, elliptic to obovate, tip obtuse, pubescence silvery grey to brown; calyx teeth short-acuminate 12
12 a Leaflets quite thick, upper side reticulate, veins concolorous, top leaflets with 5-6(-8) pairs of major secondary veins, pubescence short, greyish below, not filling reticulations; pods narrow, short, pubescent, sutures narrow .... **24. *C. pubescens***
b Leaflets thick, upper side flat, veins whitish, top leaflet with 7-9 pairs of major secondary veins, pubscence very short, close, velvety, filling reticulations; pods broad, grey-velvety, pubescence very short, sutures broad .... **6. *C. cinereus***
13 a Leaflets rounded, apex obtuse or emarginate or acuminate; pods flat, broad .... **20. *C. marmoratus***
b Leaflets obovate or lanceolate 14
14 a Leaflets lanceolate; pods broad, flat, variegated with purple .... **19. *C. mareebensis***
b Leaflets obovate; pods small, more rounded, uniformly coloured .. **27. *C. scarabaeoides***

ENUMERATION OF *CAJANUS* SPECIES

The species are enumerated here in alphabetical order, with their synonymy, as in the recent monograph (van der Maesen 1986). A short descriptive phrase highlights the main features of the species; for a full description reference should be made to the monograph. The protologues (first descriptions) and abbreviated references in these paragraphs are not all repeated in the reference list at the end of the chapter, following taxonomic usage.

1. *Cajanus acutifolius* (F.v. Muell.) van der Maesen, Agr. Univ. Wageningen Pap. 85-4:52 (1986).
Drought-tolerant shrub, 1-2m, with thin leaves and pointed leaflets, 2-3-seeded pods.
Basionym: *Atylosia acutifolia* F.v. Muell., Pl. Fitzalan 9 (1860).
Type: Australia, N. Territory, Upper Victoria River, F. v. Mueller s.n. (lectotype: K; isolectotype: MEL). Paratype: Australia, N. Territory, Gulf of Carpentaria, F. v. Muell. s.n. (MEL).
Homotypic synonyms: *Rhynchosia acutifolia* (F. v. Muell.) F. v. Muell. ex Benth., Fl. Austral. 2:264 (1864); *Atylosia acutifolia* (F. v. Muell. "ex Benth.") Reynolds and Pedley, Austrobaileya 1:423 (1981).
Heterotypic synonym: *Rhynchosia quadricallosa* Domin, Bibliothek.
Bot. 89:782 (1926). Type: Australia, Queensland, nr Pentland, Domin III 1910 (holo: PR).
Flowering: Feb-Apr, Jun, Jul, Dec. (N. Territory); Feb., Apr-Sep. (Queensland).
Distribution: Australia, N. Territory, Queensland, W. Australia.
Ecology: near rocks, in stony soils, sand hills, riverbanks, in speargrass vegetations, in *Acacia* and *Eucalyptus* open forests, 0-600 m.

2. *Cajanus albicans* (W. and A.) van der Maesen, Agr. Univ. Wageningen Pap. 85-4:55 (1986).
A climber with obovate to rounded leaflets, grey-hairy below, flowers yellow, sometimes flag brown at the base, quite fertile when fruiting, pods 1.5-3.5 cm with short adpressed hairs, sutures sturdy, 5-7 grey seeds with black mosaic.
Basionym: *Cantharospermum albicans* W. and A., Prodr. 256 (1834).
Type: India, Dindigul Hills, 2500 feet, Wight 759a (E, holotype; isotypes: B, C, F, G, P).
Homotypic synonym: *Atylosia albicans* (W. and A.) Benth. in Miq., Pl. Jungh. 1:243 (1852); Baker in Hooker, Fl. Brit. India 2:215 (1876); Gamble, Fl. Madras 2:369 (1918), 260 (repr. 1967); Matthew, Illustr. Fl. Tamilnadu Carnatic 182 (1982).
Heterotypic synonyms: *Cajanus albicans* Graham ex Wallich, nomen nudum, Wallich's Cat. 5582 (E,G,K).
Cajanus wightianus Graham ex W. and A., Wallich's Cat. 5583 (1831), nomen nudum, based on India, Dindigul Hills, 1500-2500 feet, Hb. Wight, Wallich 5583 (BR, CAL, E, G, K, MEL, W).
Cajanus wightii Graham ex W. and A., Prod. 1:256 (1834), orthographic variant.
Flowering: Oct-Jan (-Apr.)
Distribution: Peninsular India, Sri Lanka.
Ecology: scrub vegetation, edge of dry deciduous forests.

3. *Cajanus aromaticus* van der Maesen, Agr. Univ. Wageningen Pap. 85-4:61 (1986).
Shrub up to 2 m high, with membranaceous aromatic leaves, very short hairs, flowers 6 together, peduncles up to ca 4 cm, and oblong pods, 3-4 cm, with 8-10 brown to dark brown seeds.
Type: Australia, N. Territory, Nimbuwah Rock, 45 km E of Oenpelli, Maconochie 1600 (holo: NT; iso: CANB, K).
Flowering: Apr-May.
Distribution: Australia, N. Territory.
Ecology: among broken sandstone boulders.

4. *Cajanus cajan* (L.) Millspaugh, Field Columb. Mus. Bot. 2-1:53 (1900), Purseglove, Trop. Crops, Dicot. 2:326-271 (1968); De, Evol. Studies World Crops (Hutchinson, J., ed.) 79-87 (1974); Westphal, Pulses Ethiopia 64,71 (1974); Kay, Food Legumes, TPI Crop and Product Digest 3:322-347 (1979); van der Maesen, Agr. Univ. Wageningen Pap. 85-4: 65-91 (1986); van der Maesen in van der Maesen and Somaatmadja, Prosea Handbook 1, Pulses: 39-42 (1989) (Figure 2.1).

A shrubby legume crop in cultivation, 1.5-4 m tall, under short-day conditions short-statured cultivars remain shorter than 1 m. Flowers bright yellow, sometimes with dorsally red flags or red or purple veins, either in determinate inflorescences with flowers much at the same level and flowering within a short period, or flowering indeterminate with flowers along the branches appearing over extended periods. Pods 4-9-seeded, narrow and well-filled (grain cultivars) or broad and loosely filled (vegetable cultivars). Seeds globose or compressed, ellipsoid or rarely cowpea- or bean-shaped, longest axis usually parallel to the longest pod axis, white, cream, brown, purplish, or virtually black, plain or blotched with a contrasting colour. Seeds weigh 4 to 26 g per 100 seeds with a greenish strophiole when immature, vestigial or disappeared at maturity.

Basionym: *Cytisus cajan* L., Species Plantarum 739 (1753).

Type: Ceylon, *Cytisus racemis axillaribus erectis intermedio longius petiolato* Hermann Herb. I, Fol. 14 (lectotype: BM).

Homotypic synonyms: *Cytisus cayan* L. ex Mill., Gard. Dict. ed. 8, no. 11 (1768), orthographic variant.

Cajanus indicus Spreng., Syst. 3:248 (1826), based on *Cytisus cajan* L., *Cytisus pseudo-cajan* Jacq., *Cajanus flavus* DC. and *Cajanus bicolor* DC. Under this name the pigeonpea has been mainly known up to the 1940s, and even now this synonym crops up occasionally. For the many references see van der Maesen (1986).

Cajanus striatus Bojer, Hort. Maurit. 109 (1837).

Cajan cajan (L.)Huth, Helios 11:133 (1893).

Cajanus cajan (L.) Merr., Fl. Manila 255 (1912).

Cajanus cajan (L.) Druce, Rep. Bot. Exch. Cl. Brit. Isles 1916:611 (1917); Baker, Legumin. Trop. Africa 459 (1926); Dalziel, Useful Pl. W. Trop. Afr. 233 (1937); Raponda-Walker and Sillans, Pl. Utiles Gabon 248 (1961); Santapau, Fl. Khandala 3rd ed. 76 (1967).

Cajanus cajan (L.) Millsp. f. *bicolor* (DC.) Bak., Legumin. Trop. Africa 460 (1929); Cufodontis, Enumeratio, Bull. Jard. bot. Brux. 25-3:321 (1955).

Cajanus cajan (L.) Millsp. var. *bicolor* (DC.) Purseglove? and var. *flavus* (DC.) Purseglove?, Trop. Crops, Dicot. 1:237 (1968).

Heterotypic synonyms: *Cytisus pseudocajan* Jacq., Hort. Bot. Vindob. 2:54, t. 119 (1772).

Type: Plate t. 119.

Cajanus bicolor DC., Cat. Hort. Monsp. 85 (1813); DC., Prodr. 2:406 (1825).

Type: plant cultivated at Montpellier from seed sent from India (G-DC, holo; microfiche 408.4).

Cajanus flavus DC., Cat. Hort. Monsp. 86 (1813); DC., Prodr. 2:406 (1825).

Type: plant cultivated at Montpellier (G-DC, holo; microfiche 408.6).

Cytisus guineensis Schum. and Thonn., Beskr. Guin. Pl. no. 208 (1827).

Type: Guinea, Whyda, Isert s.n. (C, holo).

Cajanum thora Rafin., Sylva Tellur. 25 (1838). Based on *Cytisus pseudocajan* Jacq.

Cajanus luteus Bello, Anal. Soc. Espan. Hist. nat. 10:260 (1881). As variety of *Cajanus indicus* Spreng.

Type: Puerto Rico 231, Don Domingo Bello y Espinosa (B?).

Atylosia cajanoides Cordem., Fl. Reunion 397 (1895), van der Maesen, Agric. Univ. Wageningen Pap. 85-4:213 (1986), is not a synonym of pigeonpea, but a hybrid between pigeonpea and *Cajanus scarabaeoides*, very similar to the hybrids obtained by crossing.

Cajanus indicus Spreng. var. *bicolor* (DC.) O. Ktze, Rev. Gen. Pl. 1:167 (1891).

Type: Portorico, St. Thomas (NY?).

Cajanus indicus Spreng. var. *flavus* (DC.) O. Ktze, Rev. Gen. Pl. 1:167 (1891).

Type: India, Dekkan (NY?).

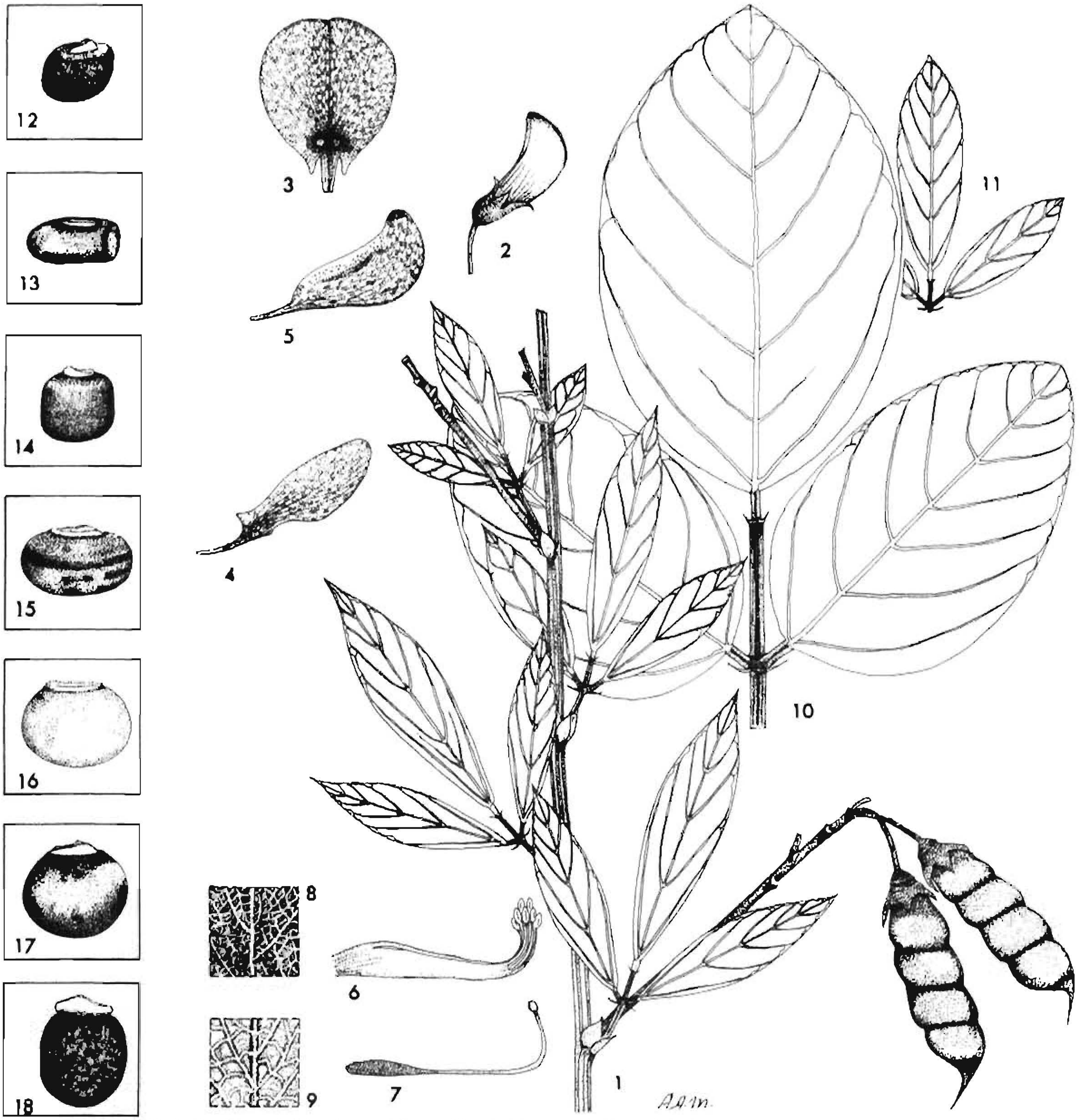


Figure 2.1. *Cajanus cajan:* 1. Branch, ×1;2. Flower, ×1½, 3. Flag, ×2;4. Wing ×2,5. Keel, ×2;6. Stamens, ×2;7. Pistil, ×2; 8. Detail upper leaflet surface, ×2;9. Detail lower leaflet surface, ×2; 10. Largest leaf, ×½, 11. Smallest leaf, ×½; 12-18. Seed shapes: 12, ×3; 13,14, ×2½; 15, 16-18, ×2; (1-9, *van der Maesen 4212*; 10, ICP 9150 from Machakos, Kenya; 11, ICP 9880 from Andhra Pradesh, India; 12, ICP 7332, small, from Madhya Pradesh, India; 13, ICP 9880, elongate, from Andhra Pradesh, India; 14, ICP 7568, square, from Madhya Pradesh, India; 15, ICP 7977, cowpea shape, from Andhra Pradesh, India; 16, pea shape, from Madhya Pradesh, India; 17, large, from Madhya Pradesh, India; 18, *van der Maesen 4212*, from Heho, Myanmar).

Source: van der Maesen, Agricultural University Wageningen papers 85-4, 1986.

Cajanus indicus Spreng. var. *maculatus* O. Ktze, Rev. Gen. Pl. 1:167 (1891).
Type: India, Bengal (NY?).

Cajanus pseudocajan (Jacq.) Schinz and Guillaumin, in Sarasin and Roux, Nova Caled. 1:159 (1920). Basionym: *Cytisus pseudocajan* Jacq.

Cajanus obcordifolia Singh, Indian J. Agric. Sci. 12:783 (1942).
Type: India, ex Gorakhpur, Bot. Garden Agric. Coll. Cawnpore (Kanpur), not preserved, mutant form, several genotypes available in germplasm collections.
Flowering: (Aug) Sep-Mar (-Apr) on the Indian subcontinent, throughout the year in Indonesia and probably in equatorial Africa, Jan, Apr, Oct-Nov in Puerto Rico, May-Aug in Kenya. Cultivars may take 56 to 210 days from sowing to flowering, pigeonpeas are usually short-day plants.
Distribution: pantropical, with the main areas of cultivation in the Indian subcontinent, eastern Africa, and Central America. For details see van der Maesen (1983).
Ecology: vegetative in the rainy season, fruiting in the dry season, semi-arid tropical cultivated crop, rarely found as an escape. Grown as an annual, sometimes persisting as a perennial in hedges, garden situations, commonly so in Kenya.

5. *Cajanus cajanifolius* (Haines) van der Maesen, Agr. Univ. Wageningen Pap. 85-4: 91.

The nearest wild relative of the pigeonpea, mainly differing by the densely white-pubescent lower leaf surface and the clearly strophioled seed with the longest axis perpendicular to the pod axis. The similarity to pigeonpea perhaps made the botanical collectors overlook this species when collecting in eastern peninsular India. There are still only few entries in herbaria and gene banks. Crossing with pigeonpea is possible, but at a rate lower than within pigeonpea, and the choice of the pigeonpea parent accession considerably influences the rate of success.
Basionym: *Atylosia cajanifolia* Haines, J. Asiatic Soc. Bengal 1919 new series 15: 312 (1920); Haines, Bot. Bihar and Orissa 3:273 (1922); idem 2:286 (repr.1961).
Type: India, forests of Orissa, Puri distr., Aran forest, Aitpur, Haines 3867 (K, holo; iso: BM, CAL).
Homotypic synonym: *Cantharospermum cajanifolium* (Haines) Raizada in Mooney, Suppl. Bot. Bihar and Orissa 53 (1950).
Flowering: Nov-Apr.
Distribution: India, S. Orissa and Bastar.
Ecology: tropical dry deciduous forest, in half shade and open grassland, tolerates high soil iron contents (Bailadila Hill).

6. *Cajanus cinereus* (F. v. Muell.) F. v. Muell., Census Austral. Pl. Suppl. 1-4:41 (1881); id., Second Census Austral. Pl. 1:71 (1889).

An erect greyish shrub with velvety leaves, 3-7 yellow flowers per bunch, flag sometimes dorsally brown striped, and oblong short-silvery hairy 3-4 cm pods with 4-6 reddish brown seeds with black mosaic. Probably quite drought-resistant.
Basionym: *Atylosia cinerea* F. v. Muell., Pl. Fitzalan 9 (1860); Bentham, Fl. Austral. 2:264 (1864); Reynolds and Pedley, Austrobaileya 1-4: 242 (1981).
Type: Australia, N. Territory, (Upper) Victoria River, F. v. Mueller s.n. (holo:K; iso: K, MEL).
Homotypic synonym: *Cantharospermum cinereum* (F. v. Muell.) Taub. ex Ewart and Davies, Fl. N. Territory 152 (1914).
Flowering: Apr-Aug.
Distribution: Australia, West Australia and Northern Territory, N of the Tropic of Capricorn.

7. *Cajanus confertiflorus* F. v. Muell., Pl. Fitzalan 9 (1890); id., Census Austral. Pl. Suppl. 1-4:41 (1881); id., Second Census Austral. Pl. 1:71 (1889).

Erect branched shrub, silvery hairy. Leaves coriaceous with conspicuous reticulate veins having medium long silvery hairs below. Flowers 5-10 per inflorescence, only 1-2 developing into oblong ca 3-cm pods, densely covered with long and short silvery hairs.
Type: Australia, Queensland, Burdekin Expedition, Magnetical Island, Fitzalan s.n. (holo: MEL?; iso: K?). Paratype: Australia, Rockhampton, Thozet 528 (MEL, P).
Heterotypic synonym: *Atylosia pluriflora* F. v. Muell. ex Benth., Fl. Austral. 2:264 (1864); Bailey, Queensland Fl. 2:439 (1900); Reunolds and Pedley, Austrobaileya 1-4: 423 (1981). Lectotype: Australia, Queensland, Burdekin Expedition, Fitzalan s.n. (holo: K; iso: MEL). Paratypes: Australia, Broad Sound Robert Brown s.n. (E, K, MEL); R. Brown 4207 without location (E, K); Rockhampton, Thozet (MEL, P); nr Princhester, Bowman 46 (MEL); Thozet's River, Dallachy (K, MEL).
Flowering: Dec-Apr, Jun-Jul, Sep, Nov.
Distribution: Australia, Queensland.
Ecology: in open *Eucalyptus* forest, grazing land, open exposed hillsides, on stony or coarse sandy alluvial soils.

8. *Cajanus crassicaulis* van der Maesen, Agr. Univ. Wageningen Pap. 85-4:103 (1986).
Erect shrub, up to 1.5 m with short whitish-velvety very dense hairs, and thick branches also at the end. Leaves very thick and hairy. Flowers 10-25 on long peduncles (to 14 cm), and pods sturdy, oblong, ca 3.5 cm, less hairy than stems, with 4-5 blackish seeds. Species newly described, only few specimens extant.
Type: Australia, N. Territory, 53 km W. Victoria River H/S, Latz 5307 (holo: NT; iso: CANB, DNA, K).
Flowering: May-Jun
Distribution: Australia, N. Territory and W. Australia, N of 20° S latitude.
Ecology: in skeletal soil, sandstone hill.

9. *Cajanus crassus* (Prain ex King) van der Maesen, Agr. Univ. Wageningen Pap. 85-4: 105.
Key to the varieties:
Pods short-puberulous (India, SE. Asia) .... var. *crassus*
Pods with long semi-caducous golden hairs (Myanmar, Yunnan) .... var. *burmanicus*

9a. *Cajanus crassus* var. *burmanicus* (Collett and Hemsley) van der Maesen, Agr. Univ. Wageningen Pap. 85-4:109 (1986).
A robust climber, differing from var. *crassus* by the long hairs on the slightly larger pods. Buds, bracts, and flowers also are larger than those of the typical variety, at least in cultivation.
Basionym: *Atylosia burmanica* Collett and Hemsley, J. Linn. Soc. 28:49 (1890).
Type: Myanmar, Shan Hills, 5000 feet, Collett 95 (holo: K; iso: CAL).
Homotypic synonym: *Cantharospermum burmanicum* (Collett and Hemsley) Raizada in Mooney, Suppl. Bot. Bihar and Orissa 53 (1950).
Flowering: Jan-Mar.
Ecology: climbing in trees, edges of dry forests or shrub vegetation, 1500-2000 m.

9b. *Cajanus crassus* var. *crassus*, van der Maesen, Agr. Univ. Wageningen Pap. 85-4:110 (1986).
A tall climber, to 10 m with rather thick coriaceous leaves, leaflets subtrapezoid and acuminate, lateral ones oblique. Up to 20 yellow flowers in crowded racemes of 3-6 cm, pods puberulous, 2.5-5 cm, 5-6 black seeds with cream mosaiç or cream-coloured. Quite common variety, does not cross with pigeonpea.
Basionym: *Atylosia crassa* Prain ex King, J. As. Soc. Beng. 66:45 (1897); Cooke, Fl. Presid. Bombay 1:408 (1903, repr. 1958, 1967); Prain, Bengal Pl. 272 (1903, repr.1963); Gagnepain, Fl. Gen. Indo-Chine 2-3:280 (1916); Haines, Bot. Bihar and Orissa 3:273 (1922), and 2:286 (repr.1961); Ridley, Fl. Malay Penins. 1:564 (1922).
Type: India, Wallich 5553, *Dolichos crassus* Grah. nomen nudum, *Glycine crassa* H. Ham. nomen nudum , e Kalkapur 18 Dec. 1810 (holo: K).

Heterotypic synonyms: *Atylosia volubilis* (Blanco) Gamble, Fl. Presid. Madras 2:369 (1918), and 1:260 (repr. 1967); Backer and Bakhuizen van den Brink, Fl. Java 1:636 (1964); Thuan, Fl. Cambodge, Laos, Vietnam 17:111 (1979). Based on *Cytisus volubilis* Blanco, but that name I consider to be the basionym for another species, *Cajanus volubilis* from the Philippines and Indonesia. Because the altitudinal ranges differ, the varieties could well be regarded as subspecies.
Flowering: (Dec) Jan-Mar (India to the Philippines), Apr-Aug (Java).
Distribution: NW. Himalaya foothills, Central India, Assam, E. Ghats, Nepal, Myanmar, Thailand, Vietnam, Java, Philippines, Malay Peninsula.
Ecology: in dry forests (sal, teak, pine) or shrub vegetation, along streams or on dry soils, alluvium, loam schists, granite rocks 0-1000 (-1300m).

10. *Cajanus elongatus* (Benth.) van der Maesen, Agr. Univ. Wageningen Pap. 85-4:115 (1986).

Slender climber-creeper, membranaceous leaves, slender racemes with 2-5, most likely yellow flowers, flattish-oblong pods with 3-4 brown or black seeds. Not found in recent years when looked for, the most recent sample was found in 1957.
Basionym: *Atylosia elongata* Benth. in Miq., Pl. Jungh. 1:243 (1852); Baker in Hooker, Fl. Brit. India 2:215 (1876); Thuan, Fl. Cambodge, Laos, Vietnam 17:112 (1979).
Type: Nepalia 1821, Wallich 5543 (holo: K; iso: BM, CAL, E, G, K, L) as *Dolichos elongatus* Grah. ex Wall., nomen nudum.
Homotypic synonym: *Cantharospermum elongatum* (Benth.) Raizada in Mooney, Suppl. Bot. Bihar and Orissa 53 (1960).
Flowering: Jul-Nov.
Distribution: Bhutan, Myanmar, NE. India, Nepal, Vietnam.
Ecology: grasslands among low scrub, open hillsides, 1300-2100 m.

11. *Cajanus goensis* Dalz. in Hooker's Kew J. 2:264 (1850); Dalzell and Gibson, Bombay Fl. 73 (1861, repr. 1973).

Very hairy climber, quite sticky, subcoriaceous leaflets, short-hairy above, flowers yellow to orange-yellow, up to 25 together on up to 25 cm peduncles, pods linear-pointed, 3.5-5.5 cm, 5-8 light brown seeds with grey to black mosaic.
Type: India, W. Ghats, Goa, Dalzell s.n. (holo: K).
Homotypic synonym: *Atylosia goensis* (Dalz.) Dalz., J. Linn. Soc., Bot. 13:186 (1873); Cooke, Fl. Presid. Bombay 1:409 (1903, repr. 1958, 1967); Gamble, Fl. Presid. Madras 2:369 (1918), 260 (repr. 1967); Backer and Bakhuizen van den Brink, Fl. Java 1:636 (1963); Ramaswami and Razi, Fl. Bangalore 297 (1973).
Heterotypic synonyms: *Dolichos barbatus* Wall., Cat. 5548 (1831-32), nomen nudum. Based on: Myanmar, Kogun on Salween river, Martaban, Wallich 5548 (K).

Dolichos ornatus Wall., Cat. 5561 (1831-32), nomen nudum. Based on: Myanmar, Phoroe, Needoun, Martaban, *Dolichos glutinosum Roxb. (K).*

Rhynchosia vestita Wall., Cat. 5505, nomen nudum. Based on: Myanmar, Kogun, Martaban 1827, Wallich 5505 (K?).

Dunbaria barbata Benth. in Miq, Pl. Jungh. 1:242 (1852).
Type: Myanmar, Kogun on Salween river, Martaban 1827, Wallich 5548 (holo: K), *Dolichos barbatus* Wall. nomen nudum.

Dunbaria calycina Miq., Fl. Ind. Bat. 1:180 (1855).
Type: Java, Surakarta, Horsfield L 123 (BM, CAL, K, U).

Atylosia calycina (Miq.) Kurz, J. As. Soc. Bengal 43:186 (1874), based on *Dunbaria calycina* Miq.

Atylosia barbata (Benth.) Bak. in Hooker, Fl. Brit. India 2:216 (1876); Collett and Hemsley, J. Linn. Soc. 28:48 (1890); Prain, Bengal Pl. 272 (1903, repr. 1963); Gagnepain, Fl. Gen. Indo-Chine 2-3:279 (1916); Thuan, Fl. Cambodge, Laos, Vietnam 17:110 (1979). Based on *Dunbaria barbata* Benth., it is the most frequently used synonym.

Endomallus pellitus Gagnep., Not. Syst. 3:185 (1914); Gagnep., Fl. Gen. Indo-Chine 2:267 (1916); Thuan, Fl. Cambodge, Laos, Vietnam 17:128 (1979).

Type: Vietnam, Son-lu, Bienhoa Prefecturate, Pierre s.n. (holo: P; iso: P).

Endomallus spirei Gagnep., Not. Syst. 3:186 (1914); Gagnep., Fl. Gen. Indo-Chine 2:268 (1916); Thuan, Fl. Cambodge, Laos, Vietnam 17:128 (1979).

Type: Laos, Luang Prabang, Spire 1561 (holo: P; iso: P).

Cantharospermum barbatum (Benth.) Koorders, Meded. Proefstat. Thee 90:15 (1924); Heyne, Nuttige Pl. Nederl. Indie" 1:831 (1927). Based on *Dunbaria barbata* Benth.

Atylosia siamensis Craib, Kew Bull. 19:65 (1927).

Type: Thailand, Saraburi to Muak Lek, 200 m, Kerr 10004 (holo: K; iso: BM).

Dunbaria thorelii Gagnep., Not. Syst. 3:194 (1914), pro parte.

Dunbaria stipulata Thuan, Adansonia ser. 2, 16-4:514 (1977).

Type: Thailand, Doi Pae Poe, 1400 m, Hansen and Smitinand 12895 (holo: P; iso: C).

Flowering: Nov-Mar (India, Indo-China), Jul-Sep (Java).

Distribution: Bangladesh, Myanmar, China-Yunnan, India, Indonesia-Java, Laos, Malaysia-Malaya, Thailand, Vietnam.

Ecology: climber in shrubs and trees, tropical dry deciduous or slightly wet forests, particularly near open spaces, 0-1600 m.

12. *Cajanus grandiflorus* (Benth. ex Bak.) van der Maesen, Agr. Univ. Wageningen Pap. 85-4:125 (1986).

A tall climber, leaflets up to 10 cm long, large probably yellow flowers, the calyx with some bulbous-based hairs, and sturdy pods, 3.5-5 cm, ca 6 brown seeds.

Basionym: *Atylosia grandiflora* Benth. ex Bak. in Hook., Fl. Brit. India 2:214 (1876).

Type: India, Uttar Pradesh, Bagesar, Kumaon 3000 ft, Strachey and Winterbottom (lecto: K; isolecto: BR, GH, K). Paratype: India, Uttar Pradesh, Upper Garhwal, Madden 150 (E, K).

Heterotypic synonyms: *Dunbaria pulchra* Benth. ex Bak. in Hook., Fl. Brit. India 2:218 (1876).

Type: India, lower hills of Sikkim, 1-2000 ft, Hooker f. (holo: K; iso: K, P).

Pueraria seguini Le'vl., Bull. Soc. Bot. France 55:426 (1908); Léveillé, Fl. Kouy-Tcheou 241 (1914); Gagnep. in Lecomte, Not. Syst. 3:205 (1916).

Type: China, prov. Kouy-Tcheou (Kweichow), nr Hoang-ko-chou, Seguin 2446 (holo: P; iso: E, P).

Flowering: Jul-Oct.

Distribution: Bhutan, Myanmar, China: Yunnan, Kweichow, Anhwei. India: Himalayas. Probably also in Nepal.

Ecology: climber on shrubs, rocks, near water, 1000-2700 m.

13. *Cajanus heynei* (W. and A.) van der Maesen, Agr. Univ. Wageningen Pap. 85-4:129 (1986).

Climber with dark green, membranaceous leaflets, shortly pubescent above, veins sparsely pubescent below, 6-12 pretty yellow flowers with flag dorsally reddish, pods sticky, with spreading hairs, depressions developing late, 4-5 seeds, brown with black mottles to black.

Basionym: *Dunbaria heynei* W. and A. Prodr. 1:258 (1834); Bentham in Miq., Pl. Jungh. 1:242 (1852); Baker in Hooker, Fl. Brit. India 2:217 (1876); Prain, J. As. Soc. Bengal 66-2:433 (1897); Trimen, Hand-Book Fl. Ceylon 2:80 (1894, repr. 1974); Cooke, Fl. Presid. Bombay 411 (1903, repr. 1967); Gamble, Fl. Presid. Madras 2:370 (1918), 261 (1967).

Type: India, 28 Dec. 1816, Wallich 5572 A. (holo: K; iso: K).

Homotypic synonym: *Collaea (Glycine) gibba* Grah. in Wall., Cat. 5572 A (1831), nomen nudum.

Heterotypic synonyms: *Dunbaria oblonga* Arn., Nov. Act. Nat. Cur. 18:333 (1836).

Type: Walker-Arnott Ceylon No. 207 (holo: E).

Cajanus kulnensis Dalz., Hook. Kew J. 2:264 (1850); Dalzell and Gibson, Bombay Fl. 72 (1861).

Type: India, nr Kulna in Warree area (W. Ghats), Dalzell s.n. (holo: K?; iso: CAL, GH).

Atylosia kulnensis (Dalz.) Dalz., J. Linn. Soc. 13:185 (1873); Prain, J. As. Soc. Bengal 66-2:433 (1897).

Flowering: (Dec-) Jan-Feb (-Mar).

Distribution: India: W. Ghats, Sri Lanka, Vietnam.

Ecology: climber in trees or shrubs, in hedges and forest edges, 0-1000 m.

14. *Cajanus kerstingii* Harms, Feddes Repert. 14:196 (1915); Baker, Legumin. Trop. Afr. 460 (1926); Verdcourt, Fl. Trop. E. Afr. Leguminosae, Pt.4:711 (1974); Hepper, Fl. W. Trop. Afr. ed 2.1:215 (1958); Berhaut, Fl. Senegal ed. 2:30 (1967); id. Fl. Illustr. Senegal 5:76-77 (1976).

Erect shrub, 1-2 m, branches green or with anthocyane, whitish pubescent. Leaves rather like pigeonpea, silvery-hairy below. Inflorescences short, ca 4-flowered, pods oblong, densely short-hairy, margins sturdy, 3-4 seeds . The only wild *Cajanus* indigenous in W. Africa, where *Eriosema* appears to be more common.
Type: Togo, Sokode to Basari, open savanna, Kersting 570 (holo: B, most likely burnt, sketch in K).
Flowering: Aug-Sep.
Distribution: Senegal, Togo, Benin, Ghana, Mali, Nigeria.
Ecology: open savanna or underscrub in forest, 50-500 m.

15. *Cajanus lanceolatus* (W.V. Fitzg.) van der Maesen, Agr. Univ. Wageningen Pap. 85-4:135 (1986).

Erect shrub, 1-3 m, with thick-coriaceous narrow-lanceolate leaflets, short silvery to pale golden brown hairs. Pods oblong, ca 3-4 cm long, with 3-6 seeds. Interesting drought-resistant species, very rare.
Basionym: *Atylosia lanceolata* W.V. Fitzg., J. Proc. Roy. Soc. W. Austral. 3:156 (1918); Reynolds and Pedley, Austrobaileya 1-4:423 (1981).
Type: W. Australia, Mt Broome, Fitzgerald s.n. (holo: PERTH).
Flowering: Apr?, Jul-Aug.
Distribution: W. Australia.
Ecology: wooded slopes, on rocky red loam, red earth on sandstone; probably below 800 m.

16. *Cajanus lanuginosus* van der Maesen, Agr. Univ. Wageningen Pap. 85-4:137 (1986).

Erect shrub, to 2 m, branches rather thick at the end, indumentum long, woolly, yellowish on young parts to whitish elsewhere. Leaves thick, coriaceous and densely covered with short woolly hairs. Corolla yellow, persistent, pods 2.5-3.5 cm long, woolly, with 4-6 brown seeds with black mosaic.
Type: Australia, Queensland, nr Mary Kathleen, 22 km from Rosebud turning off Barkly Highway en route to Fountain Springs, P. Catt 9138 (holo:CANB).
Flowering: Jul-Aug.
Distribution: Australia, W. Queensland, endemic of Mt Isa.
Ecology: not reported.

17. *Cajanus latisepalus* (Reynolds and Pedley) van der Maesen, Agr. Univ. Wageningen Pap. 85-4:139 (1986).

Erect shrub, to 1.5 m. Branches grey pubescent, striped. Leaflets thick, very hairy underneath, upper side reticulate with sunken veins. Calyx teeth broad, elliptic-acuminate, hairy. Pods hairy, broad-oblong, ends obtuse, 2-3 (to 4) black seeds with pinkish-brown mosaic.
Basionym: *Atylosia latisepala* Reynolds and Pedley, Austrobaileya 1-4:425 (1981).
Type: Australia, Northern Territory, (upper) Victoria River, F.v. Mueller (holo: K; iso: MEL).
Homotypic synonym: *Atylosia grandifolia* (F. v. Muell.) Benth. var. *calycina* Benth., Fl. Austral. 2:264 (1864).
Flowering: Mar-Jul (-Oct.).
Distribution: Australia: W. Australia and Northern Territory.
Ecology: rocky slopes, open grassland, near rivers or in watercourse, in sand or red volcanic soil, or on brown clay, 60-500? m.

18. *Cajanus lineatus* (W. and A.) van der Maesen, Agr. Univ. Wageningen Pap. 85-4:143 (1986).

Erect shrub, to 2.5 m, of open habit. Leaflets palmately trifoliolate, obovate, soft-coriaceous. Corolla yellow, persistent. Pods small, oblong, ca 12 mm, hairy, 2-3 brownish or greyish seeds with black mosaic.

Basionym: *Atylosia lineata* W. and A., Prodr. Fl. Pen. Ind. Or. 1:258 (1834); Cooke, Fl. Presid. Bombay 1:408 (1903, repr. 1958, 1967); Gamble, Fl. Presid. Madras 2: 367 (1918), 259 (repr. 1967); Santapau, Fl. Khandala 73 (1966); Saldanha and Nicolson, Fl. Hassan Distr. 238 (1976); Matthew, Materials Fl. Tamilnadu Carnatic 181 (1981).
Type: India, 28 Dec 1816, Wallich 5578 (holo: K).
Homotypic synonyms: *Cantharospermum lineatum* (W. and A.) Raizada in Mooney, Suppl. Bot. Bihar and Orissa 53 (1950).
Heterotypic synonyms: *Glycine lineata* Heyne ex Wall. nom. nud., Wallich Cat. 5578 (1831). Based on India, Heyne, Wallich 5578 2nd sheet (K).

Atylosia lawii Wight, Icon. 1. t. 93 (1840); Dalzell and Gibson, Bombay Flora 74 (1861); Dalzell, J. Linn. Soc. 13:186 (1873).
Type: Bombay (Ghats), Law s.n. (holo: K; iso: GA, K, OXF).
Flowering: Oct-Apr (Jun in Kerala).
Distribution: India, W. Ghats and Nilgiri Mountains, quite common in some areas; once also found in Sri Lanka.
Ecology: tropical dry or moist forest, in both shady and sunny places, forest and hill edges, along roadsides, in undergrowth, 400-1600 m.

19. *Cajanus mareebensis* (Reynolds and Pedley) van der Maesen, Agr. Univ. Wageningen Pap. 85-4:149 (1986).

Prostrate trailing perennial herb, to several m long. Hairs short and sparse. Leaflets elongate, pinnate, 4-10 cm long on petiole 4-13 cm. Flowers few together, yellow, pods flat-oblong, reticulate, green and red mottled, with few long hairs, and 3-4 brown seeds with black dots. Strophiole U-shaped.
Basionym: *Atylosia mareebensis* Reynolds and Pedley, Austrobaileya 1-4:422 (1981).
Type: Australia, Queensland, Granite Creek, 8 miles W. of Mareeba, Pedley 2249 (holo: BRI; iso: BRI, CANB, K).
Flowering: Apr.
Distribution: Australia, N. Queensland, very rare.
Ecology: on sand, among granite boulders, 400-600 m.

20. *Cajanus marmoratus* (R. Br. ex Benth.) F. v. Muell., Census Austral. Pl. Suppl. 1-4:41 (1881); id. Second Census Austral. Pl. 1:71 (1889).

Creeper, perennial, to several (6!) m long, sparsely hairy. Leaflets coriaceous, roundish, tip emarginate to acuminate. Flowers yellow, 1-10 together, pods flat-oblong, to 3.5 cm, rounded both ends, 3-5 (-7) brown seeds with black mosaic. Strophiole U-shaped.
Basionym: *Atylosia marmorata* R. Br. ex Benth., Fl. Austral. 2:263 (1864); Bailey, Queensland Fl. 2:438 (1900); Fitzgerald, J. Roy. Soc. W. Austral. 3:156 (1918).
Type: Australia, N. Territory, Upper Victoria River, F. v. Muell. (lecto: K; isolecto: K, MEL Victoria River). Paratypes: Australia, N. Territory Islands in the Gulf of Carpentaria, R. Brown s.n. (E, MEL); same location, id. 4206 (E, K); Sweers Isl., Henne s.n. (MEL); Queensland, Port Denison, Fitzalan s.n. (MEL); Nebo Creek and Bowen River, Bowman s.n. (MEL).
Homotypic synonym: *Cantharospermum marmoratum* (R. Br. ex Benth.) Taubert ex Ewart and Davies, Fl. N. Territory 152 (1914).
Flowering: Jan-May, Jul-Sep.
Distribution: Australia, Queensland, N. Territory, and W. Australia.
Ecology: in grass, open *Eucalyptus* forest among basaltic boulders, on loose sands with *Sorghum* and *Bauhinia*, on dunes, slopes, and along rivers, 0-700 m.

21. *Cajanus mollis* (Benth.) van der Maesen, Agr. Univ. Wageningen Pap. 85-4:154 (1986).

Sturdy climber, hairs short, brownish. Leaflets palmately trifoliolate, elliptic-obovate, densely

grey-hairy below. Flowers yellow, persistent, pods oblong, to 4.5 cm, with 7-10 brown seeds.
Basionym: *Atylosia mollis* Benth. in Miquel, Pl. Jungh. 1:143 (1852); Baker in Hooker, Fl. Brit. India 2:213 (1876) partly as to *Collaea mollis* only, King, J. As. Soc. Bengal 66-2:46 (1897); Prain, J. As. Soc. Bengal 66-2:431 (1897); Collett, Fl. Simlensis 142 (1902, repr. 1971); Osmaston, Forest Fl. Kumaon 177 (1927); Gupta, Fl. Nainitalensis 96 (1968); Ali, Fl. W. Pakistan 100, Pap. 220 (1977).
Type: Nepal, Wallich 5574, *Collaea mollis* Grah. ex Wall. nomen nudum, Wallich Cat. 5574 (1831) (holo: K; iso: BM, CAL, E, G, K, W).
Homotypic synonym: *Cantharospermum molle* (as *mollis*) Taubert in Engl. and Prantl, Nat. Pflanzenfam. 3-3:373 (1894).
Flowering: (Aug) Sep-Nov.
Distribution: Himalaya foothills from Pakistan to India, Nepal, Bhutan and China (Yunnan).
Ecology: climbing in pine or broadleaf forest, scrub vegetation, open places, 700-2100 m.

22. *Cajanus niveus* (Benth.) van der Maesen, Agr. Univ. Wageningen Pap. 85-4:157 (1986).

Shrub, to 1.5 m, in appearance very close to the climbing *C. albicans*, but its erect nature, rounded bracts, and longer rachis beyond the leaflet pair make it stand apart, and the areas are widely separated.
Basionym: *Atylosia nivea* Benth. in Miquel, Pl. Jungh. 1:243 (1852); Baker in Hooker, Fl. Brit. India 2:214 (1876); Collett and Hemsley, J. Linn. Soc. 28:48 (1890).
Type: Myanmar, below Yeranghuen, 3 Jan 1827, Wallich 5581 (hololecto: K). Paratypes: Myanmar, Prome, Wallich 5581 (other part)(K, BM, CAL, G).
Homotypic synonyms: *Cajanus niveus* Grah. ex Wall., nomen nudum, Wallich Cat. 5581 (1831).
Cantharospermum niveum (Benth.) Raizada in Mooney, Suppl. Bot. Bihar and Orissa 53 (1950).
Flowering: Aug-Dec (-Apr).
Distribution: Myanmar, China (Yunnan).
Ecology: open jungle, hill sides, 50-1350 m(?)

23. *Cajanus platycarpus* (Benth.) van der Maesen, Agr. Univ. Wageningen Pap. 85-4:160 (1986) (Figure 2.2).

Creeper or climber, perennial but usually dying within a year, sparsely hairy, to 1 m. Leaflets membranaceous, ribs hairy below, blades thinly hairy above, ovate to rounded. Flowers up to 5 together, rather elongate, pale yellow to yellow, sometimes with purple veins or dots. Pods flat-oblong, 2 to 4.5 cm long, surface reticulate, speckled with red, hairs short and long white and yellow, not persistent. Seeds 4-7, brown to almost black, mosaic. Strophiole large, U-shaped.
Basionym: *Atylosia platycarpa* Benth. in Miquel, Pl. Jungh. 1:243 (1852); Baker in Hooker, Fl. Brit. India 2:216 (1876); Collett, Fl. Simlensis 142 (1902, repr. 1971); Prain, Bengal Pl. 272 (1903, repr. 1963); Bamber, Pl. Punjab 602 (1916); Haines, Bot. Bihar and Orissa 3:274 (1922), 2:287 (repr. 1961).
Type: India, Himalaya, 7000-8000 feet, Edgeworth 186 (holo: K).
Homotypic synonym: *Cantharospermum platycarpum* (Benth.) Raizada in Mooney, Suppl. Bot. Bihar and Orissa 53 (1950).
Heterotypic synonyms: *Atylosia geminiflora* Dalz., J. Linn. Soc. 13:185 (1873). Type: India, W. Ghats, Dalzell s.n. (holo: K; iso: CAL).
Cantharospermum ? distans Royle ex Baker in Hooker, Fl. Brit. India 2:216 (1876).
Type: NW. India, Royle s.n. (holo: CAL; iso: K).
Cantharospermum geminiflorum (but as *geminifolium*) (Dalz.) Raizada in Mooney, Suppl. Bot. Bihar and Orissa 53 (1950), based on *Atylosia geminiflora*.
Flowering: Aug-Sep (India); Sep, Mar (Pakistan); Mar-Apr (Java).
Distribution: NW. and Central India, Nepal, Pakistan, Java.
Ecology: Trailing in grasses, along roadsides, in pine forests, in cultivated fields, 50-2600 m.

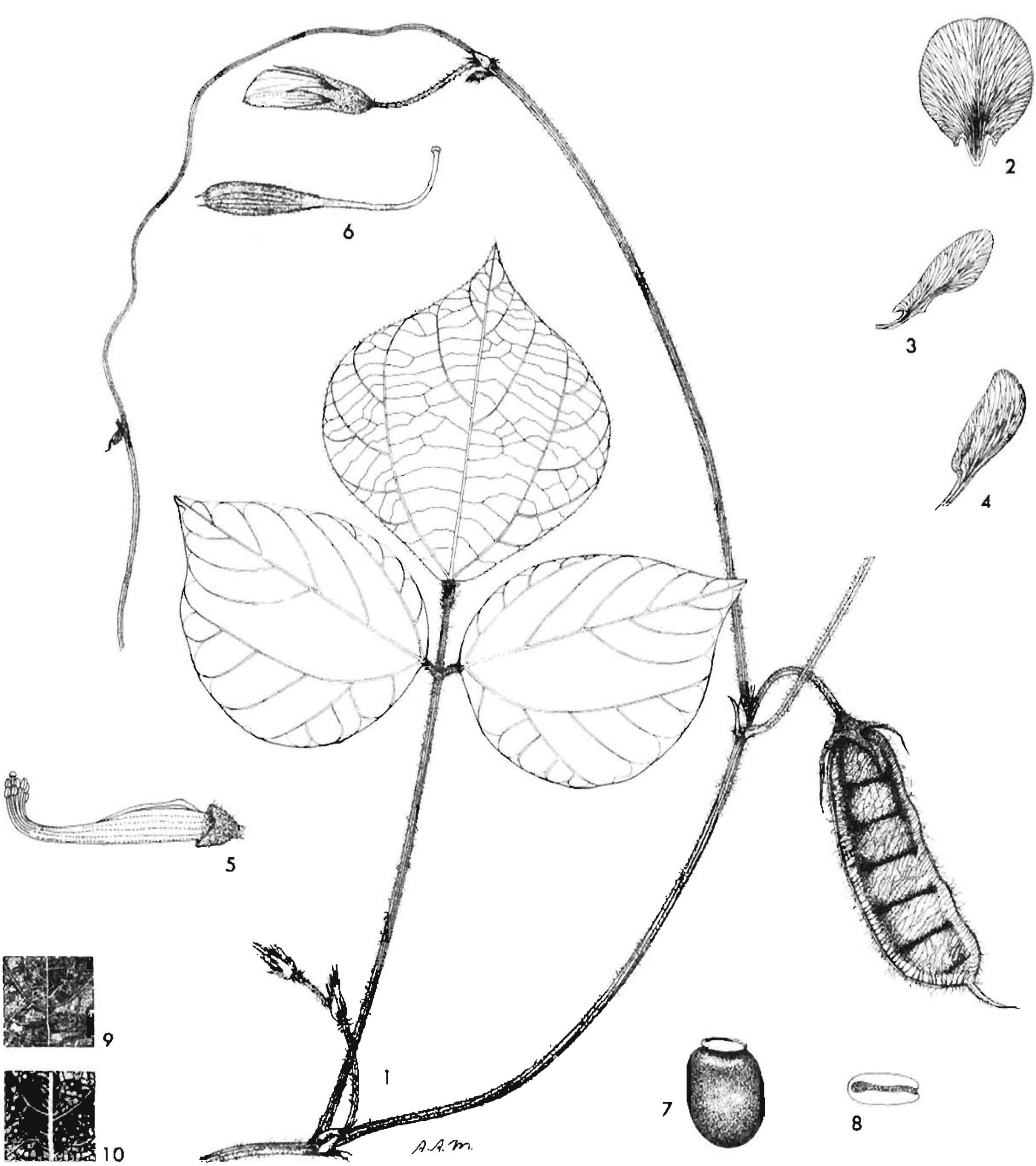


Figure 2.2. *Cajanus platycarpus:* 1. Branch × 1;2. Flag, × 2;3. Wing, × 2;4. Keel, × 2;5. Stamens and stigma, × 2;6. Pistil, × 2;7. Seed, × 3;8. Strophiole of seed shown from above, × 5;9. Detail of upper leaflet surface, × 2;10. Detail of lower leaflet surface, × 2 (1-10, *van der Maesen* 2873).

Source: van der Maesen, Agricultural University Wageningen papers 85-4, 1986.

24. *Cajanus pubescens* (Ewart and Morrison) van der Maesen, Agr. Univ. Wageningen Pap. 85-4:164 (1986).

Erect shrub, to 1.2 (-2) m, hairs short, dense, silvery on leaves, brown on stems. Leaflets thick-leathery, reticulate above, reticulate and hairy below, grey hairs below do not fill reticulations. Flowers yellow, flag sometimes with red veins. Pods oblong, 2 to 3.5 cm, 4-6 dark grey seeds with black mosaic. Reynolds and Pedley (1981) distinguish a var. *mollis* with long and spreading hairs of stems and petioles. I have not seen the type, Cole *et al*. 9098 from near Ballara, Queensland (BRI).
Basionym: *Tephrosia pubescens* Ewart and Morrison, Proc. Roy. Soc. Victoria new series 26:163 (1912); Ewart and Davies, Fl. N. Territory 147 (1917).
Type: Australia, N. Territory, Top Spring, G. Hill 535 (holo: MEL; iso: K).
Homotypic synonym: *Atylosia pubescens* (Ewart and Morrison) Reynolds and Pedley var. *pubescens*, Austrobaileya 1-4:427 (1981).
Flowering: Jan, Apr-Sep, especially Jun.
Distribution: Australia: W. Australia, N. Territory and N. Queensland.

25. *Cajanus reticulatus* (Dryander) F. v. Muell., Census Austral. Pl. Suppl. 1-4:41 (1881).
Key to the varieties:
1a. Erect shrub with horizontal or trailing branches, rust-brown hairs, leaves large when fully grown .... var. *grandifolius*
1b. Weak shrub, prostrate or trailing 2
2a. Leaflets rhomboid-ovate with acute or obtuse tip, pubescence golden brown . var. *reticulatus*
2b. Leaflets rounded to rhomboid-rounded, hairs greyish .... var. *maritimus*

25a. *Cajanus reticulatus* var. *grandifolius* (F. v. Muell.) van der Maesen.

Erect shrub with large velvety, golden-brown hairy leaflets. Branches horizontal or trailing. Flowers large, yellow with or without red veins. Pods oblong, to 3.5 cm, with 4-6 brown or black seeds with grey variegation.
Basionym: *Cajanus grandifolius* F.v. Muell., Pl. Fitzalan 9 (1860).
Type: Australia, Signal Hill, Upstart Bay, Fitzalan s.n. (holo: MEL). Paratypes: Burnett Ranges, Mr. Aug. Gregory's Expedition, F.v. Muell. s.n. (MEL); Victoria River, Jan 1856, id. s.n. (K, MEL).
Homotypic synonyms: *Atylosia grandifolia* (F. v. Muell.) Benth., Fl. Austral. 2:264 (1864); Bailey, Queensland Fl. 2:439 (1900); Verdcourt, Manual New Guinea Legumes 540 (1979).
Cantharospermum grandifolium (F. v. Muell.) Taubert ex Ewart and Davies, Fl. N. Territory 152 (1917).
Flowering: Jan - Oct.
Distribution: Australia: W. Australia, N. Territory, Queensland; Papua New Guinea.
Ecology: open grasslands e.g., *Heteropogon* spp., *Eucalyptus* forests, rocky places, hillsides, dry riverbeds, on sandy loam, laterites or granite sand, probably below 1000 m.

25b. *Cajanus reticulatus* var. *reticulatus*, Agr. Univ. Wageningen Pap. 85-4:173 (1986).

Weak shrub, prostrate or trailing with leaflets smaller than in var. *grandifolius*, hairs also golden-brown, flowers and fruits slightly smaller.
Basionym: *Dolichos reticulatus* Dryander in Aiton, Hort. Kew. ed. 1,3:33 (1789); F. v. Muell., Census Austral. Pl. Suppl. 1-4:41 (1881); id., Second Census Austral. Pl. 1:71 (1889); Bailey, Queensland Fl. 2:438 (1900).
Type: Australia, Queensland, Endeavour River, Banks and Solander dd. 1770 (lecto: BM; isolecto: BM, CANB, MEL, W).
Homotypic synonyms: *Atylosia reticulata* (Dryander) Benth., Fl. Austral. 2:263 (1864); Bailey, Queensland Fl. 2:438 (1900).
Cantharospermum reticulatum (Dryander) Taubert ex Ewart and Davies, Fl. N. Territory 152 (1917).

25c. *Cajanus reticulatus* var. *maritimus* (Reynolds and Pedley) van der Maesen, Agr. Univ. Wageningen Pap. 85-4:173 (1986).

Trailing shrub with greyish-haired rounded to rhomboid-rounded leaflets. As this variety grows on white sand of coastal dunes, the status of a subspecies may also be assigned, as rightly pointed out by Pedley (personal communication), restricted to coastal areas.
Basionym: *Atylosia reticulata* subsp. *maritima* Reynolds and Pedley, Austrobaileya 1-4:426 (1981).
Type: Australia, N. Territory, Port Bradshaw, Arnhem Land Aboriginal Reserve, Specht 714 (holo: BRI; iso: AD, CANB, K).
Flowering: Jan-Jul.
Distribution: Australia, Queensland and N. Territory.
Ecology: white sand, coastal dunes, 0-100 m.

26. *Cajanus rugosus* (W. and A.) van der Maesen, Agr. Univ. Wageningen Pap. 85-4:179 (1986).

Climber-creeper, branches greyish-hairy, often thin at the end, leaflets thick, flowers 2-4 together on peduncles 1-4.5 cm, yellow or flag the vague red stripes, pods oblong, 14-23 mm, up to 4 light or dark brown seeds with dark blotches. Can be confused with *Rhynchosia filipes* Benth. ex Bak.
Basionym: *Atylosia rugosa* W. and A., Prodr. 1:257 (1834); Fyson, Fl. Nilgiri and Pulney Hill Tops 1:120 (1915, repr. 1974); Gamble, Fl. Presid. Madras 2:369 (1918), 260 (1967); Fernando, Wild Fl. Ceylon 2nd ed. 39 (1980); Matthew, Material Fl. Tamilnadu Carnatic 181 (1981); id., Illustr. Fl. Tamilnadu Carnatic 183 (1982).
Type: India, Nilgiris?, Wight 761 (holo: E; iso: BR, CAL, E, G, K).
Homotypic synonym: *Cantharospermum rugosum* (W. and A.) Alston, Ann. Roy. Bot. Gardens Peradenya 9:209 (1929).
Heterotypic synonym: *Rhynchosia? velutina* Grah. ex Wall., nomen nudum, Wallich's Cat. 5501 (1831), based on Graham, Wallich 5501 (K).
Flowering: Sep-Apr, Jun-Jul.
Distribution: S. India and Sri Lanka.
Ecology: Forests, low scrub, open spaces (downs) and roadsides, 1300-2400 m.

27. *Cajanus scarabaeoides* (L.) Thouars, Dict. Sci. Nat. 6:617 (1817) (as *Cajan scarabaeoide*) (Figure 2.3).
Key to the varieties:
Flowers almost sessile in axils, sometimes peduncles to 1-1.5 cm long (Papua New Guinea), pods narrowly oblong, long-haired, 3-6-seeded .... var. *scarabaeoides*
Flowers on long peduncles of 1-6 cm, pods broadly oblong, 2-3-seeded (Australia) . var. *pedunculatus*

27a. *Cajanus scarabaeoides var. pedunculatus* (Reynolds and Pedley) van der Maesen, Agr. Univ. Wageningen Pap. 85-4: 188.

The long-peduncled variety with few-seeded broadly oblong pods, endemic to Australia.
Basionym: *Atylosia scarabaeoides* (L.) Benth. var. *pedunculata* Reynolds and Pedley, Austrobaileya 1-4:421 (1981).
Type: Australia, Queensland, Parada nr Dimbulah, McKee 9363 (holo: BRI; iso: K).
Flowering: Jan-May, Sep.
Distribution: Australia, N. Territory and Queensland.
Ecology: Grassland, on farms, 0-500? m.

27b. *Cajanus scarabaeoides* var. *scarabaeoides*, Dict. Sci. Nat. 6:617 (1817), as *Cajan scarabaeoide*.

Grey-green creeper-climber, supported by grasses and shrubs, winding at the end. Leaflets narrow to broad, elliptic to obovate, thin-woolly and coriaceous. Flowers 1-6 together, yellow to creamish yellow, flag sometimes with red veins. Pods oblong, hairy, to 2 cm long, with 3-6 greyish seeds with black and cream mosaic. The name is from the scarab-like seed. This species is the most widespread wild relative of pigeonpea, and is interfertile. It is a conspicuous drought-resistant

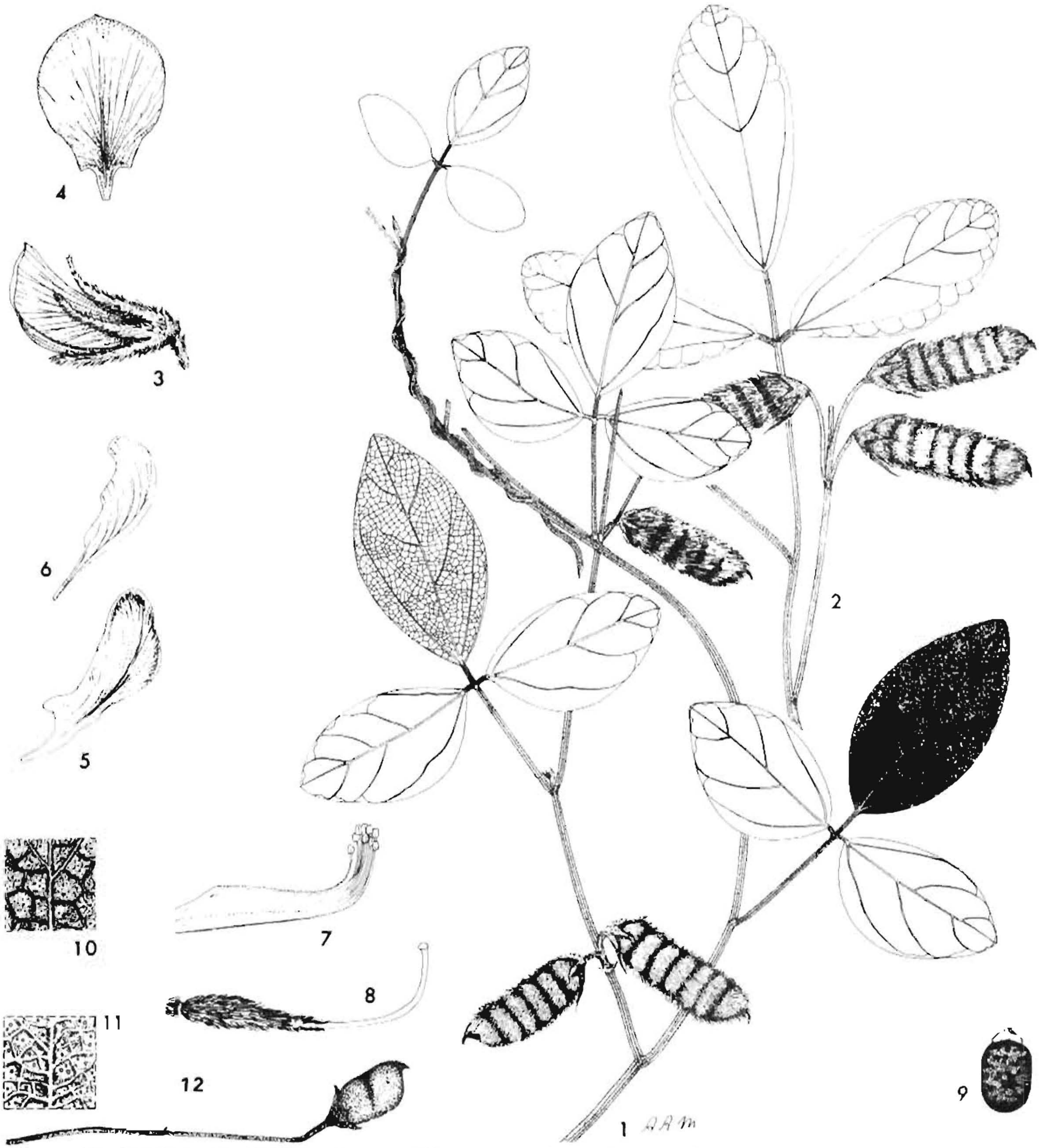


Figure 2.3. *Cajanus scarabaeoides:* 1. Branch, × 1;2. Branch of long-peduncled variant × 1;3. Flowers × 2;4. Flag, × 2;5. Wing, × 2;6. Keel, × 2;7. Stamens, × 2;8. Pistil, × 2;9. Seed, × 3;10. Detail upper leaflet surface, × 2;11. Detail lower leaflet surface, × 2;12. Fruit of var. *pedunculatus* (1,3-11, *van der Maesen 2881*; 2, *A. Floyd 5528*; 12, *McKee 9363*).

Source: van der Maesen, Agricultural University Wageningen papers 85-4, 1986.

element in the dry season, and shows off green in leafless *Shorea robusta* (sal) and *Tectona grandis* (teak) forests with little undergrowth.

Basionym: *Dolichos scarabaeoides* L., Species Plantarum 726 (1753); W.T. Aiton, Hort. Kew. ed. 2-4:294 (1812), Roxburgh, Hort. Beng. 53 (1814) (nomen as *D. scarabaeoides* Roxb).

Type: Ceylon, Hermann 1:34 (lecto: BM). Paratypes: Ceylon, Hermann 2:60 (BM); Myanmar (Burman?) in LINN 900.9 (LINN).

Homotypic synonyms: *Rhynchosia? scaraboeoides* (L.) DC. (as *scaraboeoides*), Prodr. 2:387 (1825)

Rhynchosia biflora DC., Prodr. 2:387 (1825), based on *Dolichos scarabaeoides* Roxb., Cat. Hort. Bot. Calc. 53 (1814); Nooteboom, Reinwardtia 5-4:442 (1961).

Stizolobium scarabaeoides (L.) Spreng., Syst. 3:253 (1826).

Cajanus scarabaeoides (L.) Graham ex Wallich, Wall Cat. 5580 (1831).

Dolichos medicagineus Willd. ex Roxb., Fl. India 3:315 (1832), transposed description of *Dolichos scarabaeoides* L.

Atylosia scarabaeoides (L.) Benth. in Miquel, Pl. Jungh. 1:242 (1852); Miquel, F. Ind. Batavae 1-1:162 (1855); Bentham, Fl. Hongkong. 90 (1861); id., F. Austral. 2:263 (1964); Baker in Hook., Fl. Brit. India 2:215 (1876); Baker, Fl. Mauritius Seychelles 84 (1894); Trimen, Hand-Book Fl. Ceylon 2:79 (1894); Bailey, Queensland Fl. 2:438 (1900); Prain, Bengal Pl. 272 (1903, repr. 1963); Cooke, Fl. Presid. Bombay 1:409 (1903, repr. 1958, 1967); Duthie, Cat. Pl. Kumaon 50 (1906); Haines, Forest Fl. Chota Nagpur 320 (1910); Harms, in Engler, Pflanzenw. Afrikas 3-1:665 (1915); Bamber, Pl. Punjab 602 (1916); Gagnepain, Fl. Gen. Indo-Chine 2-3:281 (1916); Gamble, Fl. Presid. Madras 2:369 (1918), 261 (1967); Parker, Forest Fl. Punjab, Hazara, Delhi 165 (1921); Collett, Fl. Siml. 142 (1921); Ridley, Fl. Malay Peninsula 1:564 (1922); Haines, Bot. Bihar and Orissa 274 (1922), 287 (1961); Baker, Leguminosae Trop. Africa 460 (1926); Sharma and Sharma, Obs. Fl. Chandigarh, Res. Bull. N.S. Punjab Univ. 17-3/4:390 (1966); Gupta, Fl. Nainitalensis 95 (1968); Verdcourt, Fl. Trop. E. Afr. ed. 2,1:707 (1971); Berhaut, Fl. Illustr. Senegal 5:64 (1976); Saldanha and Nicolson, Fl. Hassan Distr. 238 (1976); Walker, Fl. Okinawa 592 (1976); Huang and Ohashi, Fl. Taiwan 3:179 (1977); Ali, Fl. W. Pakistan 100:219 (1977); Shah, Fl. Gujarat 1:184 (1978); Verdcourt, Manual New Guinea Legumes 540, 542 (1979); Nguyen Van Thuan, Fl. Cambodge, Laos, Vietnam 17:112 (1979); Matthew, Materials Fl. Tamilnadu Carnatic 181 (1981).

Cantharospermum scarabaeoides ("scarabaeoideum") (L.) Baillon, Bull. Soc. Linn. Paris 1:384 (1883), based on *Cantharospermum pauciflorum* W. & A. and *Atylosia scarabaeoides* (L.) Benth.; Merrill, Fl. Manila 255 (1912); Mooney, Suppl. Bot. Bihar and Orissa 52 (1950).

Cantharospermum scarabaeoides (Benth.) Kds, in Koorders- Schum., Syst. Verz. 1. Fam. 128:68 (1911).

Heterotypic synonyms: *Glycine mollis* Willd., Sp. Pl. 3-2:1062 (1800); Hepper, Kew Bull. 28-2:319 (1973).

Type: Guinea, probably Ghana, Isert s.n. (holo: B, Herb Willd. 13446 IDC microfiche).

Dolichos scarabaeoides Roxb. ex Grah. in Wall. Cat. no. 5580a (1831), nomen nudum, based on India, Wallich 5580 A(K).

Glycine scarabaeoides Hb. Ham. et HBC ex Wall., nomen nudum in Wall. Cat. no. 5580 B (1831), based on India, Kattipur 30 Aug 1810, Mungger (Monghyr) Hills, and 16 Sept 1811, Bot. Gard. Calcutta 2 Jan. 1815 (K).

Hedysarum biflorum Wild. ex Wall., nomen nudum in Wall. Cat. no 5580 C (1831), based on India, in itinere Travancoras Oct 1814 (K).

Cajanus scarabaeoides Thouars ex R. Grah., Wall. Cat. no 5580, according to Index Kewensis 1:312 (1895).

Cantharospermum pauciflorum W. & A., Prodr. Fl. Penins. Ind. or. 1:255 (1834); Royle, Illustr. Bot, Himal. 192 (1833-1839) (as *"paucifolium"*); Dalzell & Gibson, Bombay Fl. 73(1861, repr. 1973).

Type: India orientalis, Wight 758 (holo: E; iso: BM, C, CAL, E, G., K, WU).

Dolichos minutus Roxb. ex W. & A, Prodr. Fl. Penins. Ind. or. 1:256 (1834).

Type: Roxburgh drawing E. Ind. Comp. Mus. Tab. 252 f.1 (CAL).

Atylosia pauciflora (W. & A.) Druce, Rep. Bot. Exch. Club Brit. Isles 1916:607 (1917). Based on

Cantharospermum pauciflorum W. & A.

Atylosia scarabaeoides (L.) Benth. var *queenslandica* Domin, Bibliothek. Bot. 89:227 (1926).
Type: Australia, opp. Pentland, Domin "4870" (holo: PR).
Flowering: end of rainy season well into dry season, or during summer, depending on the country.
Distribution: S. and SE. Asia, Queensland, Pacific Islands, Zanzibar, Madagascar, Mauritius, Coastal W. Africa, Jamaica.
Ecology: open grassland, dry scrub vegetation or (semi-) deciduous monsoon forests, trailing or climbing, 0-1000 (-2000) m.

28. *Cajanus sericeus* (Benth. ex Bak.) van der Maesen, Agr. Univ. Wageningen Pap. 85-4:195 (1986).

Erect shrub, to 1.5 m, branched, grey-green, leaflets palmately arranged, white-hairy, oblanceolate, quite narrow. Flowers 1-3 in leaf axils, pale yellow, pods 1.1 to 1.3 cm, with 2-3 (mostly 2), grey to black seeds with cream mosaic.
Basionym: *Atylosia sericea* Benth. ex Baker in Hooker, Fl. Brit. India 2:213 (1876); Cooke, Fl. Presid. Bombay 1:408 (1903, repr. 1958, 1967); Gamble, Fl. Presid. Madras 2:369 (1918), 260 (repr. 1967); Santapau, Fl. Khandala, Rec. Bot. Surv. India 16-1:72 (1966); Shah, Fl. Gujarat 1:185 (1978).
Type: India, Concan, Stocks s.n. (lectotype: K; isolectotype: GH). Paratypes: India, ?Ritchie 156(E); India, Concan, Ram Ghaut, Ritchie 156/2(K).
Homotypic synonym: *Cantharospermum sericeum* (Benth. ex Bak.) Raizada in Mooney, Suppl. Bot. Bihar and Orissa 53 (1950).
Flowering: Sep-Jan.
Distribution: India: W. Ghats, Mount Abu, rare in Satpura Mts and E. Ghats.
Ecology: dry deciduous monsoon forest, grassy fields, open hill slopes, 500-1300 (-2000) m.

29. *Cajanus trinervius* (DC.) van der Maesen, Agr. Univ. Wageningen Pap. 85-4:199 (1986).

Erect shrub to 2 m, densely hairy, golden brown at the top, leaflets thick, soft, ovate to long-ovate. Flowers 1-2 on short peduncles and pedicels, yellow with red-purple and veined flag. Pods oblong, 2-4 cm, sticky and hairy, with 5-7 dark brown seeds.
Basionym: *Collaea trinervia* DC., Mem. Leg. 6:247, t. 41(1825).
Type: India, Nilgiri Mts. Leschenault (holo: P; iso: P).
Homotypic synonyms: *Odonia trinervia* (DC.) Spreng., Syst. ed 16 Suppl. 4-2:279 (1827).

Cantharospermum trinervium (DC.) Taub. [as (Spreng.) Taub.] in Engl. and Prantl, Nat. Pflz. fam 3-3:373 (1894).

Atylosia trinervia (DC.) Gamble, Fl. Presid. Madras 2:368 (1918), 260 (repr. 1967); Fyson, Fl. S. Indian Hill Stations 1:170; 2:131 (1932); Sharma *et al.*, Bull. Bot. Surv. India 15-182:56 (1973); Fernando, Wild Fl. Ceylon 2nd ed. 39 (1980).
Heterotypic synonyms: *Rhyochosia? Wightiana* Grah. ex Wall. nom. nud., Wallich's Cat. 5500 (1831). Based on India, Herbarium Wight (K).

Atylosia Candollii W. & A., Prodr. Fl. Penins. Ind. Or. 1:257 (1834).
Type:India, Wight 763 (holo:E).

Atylosia candollei W. & A, orthographic rectification, Baker in Hooker, Fl. Brit. India 2:212 (1876); Fyson, Fl. Nilgiri Pulney Hill-Tops 1:120 (1915, repr. 1974); Trimen, Hand-Book Fl. Ceylon 2:78 (1894, repr. 1974).

Atylosia major W. & A., Prodr. Fl. Penins. Ind. Or. 1:257 (1834). Type: India, Wight 762 (holo: E; iso: CAL, G, K, MH, P).

Atylosia trinervia (DC.) Gamble var. *major* (W. & A.) Prain ex Gamble, Fl. Presid. Madras 2:368 (1918), 260 (repr. 1967), based on *A major* W. & A.
Flowering: throughout the year, less in the rainy season, fruiting mainly Jan-Mar.
Distribution: S. India and Sri Lanka, hills and hilltops.
Ecology: scrub vegetation, open forest, grasslands, between boulders at altitudes of (850-) 1400-2650 m. The introduced leguminous shrub *Cytisus sconarius* (L.) Link is more common and conspicuous in this habitat.

30. *Cajanus villosus* (Benth. ex Bak.) van der Maesen, Agr. Univ. Wageningen Pap. 85-4:205 (1986).

Creeper-climber, to 1 m. Leaflets subpalmate, ovate to obovate, hairy below, thinly hairy above. Flowers to 5 together, yellow, peduncle short to 6 cm, pods oblong, 2-3.5 cm, covered with spreading brown long silky hairs, with 5-6 blackish seeds. Only collected 8 times, this species has not been found since 1895.

Basionym: *Atylosia villosa* Benth. ex Baker in Hooker, Fl. Brit. India 2:214 (1876); Nguyen Van Thuan, Fl. Cambodge, Laos, Vietnam 17:112 (1979).
Type: India, Sikkim, lower hills, 4000 ft. Hooker fil. 376 (holo: K; isotypes: GH, K, P).
Flowering: Sep.
Distribution: India: Sikkim and Darjeeling Terai.
Ecology: in grass and low shrubs.

31. *Cajanus viscidus* van der Maesen, Agr. Univ. Wageningen Pap. 85-4: 207 (1986).

A spindly viscid shrub, ca 1 m, sparsely hairy, membranaceous leaflets, and yellow flowers, maroon in bud, to 15 together on slender peduncles, 6 to 15 cm, 3-4-seeded thinly pubescent, viscid pods. A newly described, presumably rare species, sticky at touch.

Type: W. Australia, Camp Creek, Mitchell Plateau, W. Kimberley, Kenneally 4807 (holo: K; iso: K, ex PERTH).
Paratype: Mitchell Falls, Kenneally 5018 (K, PERTH).
Flowering: Jun.
Distribution: W. Australia.
Ecology : on sandstone, near seasonal(?) water.

32. *Cajanus volubilis* (Blanco) Blanco, Fl. Filip. ed 2: 417 (1845); van der Maesen, Agr. Univ. Wageningen Pap. 85-4:210 (1986).

A climber with thin membranaceous leaflets, rather large (yellow?) flowers with some bulbous-based hairs on the calyx, and pods with short pubescence and a few long hairs, falling in due course. The name has been confused with *Cajanus crassus*.

Neotype: Philippines, Pantay Antipolo, Species Blancoanae 142, Merrill (US; isotypes A, BM, CAL, GH, K, L, W).
Flowering: Nov.
Distribution: Philippines, Indonesia (Sulawesi).
Ecology: forests and thickets.

EVOLUTION OF THE PIGEONPEA

The pigeonpea evolved as a crop from at least one wild progenitor. This process, generally more rapid than natural evolution, is called domestication. Human beings selected from the wild those seeds that were already larger than average, relatively tasty and easily obtainable. The wild progenitor would have had pre-adaptation with advantages over other related species (Plitmann and Kislev, 1986). From the available evidence, less abundant than for some other pulses, it is as yet impossible to disprove the conclusion that pigeonpea was domesticated later than most other pulses. It is, however, evident that the crop is more primitive than most pulses (Smartt 1976, 1978, 1980). The changes under domestication were relatively small, whereas in *Phaseolus* the trends of change have been considerable.

We can well imagine the automatic or deliberate early selection pressures applied by man before 2000 BC in India to the plant from which he collected seeds in nature. He started to domesticate the tall bushy plant, quite like *Cajanus cajanifolius*, with relatively low yield, and few edible seeds per pod. The seed size, judging from the present-day wild species, was already quite attractive (up to 4.5 g 100^{-1} seeds in *C. cajanifolius*, and 6 g 100^{-1} seeds in *C. platycarpus*). Even today pigeonpea is a rather unsophisticated tall and laborious crop, but it serves the farmer well, and it is not unsuited to modern agriculture. The transformation through scientific breeding into a modern, low-statured, high-yielding crop only started during this century. Only since about 1925, has scientific attention been paid to improvement, mainly within India, where also the major enhanced emphasis on improvement is now centred at the Indian Council of Agricultural Research, the International Crops Research Institute for the Semi-Arid Tropics, and in various agricultural universities. Throughout the tropics appreciation of the crop, and consequently, plant breeding activities vary considerably. The pre-1940 efforts in Hawaii (Krauss, 1932), did not yield the expected results and the use of pigeonpea as a combined green manure and pulse crop has almost completely ceased in that area.

Following Harlan (1975), Schwanitz (1966), and Smartt and Hymowitz (1985) the processes of adaptation during domestication can be described.

Plant Habit

Most pigeonpeas are perennials and tend to grow very tall, up to 4 m or so, as often found in Africa or in tribal areas, particularly in eastern and northeastern India. Perenniality is considered a primitive character (Hutchinson, 1965). Pigeonpea is almost exclusively grown as an annual, in rows and/or mixed with many other crops such as cotton, sorghum, millets, and groundnut which are harvested several months prior to the pigeonpea. The pigeonpea plants are cut down when most of their pods have ripened, often when green leaves are still present. Pressure for annuality has therefore probably been limited. Among the grain legumes only the pigeonpea has not been subjected to a radical change in life form.

Some short-statured mutations have essentially lost their ability to sprout again when the rains come. These modern short-duration cultivars do produce well if densely sown and protected with insecticides, not yet an economical practice in most areas, but may soon become so in some. These cultivars (e.g., cv. Prabhat) are likely to disappear without human intervention. Tall pigeonpeas supply farmers with valuable browsing and fuel stocks. The only relative, *C. platycarpus* (Benth.) van der Maesen, which is usually annual, is almost the most distantly related one, but even this species perrennates when conditions are favourable.

A spreading or erect habit, important for cultivar classification, seems to have little relevance to the farmer. Spreading forms are preferred if space occupied by an earlier-harvested intercrop needs to be filled in. Erect cultivars may be useful for intercropping with other crop species of similar duration, but have not proved better than spreading ones.

Crop Duration

There is a wide diversity in flowering data and maturity. African material, found close to the Equator, flowers extremely late in India at 17 °N or more, when sown under long days. Short days trigger flowering. If sown before or during the Indian winter, pigeonpea plants remain much smaller than usual. In a few areas in India (Dangs, Gujarat; Bihar) "rabi" (post-monsoon) pigeonpeas are grown, but no special selections seem to have been made for this purpose. The determinate flowering (in time, not as inflorescence type) cultivars have a shortened, more synchronized flowering period and flower early, or are of medium duration. This is a typical derivation from the usually indeterminate cultivars that flower for a long time, and are able to compensate for eventual losses however these are incurred.

Photoperiod Sensitivity

The pigeonpea did not lose photoperiodic sensitivity, but a few very recent selections e.g., QPL 1 or mutations show a reduced response to long days. There is diversity in sensitivity, so less-sensitive lines e.g., Prabhat (ICP 7220) and L 3 (ICP 7630) can be selected from the germplasm. When grown in the rainy season, flowering in India is triggered by short days after the rains cease. In northern India low temperatures in the post-monsoon period further delay flowering, and this has led to adaptation as long-duration cultivars.

Flower Number and Inflorescence Size

There is no discernable pattern regarding flower number. A higher number may be expected when pulses continue to evolve (Harlan, 1975) but in many Cajaninae flowering is very abundant and fruit set is rather low, a mechanism that enhances the ability to compensate. The inflorescence size in pigeonpea is larger than in several related creepers and shrubs, but smaller than in other related species. Among wild species, flower size is largest in *Cajanus grandiflorus* (Benth. ex Baker) van der Maesen. In pigeonpea, accessions with the largest leaflets and seeds also have the largest flowers and pods (e.g., PR 5449 from Tanzania).

Fruit and Seed Size

Wild relatives have smaller seeds, although some approach those of pigeonpea. Obviously large seeds were preferred and selected. Medium-sized seeds are preferred for dhal milling. Large-podded and large-seeded pigeonpeas are selected for vegetable use in Africa, and the Caribbean. Enlargement of plant organs is often due to an increase in cell size (Schwanitz, 1966). Larger pods require stronger stems for their support, and many small-seeded wild species are climbers, that are weaker than the cultivated pigeonpea. Pigeonpea's possible progenitor, *C. cajanifolius*, has rather weak, spreading branches, but in many pigeonpea cultivars this habit suffices to bear heavy pods.

Seed Colour

This is an important market consideration, as is seed size. Even for dhal preparation, which includes removal of the testa, white seed colour is often preferred, or at least a uniform brown colour. Dark purple, variegated, or mixed colours are often found in mixed populations grown by tribal people e.g., in eastern India.

Taste

Locally some types are preferred to others, but this has rarely resulted in cultivar name differences. Wild pigeonpeas are often somewhat bitter when eaten raw, while fresh pigeonpeas are usually free from bitter substances. Vegetable pigeonpeas that are to be eaten freshly cooked need to be sweet, while bitter substances are not detectable in dry pigeonpeas. Dry or split pigeonpeas differ in fragrance and taste, and this gives rise to local preferences.

Indehiscent Pods

In most wild legume species the pods shatter their seeds, as a means of natural dissemination, and have to be harvested daily when cultivated. *Cajanus cajanifolius* shatters its seeds quite late. If cultivated pigeonpea is left unharvested after maturity, the pods will ultimately shatter. A study of dispersal would be interesting; but it is sufficient here to say that the relatively large seeds are not carried very far, and this may have contributed to the rather localized small populations remnant in forests and untouched hillsides. This suggests that these legumes may have been more common and widespread in bygone eras.

Loss of Seed Dormancy

Virtually all known pigeonpea germplasm accessions are non-dormant. Only two or three have very hard seed coats that prevent imbibition and delay the germination of fresh seeds. By contrast, most wild species have dormant seed, at least for some months, and are routinely scarified to ensure uniform germination when grown at ICRISAT Center (Rao *et al.*, 1985).

Seedling Vigour

Larger seeds produce large seedlings, but in pigeonpea any advantage disappears within the first 4 to 6 weeks after emergence.

In the early stages of growth (2-3 months) pigeonpea and many of its relatives are not very competitive with weeds. The deep taproot develops well, but the crop can be harmed if competition is considerable. For wild species this perhaps does not matter much, since most reach above the grass level, or climb in shrubs or trees. Cajaninae are not weedy. Ultimately, the most vigorous plants contribute most to the next generation.

Habitat

Most Cajaninae are found near the forest edge, in open places within the forest, or in grassy habitats. Climbers use trees and shrubs for support, and flowering occurs in the light. They favour tropical savannahs with a marked dry season. Some species only occur at higher altitudes. Distribution tends to be scattered in suitable ecological niches, with the exception of the rather ubiquitous *C. scarabaeoides*. The progenitor *C. cajanifolius* was found earlier at only three locations in the Bastar, Puri, and Kalahandi districts of eastern India, but more locations were recently spotted when a proper search was made. It is still a rare species and may have become scarce and isolated due to habitat reduction, and this is perhaps also true of several other of the less-common wild species, rather than due to slow propagation alone. By contrast, in a crop situation the pigeonpea tends to be shaded during its early growth, and faces full sunlight later on.

Biochemical Constitution

Seed protein of wild species has a poorer solubility than that of pigeonpea, and this indicates an increase in solubility under domestication, and perhaps improved nutritional quality in this grain legume (Ladizinsky and Hamel, 1980). Trypsin and chymotrypsin inhibitor activity of several wild species, but not *C. cajanifolius*, was considerably higher than in pigeonpea (Singh and Jambunathan, 1981), the *in vitro* digestibility of wild species was quite similar to the values found for pigeonpea, but *Rhynchosia rothii* was much lower in digestibility. The appearance of typical wild species bands in some electrophoretic variants of *Cajanus cajan* suggests that there is still a gene flow between pigeonpea and its wild relatives.

CONCLUSIONS

Pigeonpea may have originated from *Cajanus cajanifolius*, but several other *"Atylosia"* ancestors, now considered congeneric with *Cajanus*, may have contributed by introgression. Pigeonpea is only now being moulded into modern crop cultivars. These are of short duration and stature, have many large seeds per pod, yield well, allow dense populations, and possess resistance against diseases and pests. The plant is perennial. A true annual will put all its reserves into seed, but so far no form of pigeonpea is truly annual. Subsistence and modern farmers still grow rather primitive landrace cultivars or selections thereof. The tall, long-duration cultivars are valued for browsing and fuel in poorer rural societies. Present cultivars are well adapted to existing husbandry, but even in intensified mixed cropping and mechanical harvesting some can be used. New cultivars must do even better and cater to improved cultivation practices (Hutchinson, 1965).

Acknowledgement

The work of A.A. Majid in the preparation of line drawings is appreciated.

REFERENCES

Baudet, J.C. (1978) Prodrome d'un classification generique des Papilionaceae-Phaseoleae. *Bulletin du Jardin Botanique Nationale de Belgigue* 48, 183-220.

Bentham, G. (1837) *Commentationes de Leguminosarum Generibus*. Vienna, 49 pp.

Bentham, G. and Hooker, J.D. (1865) *Genera Plantarum* 1(2), 541-542.

De, D.N. (1974) Pigeonpea. In: Hutchinson, J. (ed), *Evolutionary Studies in World Crops: Diversity and Change in the Indian Subcontinent*. Cambridge University Press, London, pp. 79-87.

Deodikar, G.B. and Thakar, C.V. (1956) Cyto-taxonomic evidence for the affinity between *Cajanus indicus* Spreng. and certain erect species of *Atylosia* W.&A. *Proceedings of the Indian Academy of Sciences, Section B* 43, 37-45.

Dundas, I.S., Britten, E.J. and Byth, D.E. (1983) Pachytene chromosome identification by a key based on chromomeres in the pigeonpea. *Journal of Heredity* 74, 461-464.

Harborne, J.B., Boulter, D. and Turner, B.L. (1971) *Chemotaxonomy of the Leguminosae*. Academic Press, London and New York, pp. 411-527.

Harlan, J.R. (1975) *Crops and Man*. American Society of Agronomy and Crop Science Society of America, Madison, Wisconsin, 295 pp.

Harlan, J.R. and de Wet, J.M.J. (1971) Toward a rational classification of cultivated plants. *Taxon* 20, 509-517.

Hutchinson, J.B. (1965) Crop plant evolution: a general discussion. In: Hutchinson, J.(ed), *Essays of Crop Plant Evolution*. Cambridge, London, pp. 166-181.

ICRISAT (1986) *Annual Report 1985*. Patancheru, A.P., India: ICRISAT, pp. 207-208.

Kajale, M.D. (1974) Plant economy at Bhokardan. Appendix A. In: Dev, S.B. and Gupta, R.S. (eds), *Excavations at Bhokardan (Bhogavardana) 1973*. Nagpur University and Maharashtra Marathwada University, India, pp. 7-224.

Krauss, F.G. (1932) The pigeonpea *(Cajanus indicus)*: its improvement, culture, and utilization in Hawaii. *Hawaii Agricultural Experiment Station, Bulletin* 64, 1-46.

Krishna, T.G. and Reddy, L.J. (1982) Species affinities between *Cajanus cajan* and some *Atylosia* species based on esterase isoenzymes. *Euphytica* 31, 709-713.

Kumar, L.S.S., Thombre, M.V. and D'Cruz, R. (1958) Cytological studies of an intergeneric hybrid of *Cajanus cajan* (Linn.) Millsp. and *Atylosia lineata* W.&A. *Proceedings of the Indian Academy of Sciences, Section B* 47, 252-262.

Lackey, J.A. (1977) A synopsis of Phaseoleae (Leguminosae: Papilionoideae). PhD thesis, Iowa State University, Ames, Iowa, 293 pp.

Lackey, J.A. (1978) Leaflet anatomy of Phaseoleae (Leguminosae: Papilionoideae) and its relation to taxonomy. *Botanical Gazette* 139(4), 436-444.

Lackey, J.A. (1981) Phaseoleae. In: Polhill, R.M. and Raven, P.H. (eds), *Advances in Legume Systematics, Part 1*. Royal Botanic Gardens, Kew, UK, pp. 301-327.

Ladizinsky, G. and Hamel, A. (1980) Seed protein profiles of pigeonpea (*Cajanus cajan*) and some *Atylosia* species. *Euphytica* 29, 313-317.

McComb, J.A. (1975) Is intergeneric hybridization in the Leguminosae possible? *Euphytica* 24, 497-502.

Pedley, L. (1981) *Atylosia* in Australia. In: *Proceedings of the International Workshop on Pigeonpeas, volume 2, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 51-52.

Plitmann, U. and Kislev, M. (1986) Reproductive changes induced by domestication. In: *Abstracts, Second International Legume Conference on the Biology of the Leguminosae, 23-27 June 1986*.

Plukenet, L. 1692. *Phytographia* 3, table 213, figure 3.

Pundir, R.P.S. (1981) Relationships among *Cajanus*, *Atylosia* and *Rhynchosia* species. PhD thesis, Banaras Hindu University, Varanasi, 100 pp.

Purseglove, J.W. (1968) *Tropical Crops–Dicotyledons 1*. Longmans, London, pp. 236-237.

Rachie, K.O. and Roberts, L.M. (1974) Grain Legumes of the lowland tropics. *Advances in Agronomy* 26, 1-132.

Rao, N.K., van der Maesen, L.J.G. and Remanandan, P. (1985) Breaking seed dormancy in *Atylosia* species. *Seed Research* 13(2), 47-50.

Reddy, L.J. (1973) Interrelationship of *Cajanus* and *Atylosia* species as revealed by hybridization and pachytene analysis. PhD thesis, Indian Institute of Technology, Kharagpur, India.

Reddy, L.J. (1981a) Pachytene analyses in *Cajanus cajan*, *Atylosia lineata* and their hybrid. *Cytologia* 46, 397-412.

Reddy, L.J. (1981b) Pachytene analyses in *Atylosia sericea* and *Cajanus cajan* × *A. sericea* hybrid. *Cytologia* 46, 576-577.

Reddy, L.J. (1981c) Pachytene analyses in *Atylosia scarabaeoides* and *Cajanus cajan* × *A. scarabaeoides* hybrid. *Cytologia* 46, 579-589.

Reddy, L.J., Green, J.M., and Sharma, D. (1981) Genetics of *Cajanus cajan* (L.) Millsp. × *Atylosia* spp. In: *Proceedings of the International Workshop on Pigeonpeas, volume 2, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 39-50.

Roy, A. and De, D.N. (1965) Intergeneric hybridization of *Cajanus* and *Atylosia*. *Science and Culture* 31, 93-95.

Schwanitz, F. (1966) *The Origin of Cultivated Plants*. Harvard University Press, Cambridge Mass., 175 pp.

Schweinfurth, G. 1884. Further discoveries in the flora of ancient Egypt. *Nature* 29, 312-315.

Sikdar, A.K. and De, D.N. (1967) Cytological studies of two species of *Atylosia* and *Cajanus cajan*. *Bulletin of the Botanical Society of Bengal* 21(1), 25-28.

Singh, U. and Jambunathan, R. (1981) Protease inhibitors and *in vitro* protein digestibility of pigeonpea (*Cajanus cajan* (L.) Millsp.) and its wild relatives. *Journal of Food Science and Technology* 18, 246-247.

Singh, U., Jambunathan, R. and Gurtu, S. (1981) Seed protein fractions and amino acid composition of some wild species of pigeonpea. *Journal of Food Science and Technology* 18, 83-85.

Smartt, J. (1976) Comparative evolution of pulse crops. *Euphytica* 25, 139-143.

Smartt, J. (1978) The evolution of pulse crops. *Economic Botany* 32, 185-198.

Smartt, J. (1980) Evolution and evolutionary problems in food legumes. *Economic Botany* 34, 219-235.

Smartt, J. and Hymowitz, T. (1985) Domestication and evolution of grain legumes. In: Summerfield, R.J. and Roberts, E.H. (eds), *Grain Legume Crops*, Collins Professional and Technical Books, London, pp. 37-72.

van der Maesen, L.J.G. (1979) Wild pigeonpeas in Africa. *Plant Genetic Resources Newsletter* 40, 8-10.

van der Maesen, L.J.G. (1980) India is the native home of the pigeonpea. In: Arends, J.C., Boelema, G., de Groot, C.T. and Leeuwenberg, A.J.M. (eds), *Libergratulatorius in honorem H.C.D. de Wit. Landbouwhogeschool Miscellaneous Paper no. 19*. Wageningen, Netherlands: H. Veenman and B.V. Zonen, pp. 257-262.

van der Maesen, L.J.G. (1983) *World Distribution of Pigeonpea. ICRISAT Information Bulletin no. 14.* Patancheru, A.P., India: ICRISAT, 40 pp.

van der Maesen, L.J.G. (1986) *Cajanus DC. and Atylosia W.&A. (Leguminosae). Agricultural University Wageningen Papers 85-4 (1985).* Agricultural University, Wageningen, the Netherlands, 225 pp.

van der Maesen, L.J.G. and Somaatmadja, S. (1989) *Plant Resources of South East Asia No.1. Pulses.* PUDOC, Wageningen, the Netherlands, 105 pp.

Vavilov, N.I. (1951) The origin, variation, immunity and breeding of cultivated plants. *Chronica Botanica* 13(1/6), 1-366.

Vernon Royes, W. (1976) Pigeonpea. In: Simmonds, N.W. (ed), *Evolution of Crop Plants*. Longmans, London and New York, pp. 154-156.

Chapter 3

PIGEONPEA: MORPHOLOGY

L.J. REDDY

Plant Breeder, Legumes Program, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Andhra Pradesh 502 324, India.

INTRODUCTION

Pigeonpea [*Cajanus cajan*(L.) Millspaugh], known by several vernacular and trade names such as red gram, Angola pea, Congo pea, no-eye pea, and yellow dhal belongs to the tribe Phaseoleae and subtribe Cajaninae under sub-order Papilionaceae of the order Leguminosae. *Cajanus* has been treated as a monotypic genus by most of its researchers although another African species, *Cajanus kerstingii* was described by Harms (1915). However, *C. kerstingii* should have been placed under the genus *Atylosia* because of the persistent nature of its strophiole. The genus *Cajanus* closely resembles members of the genus *Atylosia* in vegetative and reproductive characters, and some of the *Atylosia* species can produce fertile hybrids when crossed with the cultivated pigeonpea (Deodikar and Thakar, 1956; Kumar *et al.*, 1958, 1966; Roy and De, 1965; Kumar and Thombre, 1958; Reddy, 1973; De, 1974; Reddy *et al.*, 1981a). Based on their observations some of these workers suggested merger of *Atylosia* with *Cajanus*, and in 1986 van der Maesen finally revised the taxonomy, and merged these two genera following systematic analysis of morphological, cytological, and chemo-taxonomical data which indicated the congenenicity of the two genera.

The genus *Cajanus* now comprises 32 species including 17 from the Indian sub-continent, 13 endemic to Australia, one endemic to West Africa, and one ubiquitous species, *C. scarabaeoides* (van der Maesen, 1986).

In this chapter a complete description and development of various morphological parts of the cultivated species *Cajanus cajan* (pigeonpea), the influence of environment on its morphology, and inter-relationships between various plant characters are reviewed and discussed. Various morphological mutants that have arisen either spontaneously, or been created through hybridization and mutagen treatment are also described.

GENERAL DESCRIPTION OF THE GENUS *CAJANUS*

Following van der Maesen (1986) the salient morphological features of the revised genus *Cajanus* are given below.

"Perennial, rarely annual, erect bushes, 0.5 to 4 m, or creepers, or climbers, strong or weak. Pubescence various. **Leaves** pinnately, sometimes digitately trifoliolate. **Leaflets** with vesicular glands below, membranaceous or rather thick. **Stipellae** present or absent. **Flowers** in axillary or terminal pedunculate or almost sessile racemes, yellow, or lined with red, or flag dorsally reddish, up to 3 cm long. **Bracts** small or large, caducous, bracteoles absent. **Calyx** teeth acute, acuminate or elongate-acuminate, two upper ones more or less connate. **Corolla** persistent or not, vexillum obovate-orbicular, reflexed, clawed, auriculate. Wings obliquely obovate, auriculate, keel rounded-oblique, obtuse. **Ovary** subsessile, ovules (2-)3 to 10. **Style** thickened above the middle, upcurved, upper part glabrous or slightly hairy, not bearded. **Stamens** 9 connate, vexillar stamen free, anthers uniform. **Fruit** a pod, linear-oblong, apex obtuse or acute, compressed, bivalved, depressed between the seeds with transverse lines, more or less septate between the seeds. **Seeds** reniform to suborbicular, shiny, white, brown, grey, purple or black, variegated or not, strophiole conspicuous or vestigial".

MORPHOLOGY OF *CAJANUS CAJAN*

The morphological variation in pigeonpea (*Cajanus cajan*) is greatest in Asia especially in India, its place of origin. Several researchers working in India (Mahta and Dave, 1931; Shaw *et al.*, 1933; Pathak, 1970; van der Maesen, 1986; Sheldrake, 1984) have described the morphology and studied the variation available within pigeonpea. Similarly Westphal (1974) studied the morphology and variation of the pigeonpea types available in Ethiopia.

On the basis of flower colour, seed numbers per pod, length of stipels, de Candolle (1813) distinguished two species under *Cajanus* viz., *C. bicolor* and *C. flavus*. Later workers (Purseglove, 1968) reduced these two species to botanical varieties. Variety *flavus* (DC) is characterised by early maturity with shorter stature, yellow standard petals, green glabrous pods, lighter in colour when ripe, and usually 3-seeded. Variety *bicolor* (DC) is characterised by late maturity, large bushy stature, red or purple streaked standard petals, and hairy pods blotched with maroon, or dark coloured with 4 to 5 seeds, that are darker coloured or speckled when ripe.

The above varietal distinctions appear to be of doubtful taxonomic validity since the two varieties are readily crossable, and a range of combinations of the above distinguishing features occurs in the present-day varieties.

Based on the morphology, Shaw *et al.* (1933) distinguished 86 different pigeonpea types from collections throughout India, while Mahta and Dave (1931) recognised 36 types from Madhya Pradesh State alone. Recently Remanandan *et al.* (1988) measured the variability in more than

11,000 germplasm accessions assembled at ICRISAT Center from 52 countries. They recorded 40 morpho-agronomic traits, of which 22 traits were entered in the computer-based catalogue. A detailed morphology and anatomy of various traits and discussion on the influence of environment on the development of these traits are presented here.

Structure, Development, and Influence of Environment

Seeds

In pigeonpea, four seed shapes; oval, pea, square, and elongate (Figure 3.1) are recognised. The most common shape is oval. Pea-shaped seed is usually found in late-maturing varieties with large seeds, but not all the late-maturing, large-seeded varieties have pea-shaped seeds. This trait is very rare in early-maturing varieties. Pea-shaped seeds are preferred in areas where pigeonpea is used as a green vegetable.

The seed coat (testa) colour in pigeonpea ranges from white to almost black. Although the seed coat colour variation is continuous, it has been suggested (IBPGR/ICRISAT, 1981) that 10 seed base colour classes (Table 3.1) and five colour patterns are used to achieve uniformity in recording. The major colour classes are orange, cream, reddish brown, and light brown. Of the five different colour patterns (Figure 3.2) plain is predominant followed by mottled, speckled, and mottled + speckled. The ringed seed colour pattern is rare.

Seed mass (weight) is an important yield component and varieties vary widely in this trait

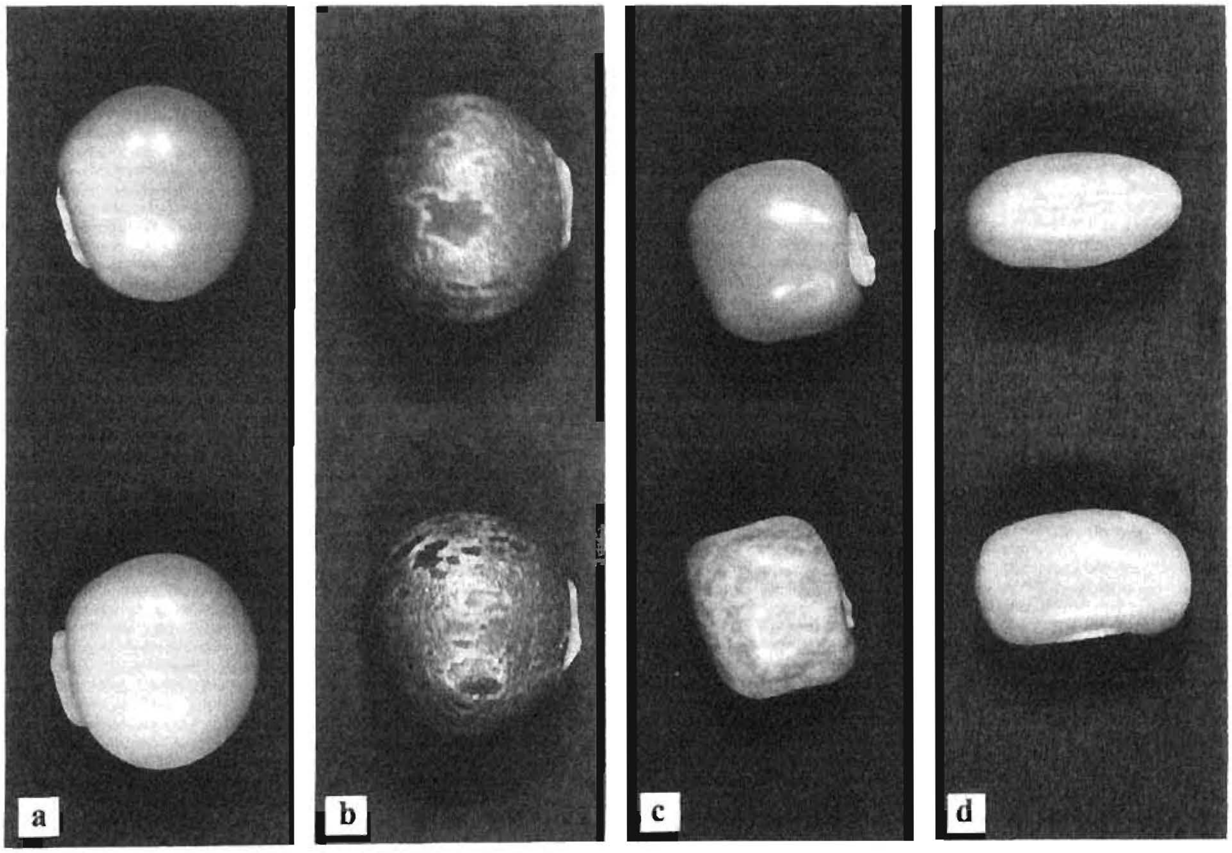


Figure 3.1. Pigeonpea variation in seed shapes: a. Oval; b. Pea; c. Square; d. Elongate.
Source: Remanandan *et al.*, 1988.

Table 3.1. Pigeonpea seed colours.

Colour	RHSCCN[1]
White	Yellow white 158C
Cream	Greyed white 156C
Orange	Greyed orange 163C
Light brown	Yellow orange 22C
Brown	Brown 200D
Light grey	Grey brown 199B
Grey	Greyed green 197A
Purple	Greyed purple 187A
Dark purple	Greyed purple 187B
Black[2]	Black 202A

1. RHSCCN = Royal Horticultural Society Colour Chart Number.
2. Black, with a purple shine that lessens as the seed ages.

Source: IBPGR/ICRISAT, 1981.

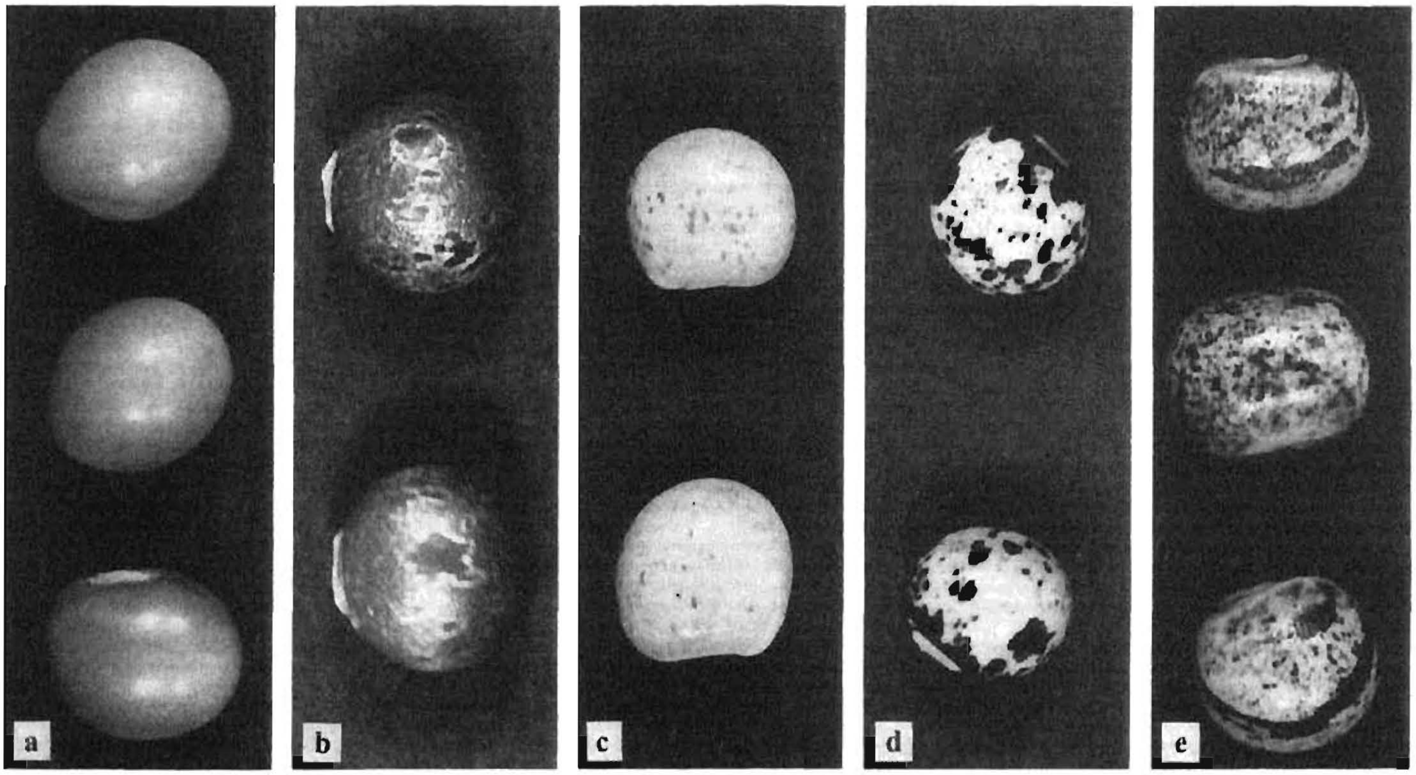


Figure 3.2 Pigeonpea seed colour patterns: a. Plain; b. Mottled; c. Speckled; d. Mottled and speckled; e. Ringed.

Photo: ICRISAT.

(Figure 3.3). The mass of 100 seeds ranges from 2.8 to 22.4 g. However, the majority of varieties possess a 100-seed mass between 7.0 and 9.5 g. Large seeds are preferred by consumers partly because with seed size the pericarp percentage reduces, and dhal out-turn increases. There is a definite preference for large-seeded types where these are used as green peas. However, in the large-seeded types pod setting is generally poor because of a high rate of ovule abortion.

The number of seeds per pod is an important yield component that is remarkably constant within a genotype, although there is large variation among genotypes (Sheldrake, 1984) The average seed number per pod ranges from 1.6 to 7.6. However, majority of varieties possess 3 to 4 seeds per pod. Varieties with more seeds per pod are preferred in areas where pigeonpea is used as a vegetable.

The seeds of pigeonpea are nonendospermic and contain two massive cotyledons which fill most of the seed. The cotyledons are hinged to an axis (tigellum) that represents the future axis of the plant. The parenchymatous cells of the cotyledons contain large starch grains and numerous protein bodies. Vascular strands run throughout the ground tissue of the cotyledons.

As in other legumes, the pigeonpea seed coat comprises an outer palisade layer of sclereids, and a subepidermal layer of "pillar cells" (Figure 3.4a). These two layers are separated by large intercellular spaces. Below the subepidermal cells, a thin layer of collapsed parenchymatous cells and the remains of the endosperm can be seen. In the hilum region, a hole in the seed coat leads into a "tracheid island" (Figure 3.4b). The tissue outside the seed coat at the hilum, known as

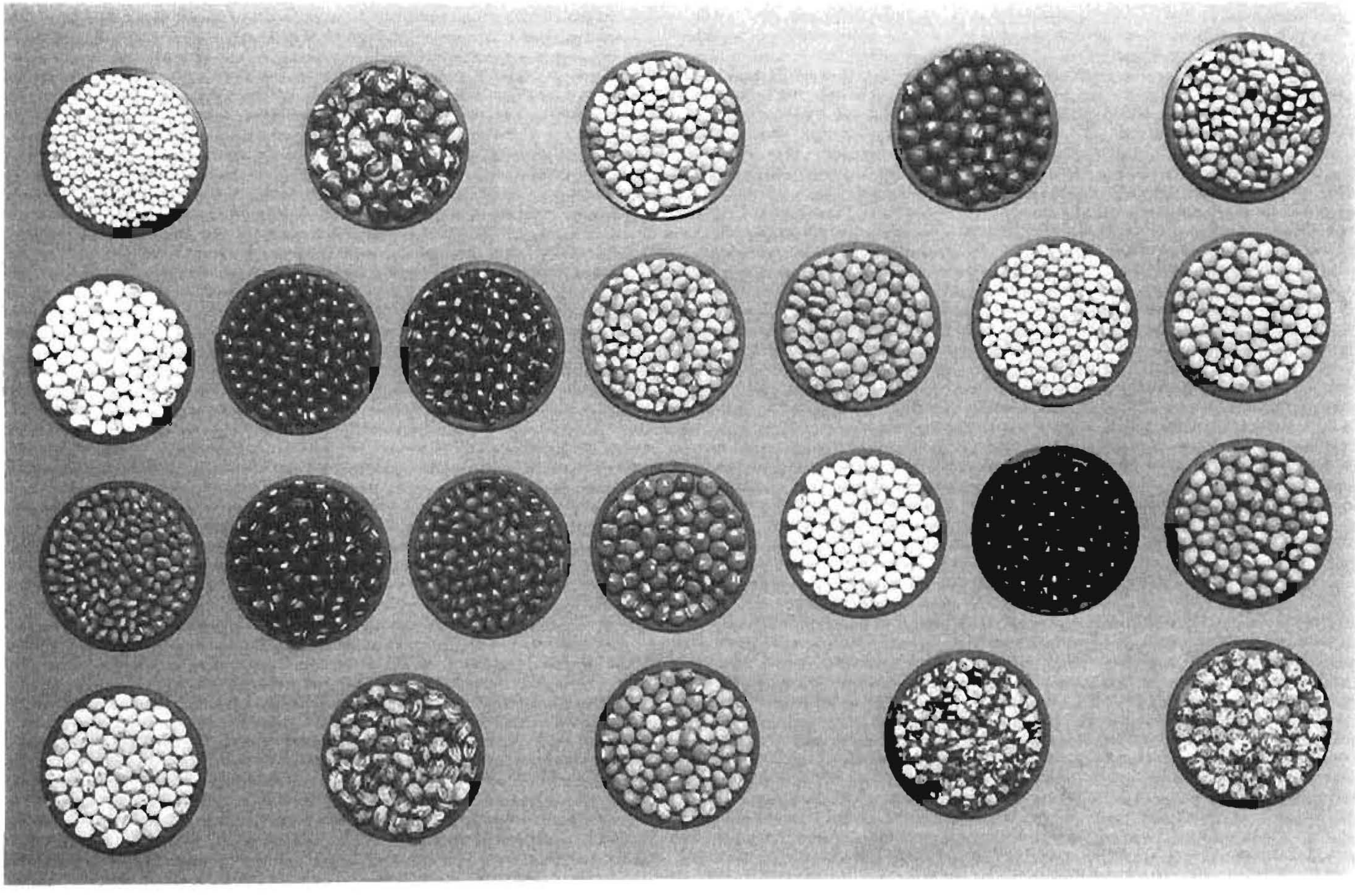


Figure 3.3. Pigeonpea variation in seed size and colour.

Source: Remanandan *et al.*, 1988.

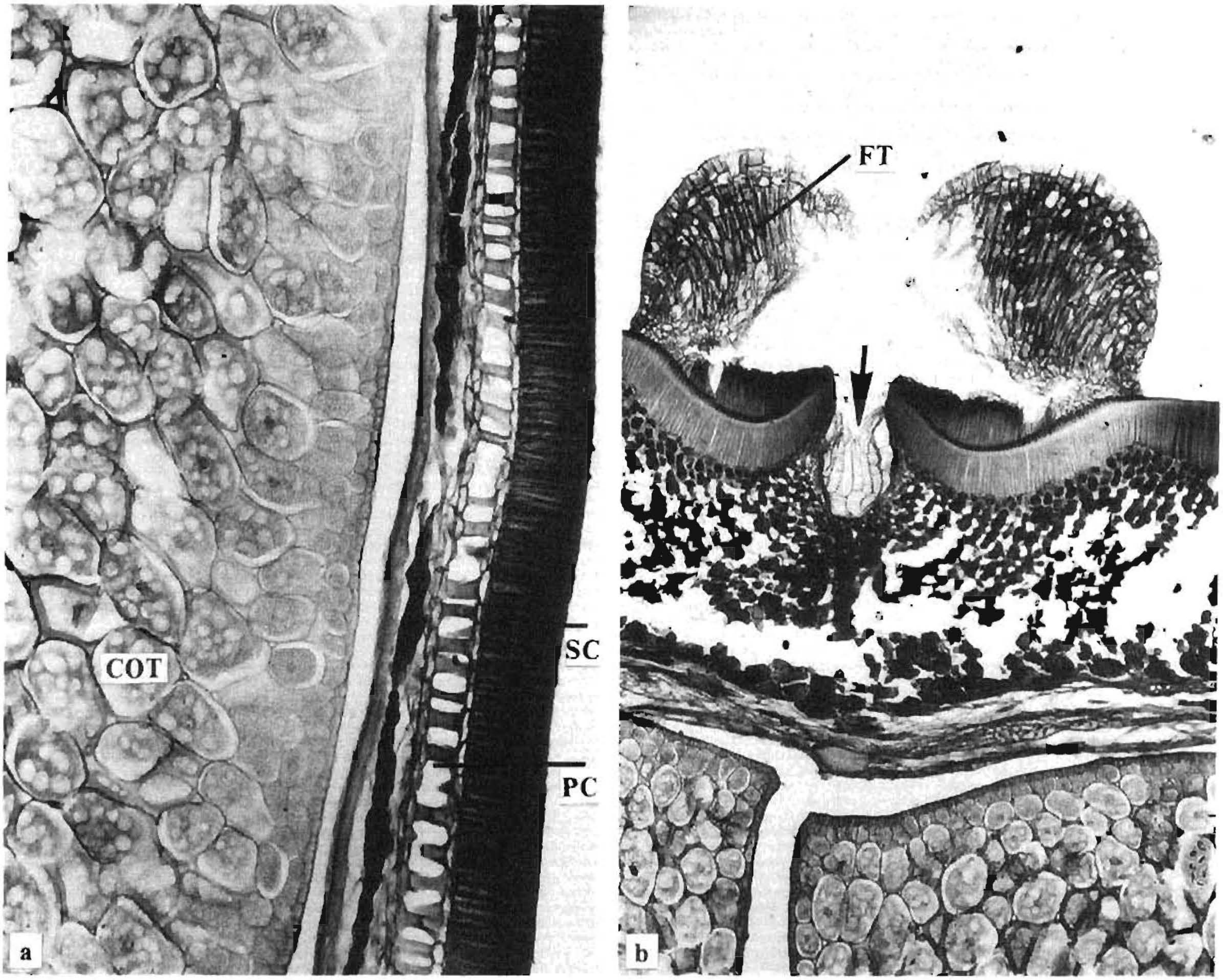


Figure 3.4. Transverse section of pigeonpea (T21): a. Seed coat, × 174, showing outer layer of sclereids (SC) and inner layer of pillar cells (PC); b. Seed in the hilum region, × 236, showing funicular tissue (FT) and the tracheid island (arrowed).
Source: Bisen and Sheldrake, 1981.

funicular tissue, includes a palisade layer adjacent to that of the seed coat (Bisen and Sheldrake, 1981). The funicle is extended to a long raphe above the hilum. An external structure around the hilum, a rim-aril, referred to as the strophiole, is seen on developing seeds: this strophiole usually shrivels completely when the seeds are ripe. However, in some genotypes the seeds show a more or less well developed seed strophiole. The strophiole has a lengthwise groove that divides the structure into two parts. It is a conspicuous, regular rim-aril in Gunn's (1981) terminology.

Seedling

Pigeonpea seeds do not have dormancy, and germination is generally good except under cool conditions. Laboratory studies have revealed a broad optimum temperature range (19-43°C) for germination, with the most rapid seedling growth occurring between 29 and 36°C (de Jabrun *et al.*, 1981). Germination is hypogeal, and the cotyledons remain underground (Figure 3.5). Under suitable field conditions the seedlings appear above the ground in about 5-6 days. On the second day, the testa splits open near the micropyle, and the tip of the radicle elongates and emerges from the seed coat. On the third day the hypocotyl appears as an arch and continues to grow upwards. The hypocotyl developes a light purple colour and becomes straight. The seedling epicotyl is light green, green, or purple in colour. The first pair of leaves are simple.and opposite. The epicotyl elongates to 3-7 cm before the first trifoliate leaf emerges. The first pair of leaves generally drop off within 30 to 40 days, but they may remain longer.

When the young plumules or axillary shoots are damaged, secondary shoots develop from the cotyledonary axils of the seeds, resulting in multiple shoots. This phenomenon helps the plant to overcome germination and establishment problems under harsh environmental conditions. The occurrence of secondary shoots is often mistaken for twin seedlings in pigeonpea. Reddy and Rao

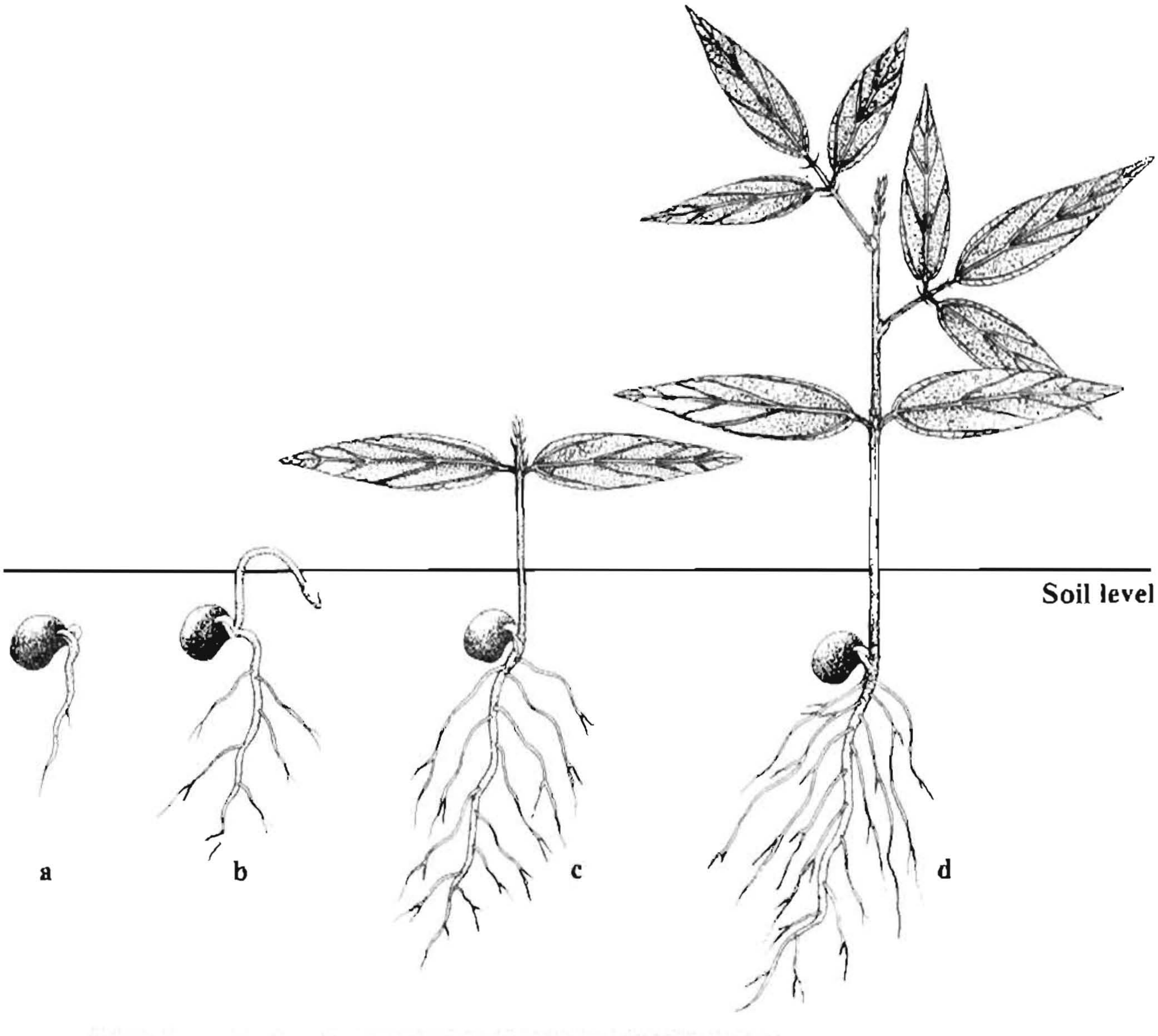


Figure 3.5. Stages in the hypogeal germination of pigeonpea seed. Seedlings aged: a. 2 days; b. 5 days; c. 10 days; and d. 15 days.

(1975) reported variation in maturity, leaf size, flower, pod and seed size, and plant pigmentation between secondary shoots developed from the same seed.

Large-seeded varieties produce bigger seedlings than those of the small-seeded types, but these differences disappear as the plant grows (Narayanan *et al.*, 1981).

Root System

The root system in pigeonpea consists of a deep, strong, woody tap root with well developed lateral roots in the superficial layers of the soil. Under certain conditions the roots can go more than 2 m deep, but the most extensive development takes place in the upper 60 cm of the soil (Sheldrake and Narayanan, 1979; Natarajan and Willey, 1980). Normally root depth ranges from 30 to 90 cm and is influenced by the date of sowing and the availability of moisture in the soil profile. Root growth continues during the reproductive phase and the total root length approximately doubles after the onset of flowering (Sheldrake and Narayanan, 1979). The root system appears to be closely related to plant habit. Tall, compact varieties produce longer and more deeply penetrating roots, whereas spreading types produce shallower, more spreading, and denser root systems (Pathak, 1970).

In a dormant seed, the radicle measures 0.2 cm below the cotyledonary node. Before the first pair of simple leaves unfolds, the radicle grows to a sufficient length with a clear demarcation between the tap root and the hypocotyl region. The radicle comes out through the hilum within 1.5-2.0 days. In about 5 days the radicle attains a length of 4-6 cm. From the third day onwards, lateral roots make their acropetal appearance.

The primary structure of both the tap root and secondary roots is tetrarch. Young roots possess parenchymatous pith that is disorganised at the onset of secondary growth. The epidermis of the young root is single-layered with a thin layer of cuticle. The wide cortex is parenchymatous, and consists of numerous rhomboidal crystals. The endodermal cells do not show casparian thickening on their radial walls. The pericycle is multilayered. Older roots with secondary growth appear more or less eccentric. Secondary growth occurs through the activity of a vascular cambium. The development of this cambium is typically dicotyledonous. The cork consists of a few layers. In the secondary phloem some dilation of phloem rays is observed (P. Venkateswara Rao, unpublished). Within the phloem region, secretory ducts containing a tannin-like material are present (Bisen and Sheldrake, 1981); these ducts are also present in stems and other aerial organs.

Mycorrhizae are often present in cortical cells of the roots, and occasionally mycorrhizal fruiting bodies can be observed (Bisen and Sheldrake, 1981).

Nodules

Pigeonpeas are nodulated by rhizobia of the cowpea group, usually by a slow-growing *Rhizobium* species, although fast-growing rhizobia also have been isolated from pigeonpea nodules (Nambiar *et al.*, 1988).

Nodule formation in pigeonpea is initiated by infection thread development in root hairs (Kapil and Kapil, 1971). Nodules grow through the activity of a meristematic zone arching around the apical end, and the medulla contains numerous bacterioid-filled cells. Sometimes the latter are highly vacuolated (Bisen and Sheldrake, 1981). The nodule is exogenous in origin. A mature nodule shows a well-marked bacterioid zone, an apical meristem, and a vascular zone. Uninvaded cells can be observed in the bacterioid zone (Arora, 1956). The bacterioid zone of pigeonpea nodules may be pink or brown in colour. In certain cases deep purple to black pigmentation is also observed in this zone. The vascular bundles may be collateral, inversely collateral, or bicollateral. In later stages they develop secondary elements. Unlike the herbaceous nodules present in other legumes such as chickpea and groundnut, pigeonpea nodules possess a sclereid layer in the cortex, a diffuse area of tissue degeneration, and an inconsistent oriculation of xylem and phloem (Arora, 1956). The nodules differ in size and shape. The size may vary from 2 mm to 2 cm, and the shape may be spherical, oval, elongate, or branched (see Chapter 10).

Nodule formation and development are affected by the soil type, season, and the duration of the cultivar (Thompson *et al.*, 1981). Most nodules are formed on the secondary roots and are located in the top 30 cm of the soil profile. Smaller nodules are frequently found in the 120-150 cm zone and may occur at even greater depths (see Chapter 10). The nodules continue to form up to 120 days after sowing and start to senesce approximately 30 days after sowing.

Leaves

The first two leaves are simple, opposite, and caducous. They are narrowly ovate with a cordate to truncate base, and an acute to acuminate apex. The apices may have a small mucro. The stipules are lanceolate and conspicuously forked. Rarely, the second and third nodes, show either a simple leaf or a compound leaf with only two leaflets.

Subsequent leaves are compound, pinnately trifoliate, and arranged in a 2/5 type of spiral phyllotaxy. A pair of free lateral, lanceolate stipules is present at the pulvinate base of the petiole that bears the leaflets. In a fully developed leaf, petiole length ranges from 2.4 to 6.0 cm and is prominently grooved on the adaxial side. Lateral leaflets possess one stipel each, whereas the terminal leaflet has a pair of stipels. The leaflets are lanceolate or elliptic, with acute or obtuse apices. Terminal leaflets are mostly symmetrical, but the side leaflets are broader at the side furthest away from the terminal leaflets. Terminal leaflets are usually bigger than lateral leaflets.

Genotypic differences exist for leaf size and shape (Figure 3.6), and are also influenced by the environment. Under extended daylength conditions the leaflet size considerably increases (Figure 3.7). The leaf surface area varies from 13.0 to 93.5 cm^2 in various genotypes (Murthi and van der Maesen, 1979) whereas in a minute leaf variant the total leaf surface for three leaflets only measures 6 cm^2. The lengths of the petiole and rachis also vary greatly, but the petiolule length is not so variable. The stipellae vary from traces to 4 mm.

In the midrib region of the leaf, the vascular tissue in the ventral half occurs in a continuous arched band with phloem on the outside and xylem inside (Bisen and Sheldrake, 1981). Two distinct strands mostly consisting of phloem are seen on the ventral side. The centre of the dorsal part of the midrib is occupied by fibres capped by collenchymatous cells (Figure 3.8).

The leaf lamina comprises a distinct palisade layer, and in the lower part of the leaf a spongy mesophyll with large air-filled intercellular spaces (Figure 3.9). There are far more stomata on the lower surface of the leaf than on the upper surface. Stomata are distributed between and over the minor veins, but not over the major veins. Mature stomata are either anomocytic, diacytic, or paracytic. Paracytic stomata are predominant (P. Venkateswara Rao, unpublished).

The venation pattern consists of the mid vein and conspicuously arranged secondaries which end at the leaf margins. The major veins form regular meshes, each of these is further divided several times with free vein endings (Figure 3.10). The vein ends have tracheids that are often forked.

The petiole contains a number of distinct vascular strands above which lie fibre bands (Figure 3.11). Occasionally some of the xylem vessels of the petiole are filled with a darkly stained tanin-like substance. Pulvini are found at the bases of the petiole and the leaflets. These are responsible for leaf and petiole movements. Under drought stress conditions when the sunlight is intense the leaflets exhibit paraheliotropy i.e., they take up a position parallel to the incident light. Similarly, during the night the leaflets are folded vertically upwards into the "sleep" position. Most of the pulvinus consists of cortical tissue (Figure 3.12). Changes in the turgor of these cortical cells are responsible for the movements of the pulvini.

As the leaves approach senescence, an abscission zone develops at the junctions between the leaflets and the petiole, and between the petiole and the stem. The cells in the abscission zone

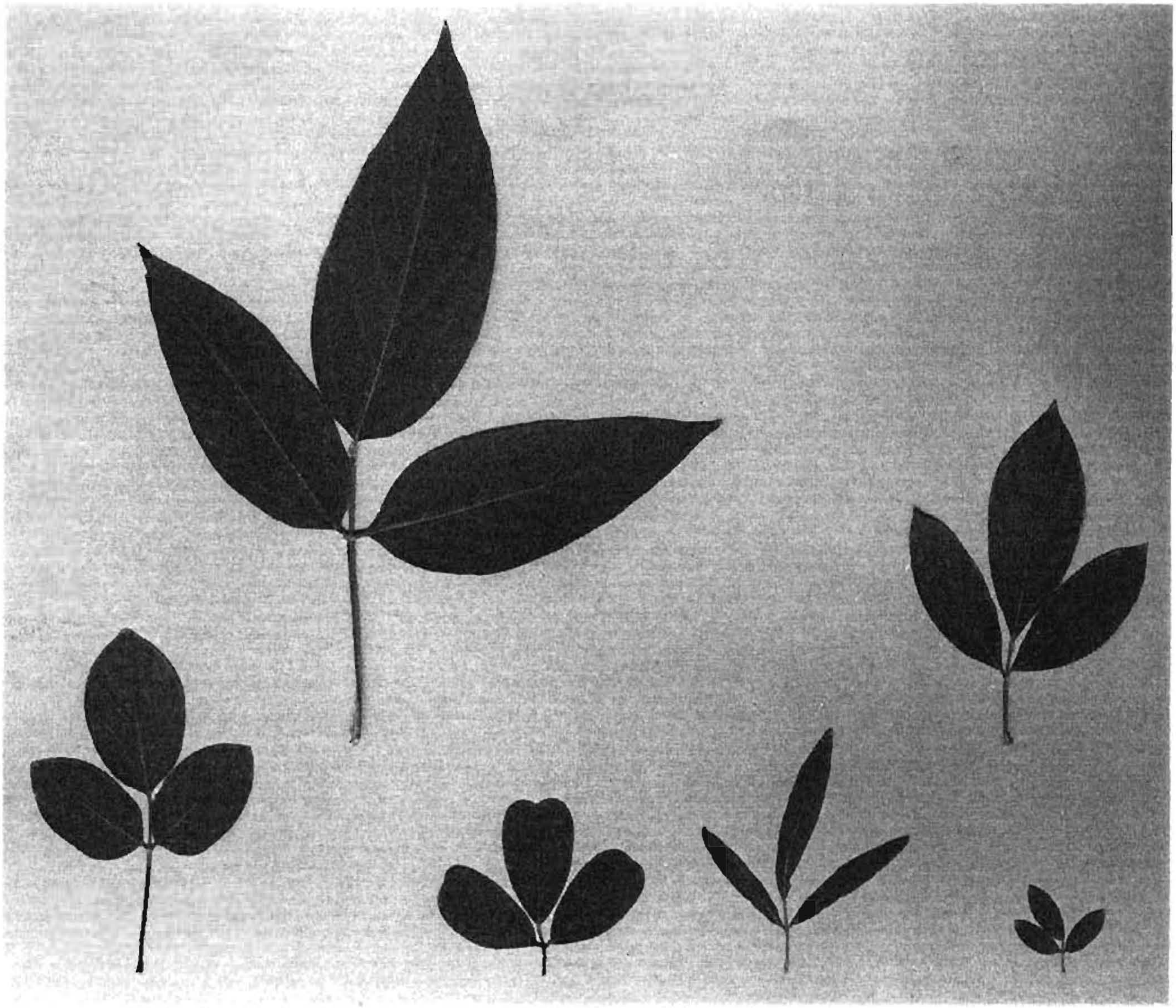


Figure 3.6 Diversity in pigeonpea leaf size and shape, left to right: largest; normal; ovate; retuse; sesame; and minute types.
Source: Remanandan et al., 1981.

show divisions parallel to the plane of abscission. The weakening of the walls of these cells results in an easy separation of the abscission zone, and consequently the leaflet or petiole falls.

Trichomes

The leaves are pubescent, more so on the lower than on the upper surface (Bisen and Sheldrake, 1981). There are two main types of trichomes, simple and glandular. Simple trichomes are eglandular, uniseriate, either filiform, or with a large terminal pointed cell. Glandular hairs are clavate, capitate and fusiform. They contain a yellow oily substance which probably imparts fragrance to the vegetative parts of pigeonpea. These fluid-filled sacs appear to develop from the short, multicellular glandular hairs found on young leaves. Simple and glandular hairs are also seen on all aerial parts of the plant, with the exception of some flower parts such as the petals and stamens.

Stem

Stems are ribbed, up to 15 cm diameter, show enormous secondary growth, and become woody with age. In early-maturing types stem girth seldom reaches 3 cm, whereas in late-maturing types it ranges from 4 to 10 cm at the base of the plants. Four different stem colours, dark purple, purple, sun red, and green (the most common) are recognised (Remanandan *et al.*, 1988).

The internodes of the stem develop by elongation of the tissue between the leaf initials in the apical meristem (Bisen and Sheldrake, 1981).

The primary vascular tissue of the stem is organised in strands connecting the nodes. Each strand is associated with a ridge on the stem, that is distinctly visible even in old, secondarily thickened stems. Collenchymatous bundle caps underlie the epidermis of the ridges.

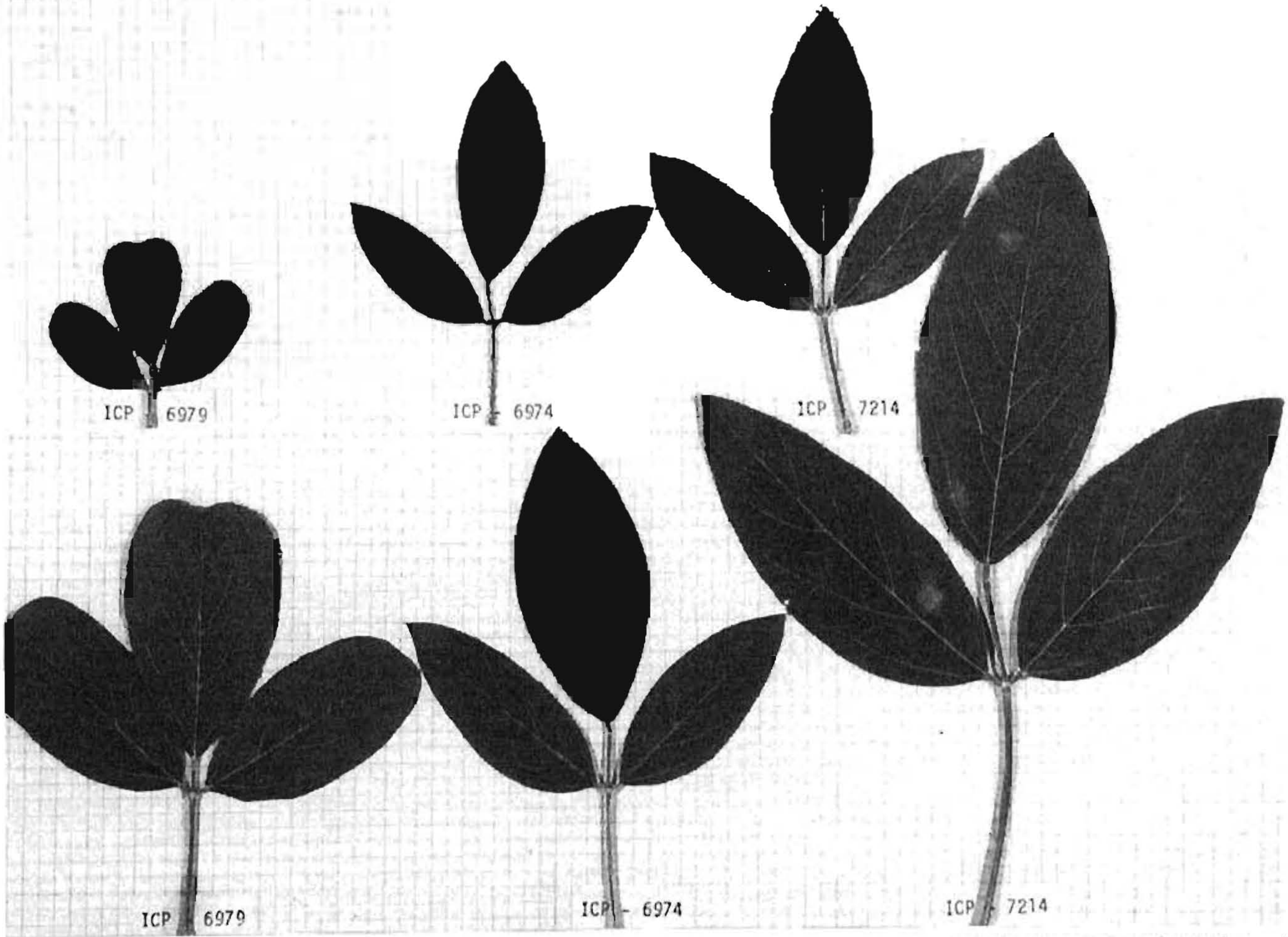


Figure 3.7 Leaf sizes of some pigeonpea genotypes grown under normal daylength (above) and extended daylength (below).
Photo: ICRISAT.

In young stems, the xylem and phloem are organised into fairly distinct strands. However, towards the exterior of the phloem the fibres are not confined to these primary vascular strands, but form a continuous ring covered by a layer of thin-walled cells.

The stem thickens as a result of vascular cambium activity that produces a continuous ring of xylem inside, and phloem outside (Figure 3.13a). Within the xylem the vessels are either solitary, or in radial, or infrequently, tangential multiples (Figure 3.13b). The vessels are surrounded by parenchymatous cells, and tangential bands of parenchyma run between the vessels. Much of the remainder of the xylem tissue between the medullary rays consists of xylem fibres (Bisen and Sheldrake, 1981).

During the vegetative phase, the xylem parenchyma and the medullary rays contain large quantities of starch. During the reproductive phase, these starch reserves disappear, but when the flowers on the plant are continuously removed, the starch reserves in the stem are not depleted, indicating that these reserves are mobilized due to pod development (Bisen and Sheldrake, 1981).

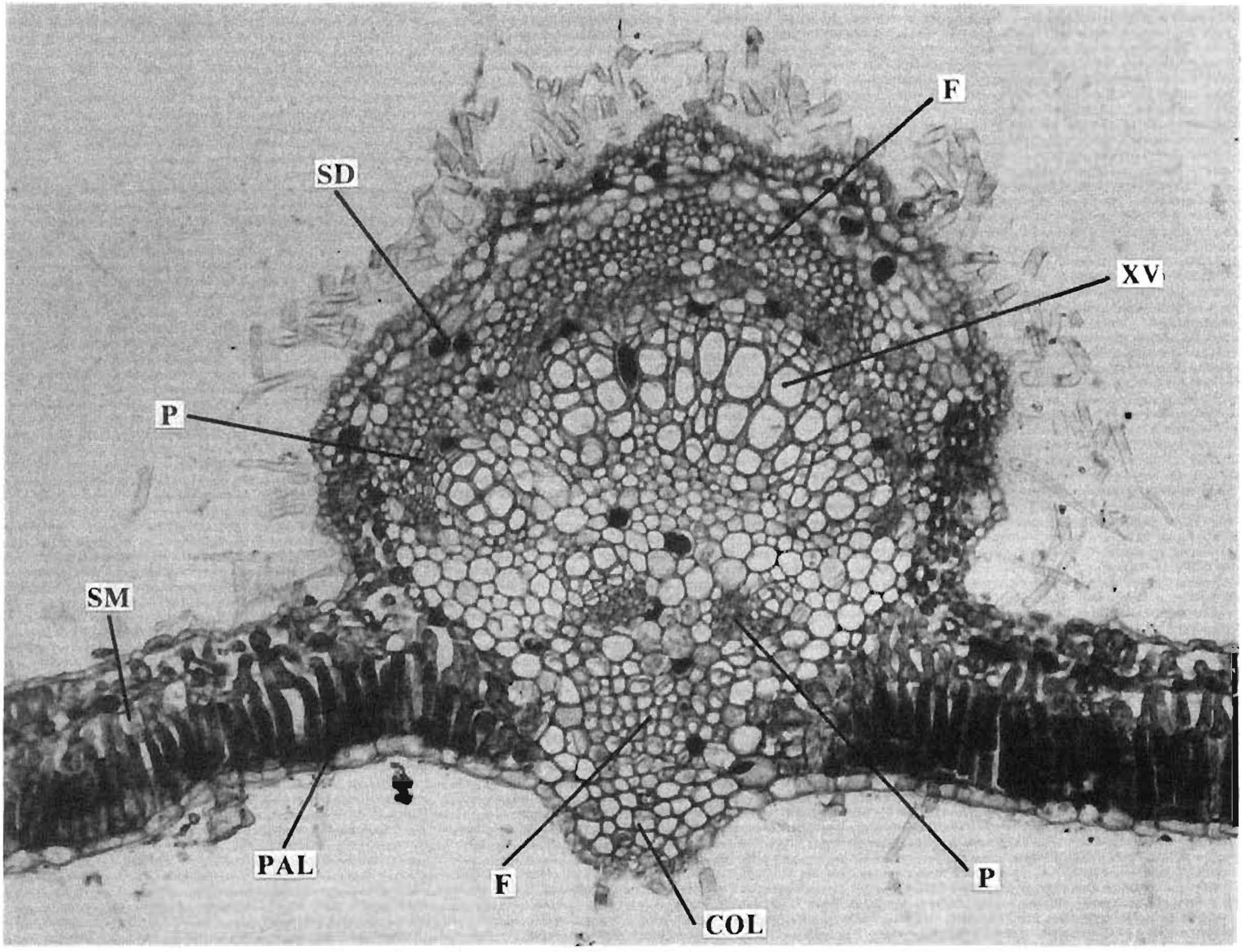


Figure 3.8. Transverse section of a pigeonpea (ST 1) leaf in the mid-vein region, × 202, showing xylem vessel (XV); fibre (F); secretory duct (SD); phloem (P); spongy mesophyll (SM); palisade tissue (PAL); and collenchyma (COL).

Source: Bisen and Sheldrake, 1981.

Secretory Ducts

Cells containing densely staining material, probably polyphenolic or tannin-like in nature, are found within the phloem region and also in the outer parts of the pith near the primary xylem tissue of the stem. These cells are elongated and joined end-to-end forming ducts. Such secretory ducts differentiate at an early stage within primary tissues and are also formed within secondary phloem tissue. In addition to the stem, these ducts are also found in leaves, petioles, roots, flowers, and pod walls.

When pigeonpea tissues are damaged, a colourless exudate from the secretory ducts oozes out and turns red on exposure to the air. This exudate, that has an extremely astringent taste, may play a role in protecting the plant against pests and/or diseases (Bisen and Sheldrake, 1981).

Height, Branching, and Habit Groups

Plant height is influenced by maturity duration, photoperiod, and environment. Late-maturing, long-duration varieties are generally tall, because of their prolonged vegetative phase. Similarly, short-duration or early-maturing varieties are comparatively short in stature due to their short

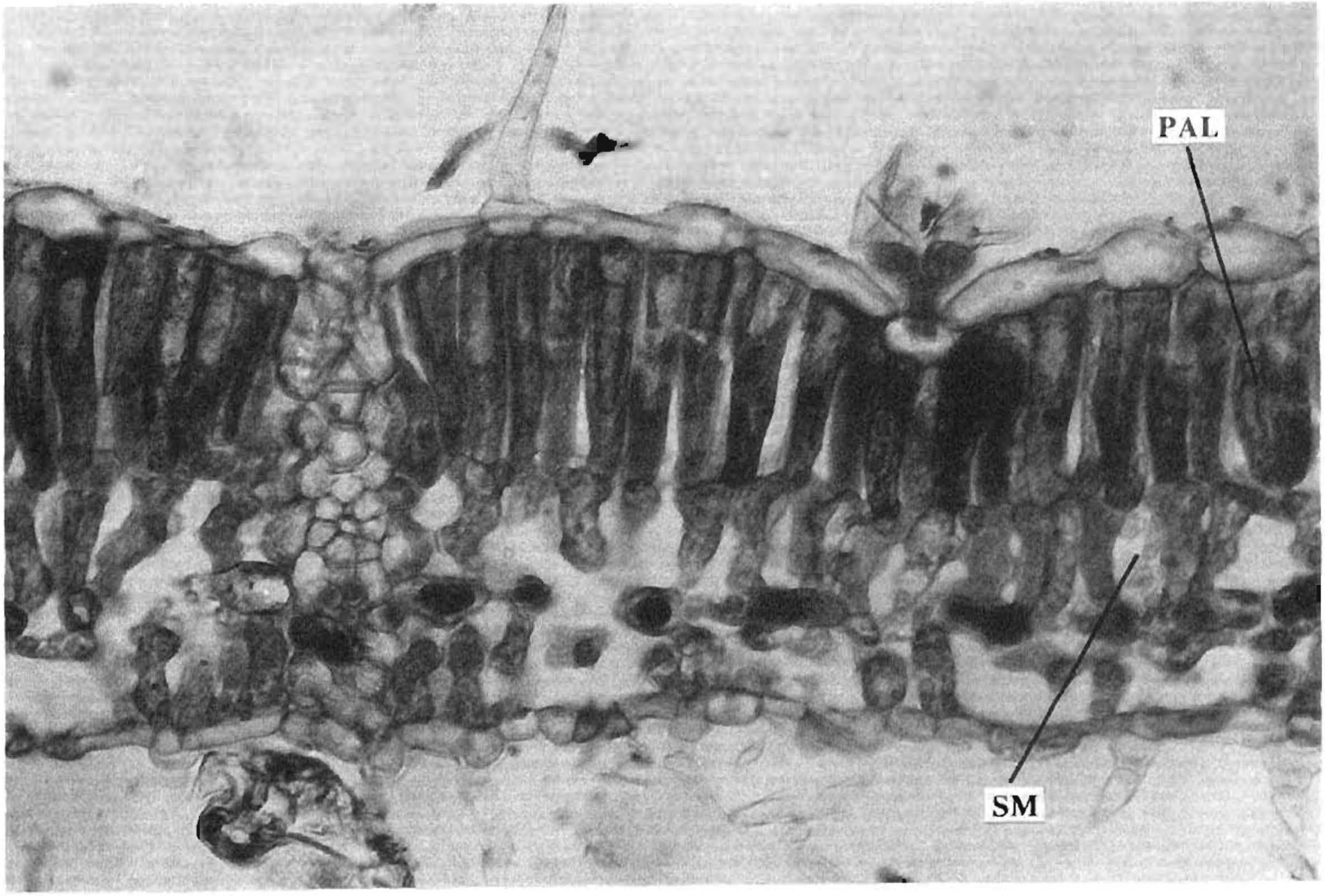


Figure 3.9. Transverse section of a pigeonpea (ST 1) leaf lamina × 692, showing: palisade tissue (PAL); and spongy mesophyll (SM).
Source: Bisen and Sheldrake, 1981.

vegetative growth phase. At ICRISAT Center the plant height at maturity in over 8,520 germplasm accessions ranged from 39 cm to 385 cm in June/July sowings (Remanandan *et al.*, 1988). However, the majority of the germplasm fell in the plant height range of 150-200 cm. Plant height can be substantially increased through prolongation of the vegetative phase by exposure to long-day conditions. So, this trait is influenced by both location and time of sowing. Although several factors influence plant height in pigeonpea, the ranking of varieties for this trait mostly remains unaltered within a given environment, and the germplasm can be readily classified into three groups; short, medium, and tall.

Initially the plant grows slowly and branches start appearing from the 6th to 10th nodes. Varieties differ greatly in the number and angle of their branches when grown at fairly wide plant-to-plant spacings.

In over 8000 world germplasm accessions the average number of primary branches at harvest time ranged from 2-3 to 66 with a mean of 13.2. Similarly the number of secondary branches ranged from 0 to 145 with a mean of 31.8 (Remanandan *et al.*, 1988).

Based on the angle of branching, alone or in combination with such other traits as plant height and number of branches, pigeonpea varieties have been grouped into different classes (Table 3.2). Reddy *et al.* (1981b) classified the pigeonpea germplasm into 10 groups based on angle of branching, plant height, flowering habit, and maturity. Based on various agronomic and morphological charac-

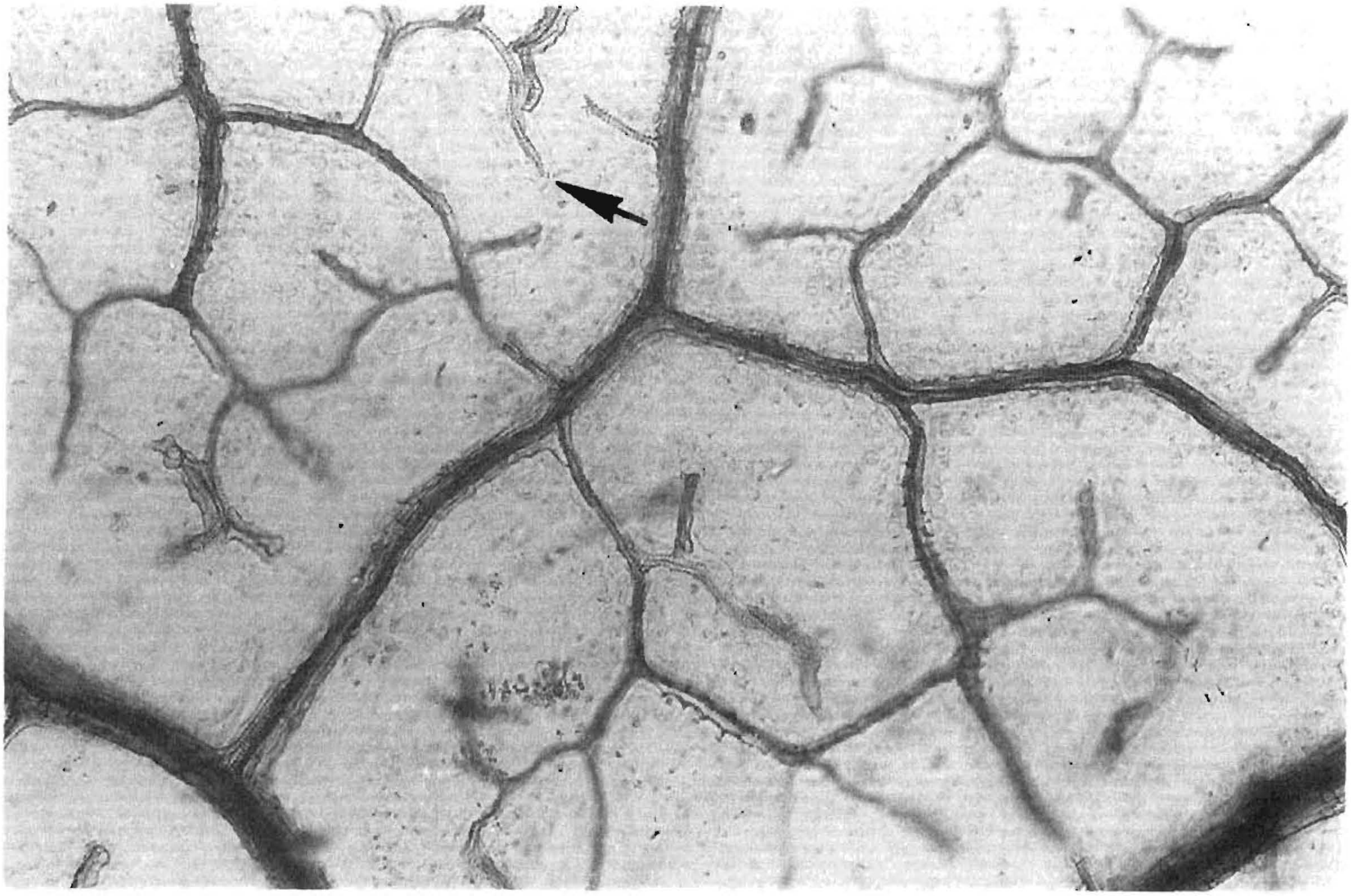


Figure 3.10. Surface view of a cleared pigeonpea leaflet, × 500, showing the pattern of venation. Note the minor veins with free ends (arrowed).

Source: Bisen and Sheldrake, 1981.

teristics, Akinola and Whiteman (1972) classified 95 accessions of pigeonpea into 15 groups. However, for agronomic purposes only three broad classes viz., compact (= erect), semi-spreading (= semi-erect), and spreading types are recognised.

In all varieties, branching is reduced in dense sowings, and in intercropping systems where the pigeonpea is shaded by faster-growing companion crops such as sorghum and maize (Sheldrake, 1984). However, the semi-spreading types are reported to possess higher branching-habit plasticity than the compact and spreading types, and this makes the former types more suitable for intercropping systems (Baldev, 1988).

On the basis of flowering, two habit groups, determinate and indeterminate are recognised. As pointed out by van der Maesen (1986) these terms do not conform to basipetalous and acropetalous as used by Rachie and Roberts (1974). In the determinate types flowering duration is short, the flowers occur more or less in the same plane, and the apical buds of main shoots develop into inflorescences. In the inderterminate types, flowering duration is longer, and flowers occur in axillary racemes spread over considerable lengths of stem. In both determinate and indeterminate types flowering within the racemes is always acropetalous. In indeterminate types flowering on

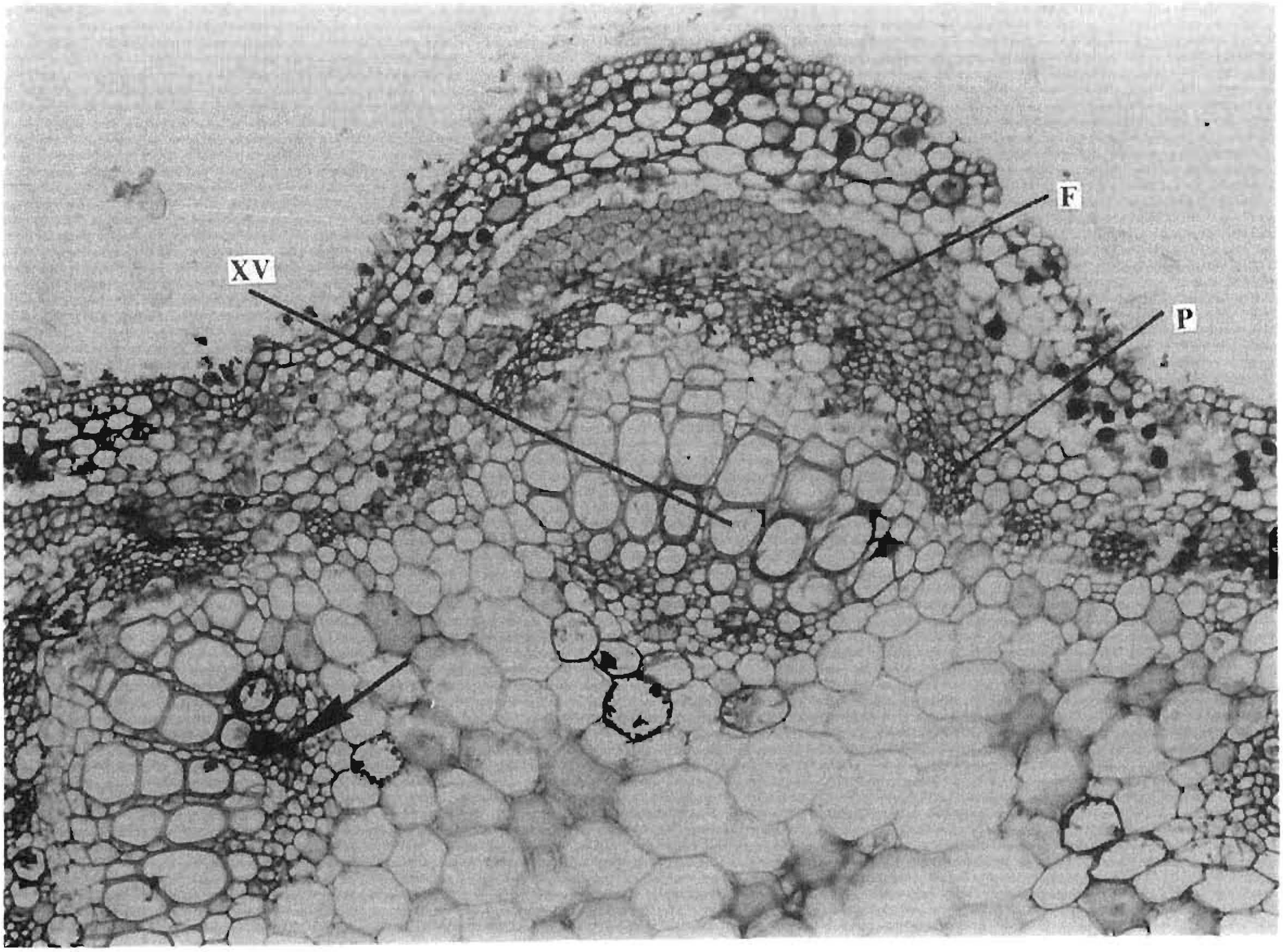


Figure 3.11. Transverse section of pigeonpea (T 21) petiole, × 202, showing vascular bundles. Note some xylem vessels filled with densely stained material (arrowed); xylem vessel (XV); phloem (P); and fibre (F).

Source: Bisen and Sheldrake, 1981.

the branches is also always acropetalous. In determinate types flowering on the branches is usually, but not necessarily, basipetalous (L.J. Reddy, unpublished). Some researchers (Remanandan *et al.*, 1988; Sheldrake, 1984) felt that flowering on the branches of determinate types is always basipetalous and they described another type, "semi-determinate" where flowering starts at nodes below the apex and proceeds both acropetally and basipetally. However, in the authors' opinion, recognition of "semi-determinate" is not justified since all the determinate types occasionally show both acropetalous and basipatalous flowering on their branches. Recently, a true-breeding semi-determinate plant type has been observed at ICRISAT Center (Figure 15.1). In this type the apical buds of the main shoots develop into inflorescence as in a determinate type, but the mode of flowering on the branches is always acropetalous as in indeterminate types.

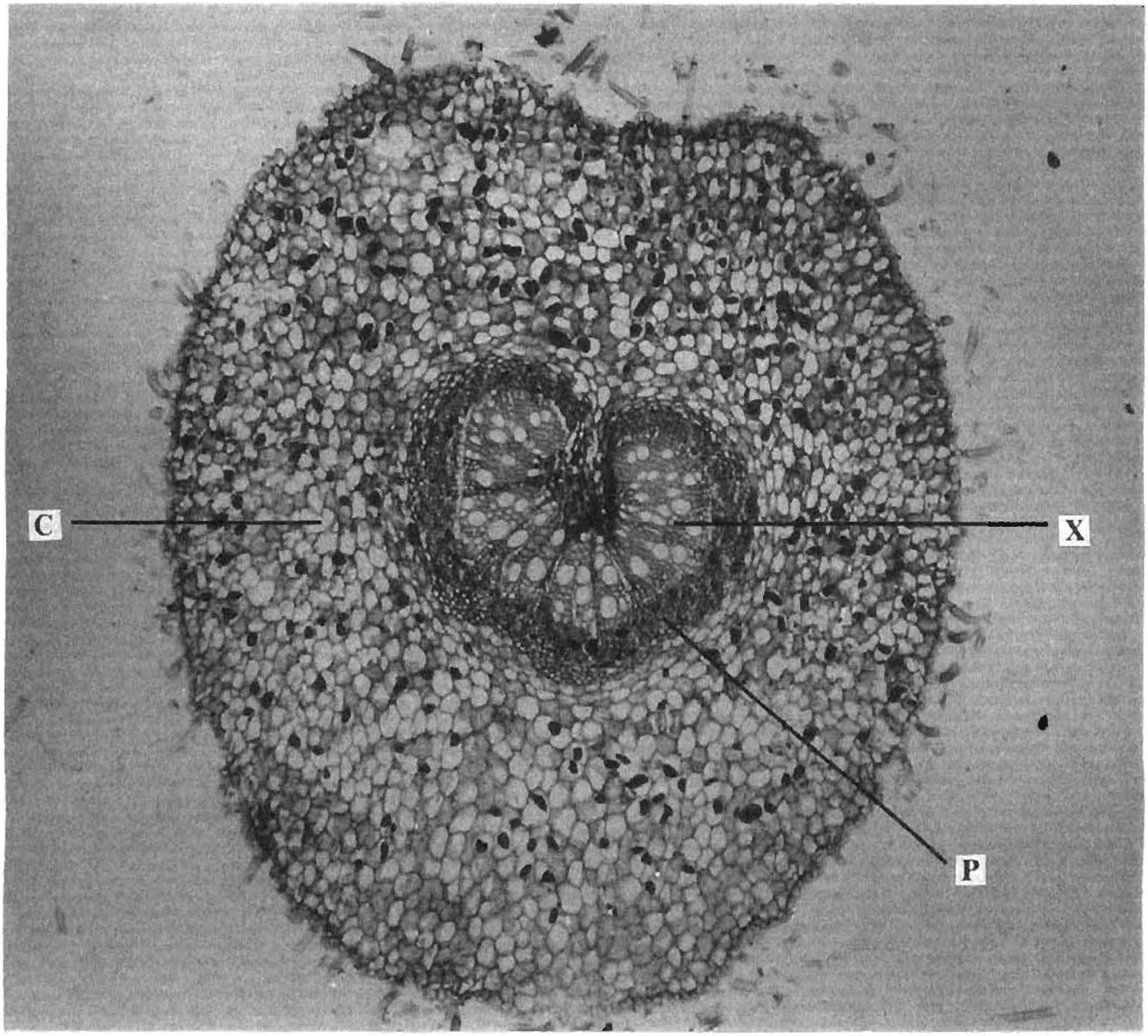


Figure 3.12. Transverse section of pigeonpea (T 21); petiolar pulvinus, × 96, showing: xylem (X); phloem (P); and cortex (C).

Source: Bisen and Sheldrake, 1981.

Days to Flowering and Maturity Duration

Days to 50% flowering and maturity duration in pigeonpea are very highly and positively correlated. Maturity duration is a very important factor that determines the adaptation of varieties to various agroclimatic areas and cropping systems (Sharma *et al.*, 1981). A broad maturity classification of early (<150 days), medium (151 to 180 days), and late (>180 days) has been in vogue for a long time in India. With the development in recent years of several early-maturing pigeonpea varieties, the All India Coordinated Pulse Improvement Project (AICPIP) has further subdivided the early group into three classes viz., extra, extra-early (≤100 days), extra-early (101-120 days), and early (121 to 150 days). Pigeonpea breeders at ICRISAT have developed a maturity duration scale consisting of 10 classes based on days to 50% flowering (Table 3.3). In the world germplasm collections studied at ICRISAT Center the number of days taken to 50% flowering ranged from 55 to 210 days, and maturity duration from 97 to 260 days (Remanandan *et al.*, 1988). On the basis of the

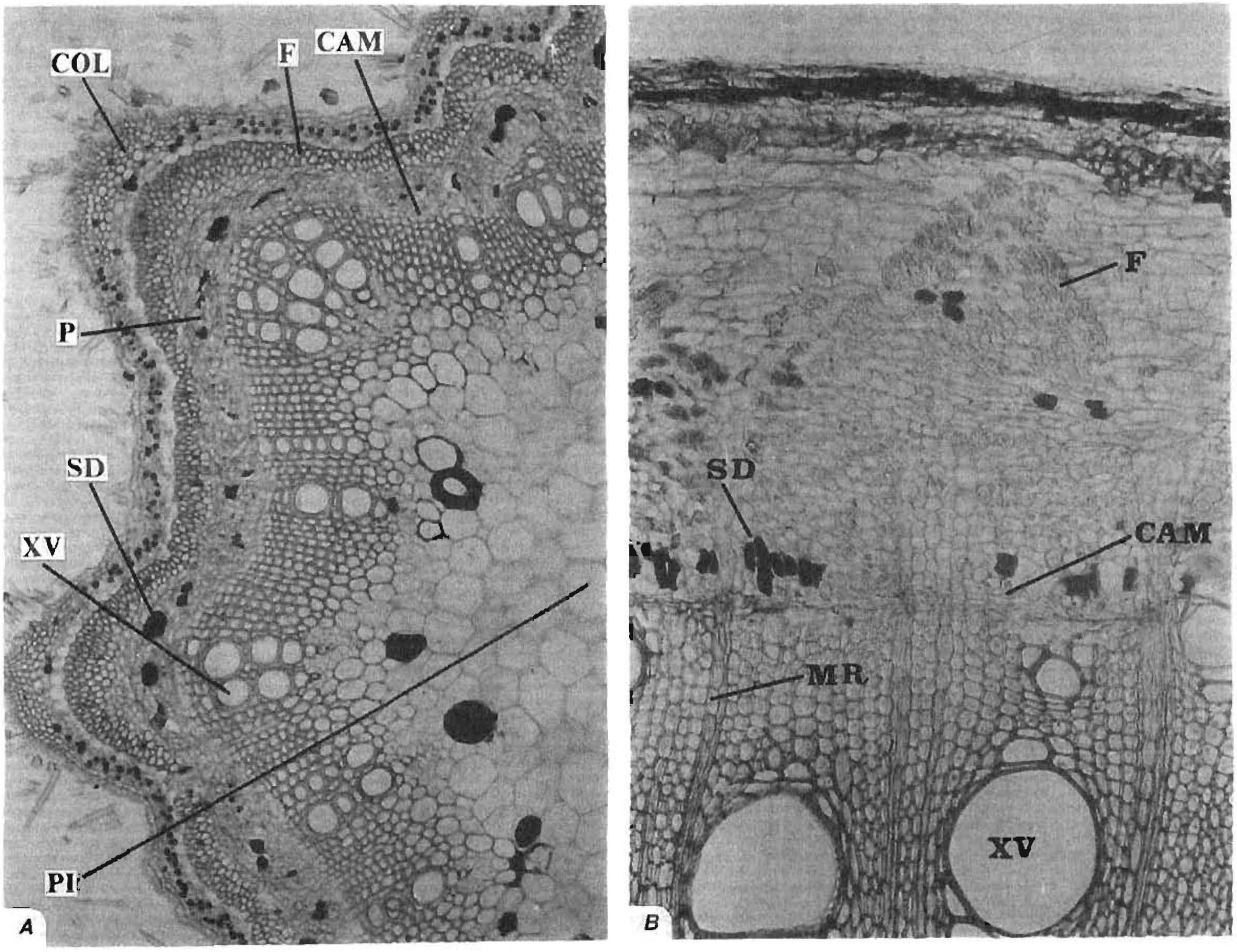


Figure 3.13. Transverse section of young pigeonpea: a. Secondarily thickening stem, × 95; b. Woody main stem, × 142, showing: pith (PI); cambium (CAM); secretory duct (SD); xylem vessel (XV); phloem (P); fibre (F); collenchyma (COL); and medullary ray (MR).

Source. Bisen and Sheldrake, 1981.

Table 3.2. Classification of pigeonpea based on growth habit.

Classes	Basis of classification	Reference
Very erect (30°) Erect (40°) Semi-erect (50°) Spreading (60°)	Angle of branching	Mahta and Dave, 1931; Pathak, 1970
Erect (30-40°) Semi-erect (40-50°) Spreading (60-70°)	Angle of branching	Baldev, 1988
Erect and compact Semi-spreading Spreading Trailing	Angle of branching	IBPGR/ICRISAT, 1981
Tall compact Tall open Medium-height compact Medium-height open Dwarf bushy	Plant height and angle of branching	Sharma *et al.*, 1971
Compact Spreading Semi-spreading	Angle of branching and number of branches	Remanandan *et al.*, 1988

Table 3.3. Maturity classification of pigeonpea when sown at the beginning of the rainy season (June/July), ICRISAT Center, India.

Maturity group	Days to 50% flowering	Reference cultivars	Description
0	≤ 60	Pant A3	Photoperiod insensitive
I	61-70	Prabhat, Pant A2	Extra early
II	70-80	UPAS 120, Baigani	
III	81-90	Pusa Ageti, T 21	Early
IV	91-100	ICP 6	
V	101-110	No.148, BDN 1	Medium
VI	111-130	ICP 1, ICP 6997, ST 1, C 11	
VII	131-140	Hy 3C, ICP 7035	Late
VIII	141-160	ICP 7065, ICP 7086	
IX	> 160	NP(WR) 15, Gwalior 3, NP 69	

Source: ICRISAT, 1978; Sharma *et al.*, 1981.

above scale, a large number of accessions from the world germplasm collection fell into maturity groups, VIII, VI, and VII.

Photoperiod and temperature exert profound influence on days to 50% flowering and maturity duration in pigeonpea, which is considered to be a quantitatively short-day plant. Genotypes differ in their response to photoperiod.

In general, early-maturing types are relatively photoperiod-insensitive compared to the medium- and late-maturing varieties. Other factors such as soil moisture status and nutrition also influence maturity duration to some extent. Days to 50% flowering by a variety vary from location to location, and season to season. For instance, Hy 3C took 138 days to 50% flowering at Patancheru, India whereas it took only 86 days in Puerto Rico, and 64 days in Kenya (Sharma *et al.*, 1981). Similarly, depending on the genotype, days to 50% flowering can range from about 60 to more than 200 in sowings made prior to the longest day at 17°N (Whiteman *et al.*, 1985). Most photoperiod-sensitive cultivars flower more readily when sown after the longest day.

Both low and high temperatures delay flowering in pigeonpea (Whiteman *et al.*, 1985). Flowering of all maturity groups occurs sooner in moderate temperatures (22°-30°C) even under relatively long days (12.5-16 h).

Light affects inflorescence development and pod setting. Under dense crop canopies no pods are set. Bright, dry days are favourable for fertilization, while cloudy, damp weather results in excessive flower drop (Howard *et al.*, 1919; Mahta and Dave, 1931).

Flowers

The flowers are borne in short racemes (Figure 3.14a). In the world germplasm collections the number of racemes per plant ranged from 6 to 915 (Remanandan *et al.*, 1988). Peduncles are (0-) 1-8 cm, long. Pedicels are thin, 7-15 mm long, downy, and covered with hairs. Flowers (Figure 3.14b,c) are predominantly yellow. Bracts (Figure 3.14d) are small with a thick medium nerve, triangular or ovate-acuminate scales, 1-4 mm long; their margins curve inwards to form a boat-like structure, and enclose 1-3 very young flower buds. The calyx tube (Figure 3.14e) is companulate with numerous glandular hairs with bulbous bases, the tube dorsally gibbous, about 5 mm long, with five subequal, narrowly triangular lobes 4-7 mm long. The smaller upper lobes are paired, free or partly connate, and the lower one is the longest.

The corolla is highly zygomorphic, papilionaceous, and generally yellow in colour. The petals are imbricate in the bud. The standard petal (vexillum, flag) is erect and spreading (Figure 3.14f), more or less orbicular, 14-22 mm long, 14-20 mm wide, base clawed, biauriculate, with two callosities. Madhusudana Rao *et al.* (1979) reported both right- and left-handed flowers in pigeonpea with regard to contortion of the vexillum petal either to the right or to the left. Wing (aloe) petals (Figure 3.14g) are obovate with a straight upper margin, clawed base, asymmetrically biauriculate, 15-20 mm long, 6-7 mm wide, with a callosity. Keel petals (Figure 3.14h) are boat-shaped, 14-17 mm long, 5-7 mm wide, clawed, entirely split dorsally, ventrally split near the base, left- and right-lengthwise furrowed, glabrous, and more greenish than other petals.

Stamens are 10, diadelphous (9 + 1), 15-18 mm long, with 4-7 mm free parts, flattening towards the base, tapering towards the top, geniculate near the base, the staminal sheath (Figure 3.14i) is about 12 mm long. Anthers (Figure 3.14j) are ellipsoid, about 1 mm long, dorsifixed, and light or dark yellow in colour.

According to Bahadur *et al.* (1981) pigeonpea stamens exhibit dimorphism. Of the 10 stamens, four have short filaments and six, including the odd posterior one, have long filaments. The odd stamen has a groove for the passsage of nectar that is secreted from the base of the filaments. The long stamens are antisepalous, and the short ones antipetalous. The anther lobes also exhibit dimorphism, those of the shorter stamens have blunt lobes, and the longer ones pointed lobes. The filaments of shorter stamens are thicker than those of the longer. Bahadur *et al.* (1981) also reported that growth and development in short stamens is faster than in longer ones. The maturity of short stamens coincides with that of the stigma. The pollen produced by short stamens is used for self-fertilization, whereas that produced by long stamens is used for outcrossing.

The ovary is superior, 5-8 mm long, sub-sessile, since it has a very short stalk, densely pubescent and glandular-punctate, with 2-9 ovules. The stigma (Figure 3.14k) is capitate and glandular-papillate. The style (Figure 3.14l) is long, filiform, upturned beyond the middle, 10-12 mm long, and glabrous.

Flower Colour

Colour on the flower is recorded as base flower colour i.e., the main colour of the petals, and secondary flower colour i.e., the colour of the streaks on the dorsal side of the flag. At ICRISAT Center, six colour classes are used in base flower classification (van der Maesen, 1986): these classes include light yellow, yellow, orange, red, and purple. More than 95% of the germplasm

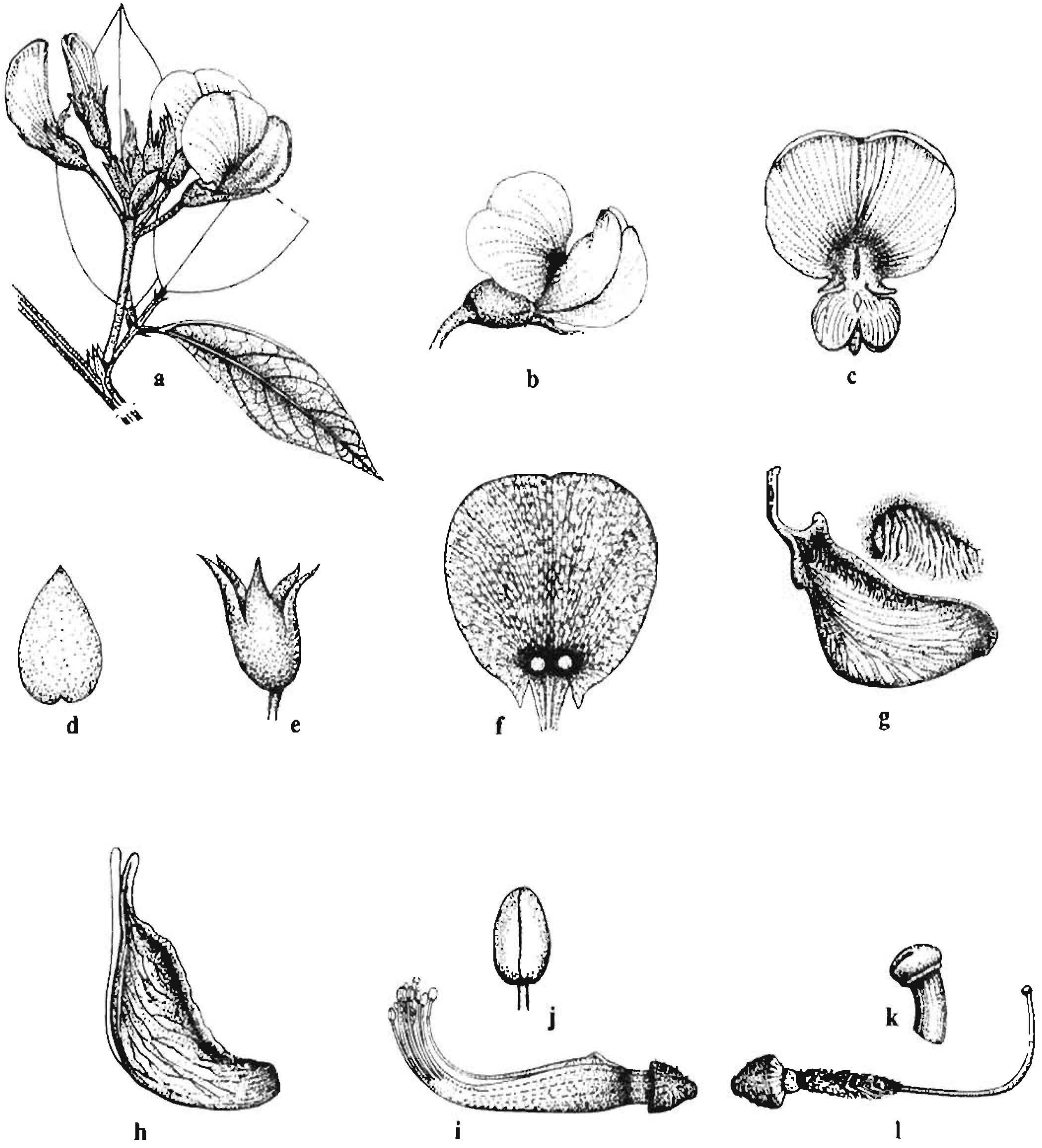
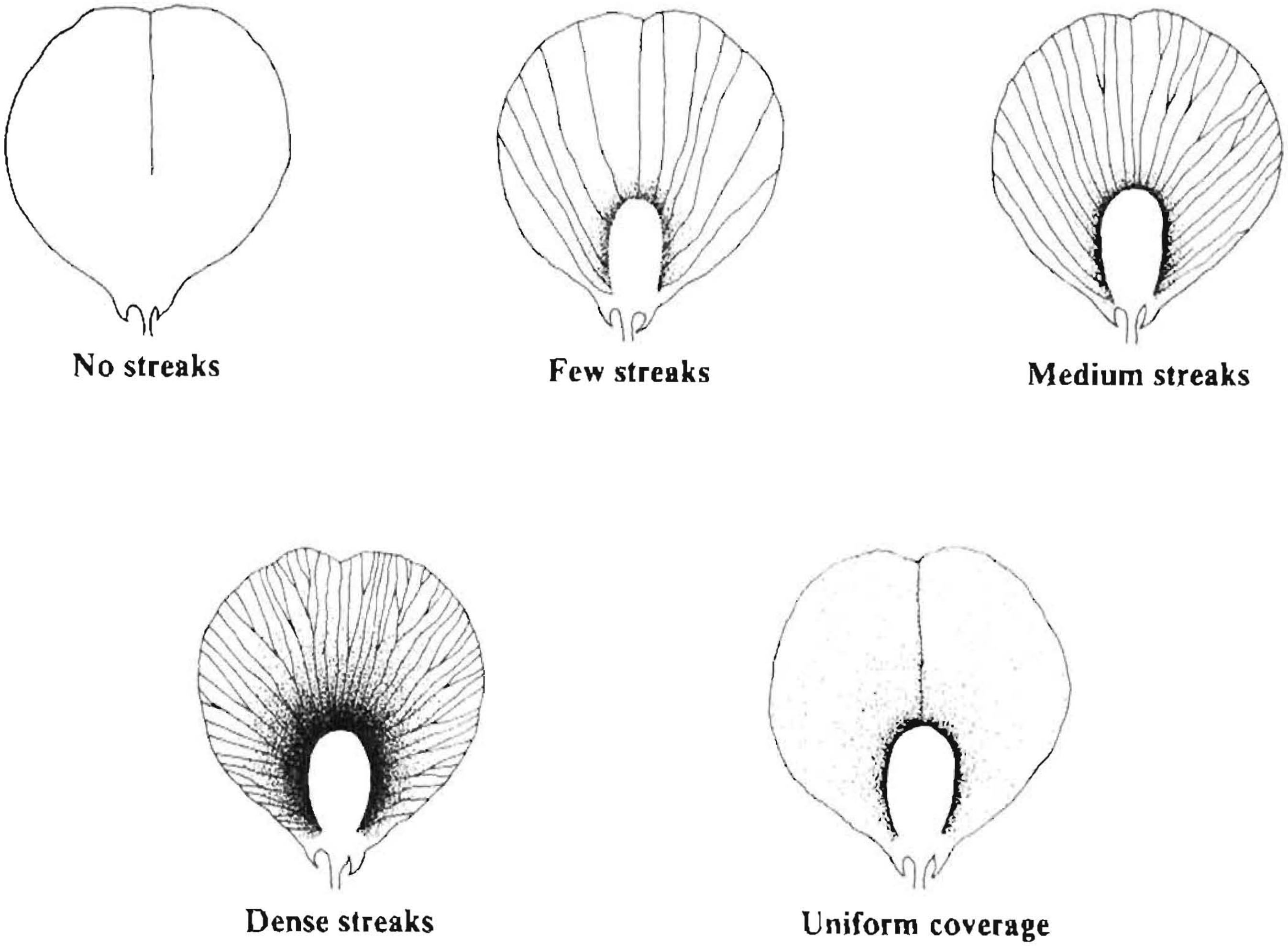


Figure 3.14. Pigeonpea flowering twig and flower structure: a. Inflorescence; b. Side, and c. Front view of flower; d. Bract; e. Calyx; f. Standard petal; g. Wing petal with detail of 'pocket'; h. Keel petal; i. Staminal sheath; j. Dorsifixed anther; k. Stigma; and l. Pistil with disc.

Source: a,g,h,i,k, and l Westphal, 1974; b,c,d,e,j Baldev, 1988; and f van der Maesen, 1986.

accessions held at ICRISAT Center have yellow flowers. The wing, and especially the keel petals are often paler in colour than the flag. Three classes of secondary flower colour; none, purple, and red occur in world germplasm collection, but most of the varieties are streaked with red. The intensity of streaks on the flag varies (Figure 3.15) and five classes are recognised by IBPGR/ICRISAT (1981). The classes are; no pigmented streaks, few streaks, medium streaks, dense streaks, and uniform coverage of secondary colour.



No streaks

Few streaks

Medium streaks

Dense streaks

Uniform coverage

Figure 3.15. Patterns of streaks on the flag of pigeonpea flowers.
Source: Remanandan *et al.*, 1988

Microsporogenesis and Male Gametophyte

Microsporogenesis in pigeonpea is typical of the majority of angiosperms. Following Baldev (1988) a brief description of the development of the male gametophyte is given here. The young anthers consist of homogeneous meristematic cells surrounded by the epidermis. The anthers become four-lobed. An archesporial layer of cells is differentiated and cuts a layer of parietal cells on the outside. These divide further by developing periclinal and anticlinal walls to form a layer of endothecium, a row of middle layer, and the innermost layer–the tapetum. The parietal cells towards the inside cut off a primary sporogenous layer, that divides further to form a large number of spore mother cells (Figure 3.16a). By this stage, the wall layers are well differentiated. The outermost layer constitutes the epidermis, below which lies the endothecium, followed by the two-celled middle layer. The cells of the tapetum at this stage are full of cytoplasm, uninucleate, and quite distinct from the cells of the rest of the wall layers. The microspore mother cells are

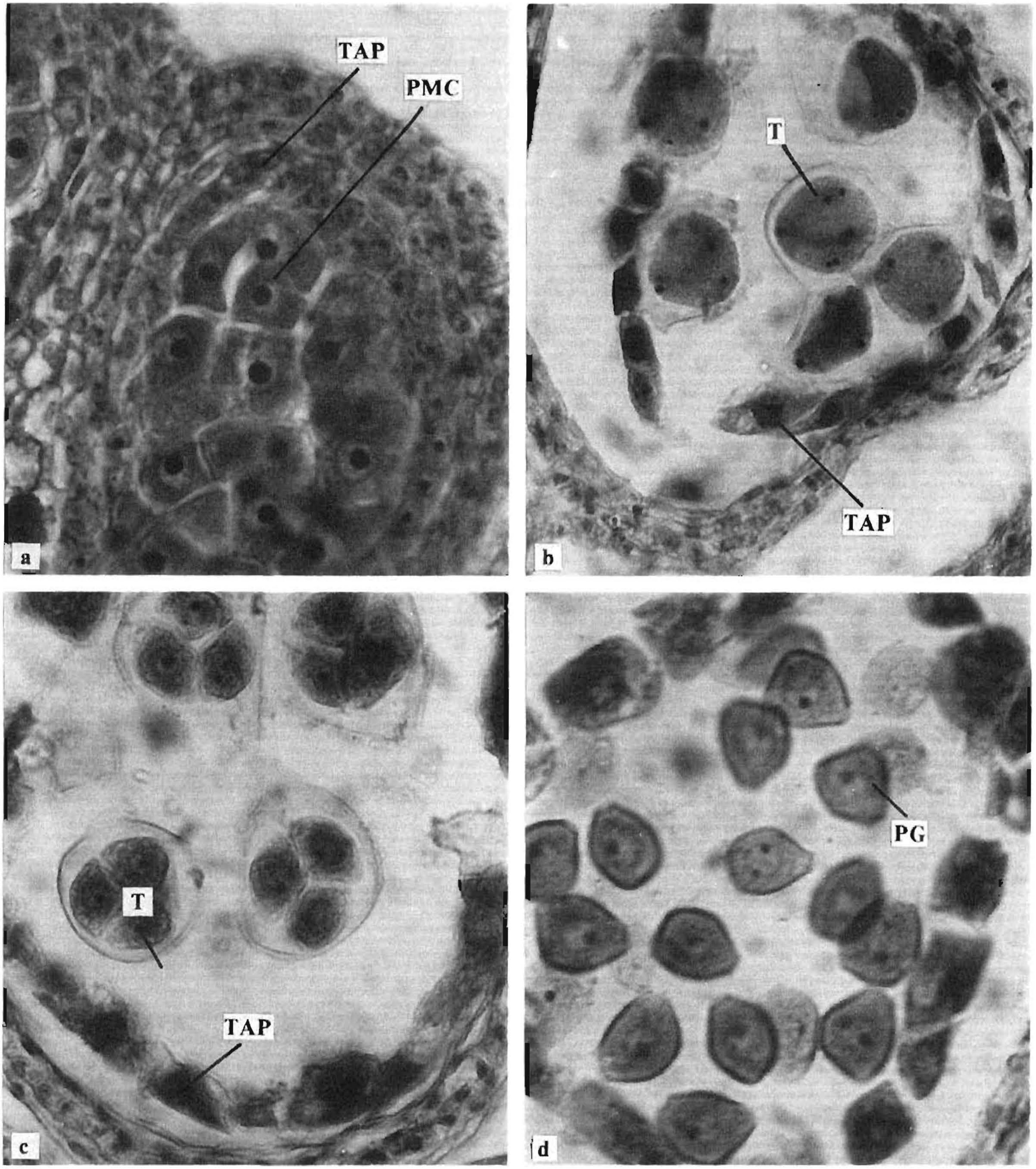


Figure 3.16. Transverse sections of pigeonpea anthers showing stages of pollen grain development: a. Young anther, × 971, showing pollen mother cells (PMC) and tapetum (TAP); b. Developing anther, × 797, showing early tetrads (T); c. Developing anther, × 790, showing well-formed tetrads; and d. Anther, × 400, just before anthesis showing pollen grains (PG).

Source: Bisen and Sheldrake, 1981.

very prominent, rich in cytoplasm, and contain large nuclei. The division of microspore mother cells is of the simultaneous type, where no cell wall is seen after the first meiotic division, and the cell contents are separated into four parts after both the divisions are over, resulting in the formation of tetrads containing four nuclei (Figure 3.16b). By this time no further appreciable change occurs in the wall layers, except that some of the tapetal cells become binucleate. Soon the tetrads separate into four distinct cells (Figure 3.16c), rapid changes occur in the anther wall layers, and a thick wall develops. The tapetum completely degenerates by the time the spores are fully developed. The newly formed microspore has dense cytoplasm with a centrally located nucleus. This cell then increases rapidly in size and a vacuole is formed in the centre (Figure 3.16d) by pushing the nucleus to the wall. The microspore nucleus divides to give rise to vegetative and generative nuclei. The pollen appears to be shed at the two-celled stage when the thin-walled cells break down at the incurved notch between the two locules. The generative nucleus probably divides in the pollen tube.

Pollen Morphology

There are few studies on pollen morphology in pigeonpea. Srivastava (1978) studied pollen morphology in three pigeonpea varieties and their hybrids. He described the mature pollen grains as three-colporate with areolate (i.e., negatively reticulate) ornamentation. Bahadur *et al.* (1981) from their light and scanning electron microscopic studies reported that pigeonpea pollen grains exhibit dimorphism with regard to grain size and exine structure. In general, the pollen grains from "short" stamens are larger than those from "long" stamens. According to Bahadur *et al.* (1981) the pollen grains from "long stamens" are monad, three-colporate, prolate sub-prolate. The colpi are elongated with pointed ends. Ora are 5-7 µm in diameter, and circular to elongated. Sexine is eureticulate and heterobrochate. Lumina are of various sizes. Muri are simplibaculate and punctate. Punctae and luminal bacules are scattered along the margins. Pollen grains from "short" stamens are larger with shorter colpi (5-6.5 µm), and blunt-ended with granulated membranes. Ora are elongated with an annulus (porate) and lumina mostly polygonal. Punctae are numerous. Luminal bacules are prominent, and are denser than those of the pollen from "long" stamens.

Megagametogenesis

The embryo sacs in pigeonpea show monosporic development and are of polygonum type, i.e., their development initiates from a single megaspore followed by three successive mitotic divisions. The megaspore farthest from the micropyle divides and forms two nuclei that move to the poles of the embryo sac. Each of these nuclei then divides, and a final division produces a total of eight nuclei, that are arranged in quartets at the micropylar and chalazal ends of the embryo sac. Three of the nuclei at the micropylar pole become differentiated as cells and constitute the central egg apparatus consisting of the female gamete (egg cell) flanked by two synergids. At the opposite end of the embryo sac, three of the four nuclei differentiate as antipodal cells. The two remaining polar nuclei migrate from the opposite ends of the sac to the central region of the embryo sac to constitute the primary endosperm nuclei. The antipodal cells start degenerating soon after the two primary endosperm nuclei fuse to form a diploid secondary nucleus. Thus, a seven-celled embryo sac is formed.

Pollination and Fertilization

Pigeonpea flowers can be self-pollinated or cross-pollinated. Self-pollination occurs in the bud before the petals open. When the petals are open insect pollination may take place (van der Maesen, 1986). Only part of the flowers' life cycle is cleistopetalous, and this condition is not cleistogamous where the flowers completely fail to open. In Lord's (1981) terminology this condition is known as preanthesis cleistogamy. However, true cases of cleistogamy have been reported in pigeonpea by Mahta and Dave (1931) and Datta and Deb (1970). According to van der Maesen (1986) this phenomenon is apparently induced by environmental factors, since under short-day and lower temperature conditions more cleistogamous flowers are found.

In the young buds, the stigma lies above the level of anthers, and the style is so curved at the tip that the stigmatic surface is directed towards the anthers. These are arranged around the style in two groups, five above and five below. As the bud develops, the filaments elongate, bringing the top five anthers to the level of the stigma. This stage is completed before the anthers dehisce in the bud a day before the flowers open. Once a flower bud becomes visible, it takes about 15-20 days to bloom (Durga Prashad and Narasimha Murthy, 1963).

The duration of flower opening varies according to climate and environment. Mahta and Dave (1931) observed that the flowers remained open at Pusa, Bihar, in northeast India for a day and a half, while at Nagpur in central India they remained open only for 6 hours. In the northeastern Indian state of West Bengal Reddy (1973) found that the pigeonpea flowers began to open from 0630 and anthesis continued until 1400 with maximum anthesis taking place between 1030 and 1230. The flowers remained open for 15 to 24 h. Anthers dehisced in 90% of the flowers before they opened. Pathak (1970) reported that flowers that open in the evening usually remain open throughout the night and close before noon on the following day.

Although the stigma is completely covered with the pollen of its own flower, considerable outcrossing occurs in pigeonpea. Reddy and Mishra (1981) reported that the percentage of "selfs" was negligible when flower buds were pollinated with foreign pollen without emasculation. This indicates that foreign pollen has an advantage over native pollen in affecting fertilization. According to Onim (1981), although anthers dehisce during the bud stage, they do not start germinating until the flowers start to wither 24-28 h after dehiscence. It has also been found (Prasad *et al.*, 1977) that the receptivity of stigmas starts 68 h before anthesis, and continues for 20 h after anthesis. Datta and Deb (1970) reported that pollen-tube growth in styles pollinated with the pollen from the same flower is very slow, taking 54 h to reach the base of the ovary. These mechanisms provide a sufficient gap for foreign pollen to be introduced onto the stigma, and thus favour outcrossing in pigeonpea.

Many insect species have been reported to forage and affect cross-pollination in pigeonpea (Williams, 1977; Onim, 1981). However, *Megachile* spp, *Aphis florea*, and *Aphis dorsata* seem to be the most important pollinators (Williams, 1977; Pathak, 1970).

Several simply inherited morphological traits such as stem colour (green *vs* purple), leaf type (obtuse *vs* normal), seed colour (white *vs* brown), growth habit (determinate *vs* indeterminate), and flower colour (yellow *vs* red) have been used to estimate the extent of outcrossing in pigeonpea. Estimates of natural outcrossing vary between countries, or at locations within a country. In India, outcrossing estimates ranged from 0 at Badnapur, Maharashtra, to as high as 70% in Coimbatore, Tamil Nadu (Bhatia *et al.*, 1981). Onim (1981) reported a range from 12.6 to 45.9% at various locations in Kenya. Estimates of outcrossing ranged from 2 to 40% in Australia (Byth *et al.*, 1982), 8 to 22% in Uganda (Khan, 1973), and 5.9 to 30% in Hawaii (Wilsie and Takahashi, 1934). While the high rate of outcrossing in pigeonpea poses problems in the maintenance of varietal purity, it offers opportunities for crop improvement through the exploitation of hybrid vigour, and population improvement schemes.

Saxena *et al.* (1987a) reported a case of cross-incompatibility in crosses between some interspecific derivatives of *C. cajan* and *C. scarabaeoides* with HPL 31 as female parent where cessation of pod growth 3 weeks after crossing was followed by drying of the ovules and pod drop. They suggested that the *C. scarabaeoides* transmitted a cross-incompatibility factor to HPL 31.

Pod Development

Pigeonpea produces large numbers of flowers, of which only about 10% set pods (Pathak, 1970; Ariyanayagam, 1975; Sheldrake *et al.*, 1979; Tayo, 1980; Pandey and Singh, 1981). In each raceme 1-5 pods may mature; up to 10 pods per raceme are rarely observed.

Fertilization in pigeonpea occurs on the day of pollination, and seeds mature by 38-40 days after pollination (Sehgal and Gandhi, 1986). In the first 3 weeks after anthesis, the pod wall grows more rapidly than the young seeds, but thereafter undergoes little further growth (Narayanan and Sheldrake, 1975).

The pod wall is well supplied with secretory ducts that contain a tannin-like material. The outer epidermis bears many stomata, and simple and globular secretory hairs (Figure 3.17a) that contain a yellow oil, and are similar to those found on leaves (Bisen and Sheldrake, 1981). On the pod wall, there are large numbers of a third type of hair that has secretory cells towards the base and a long tubular neck (Figure 3.17b). Such hairs are only seen occasionally on vegetative organs. Internally the pericarp is composed of three zones; the outer epicarp, the middle mesocarp, and the inner endocarp. During the earlier stages, the outer zone is made up of 4-6 layers of parenchymatous cells that contain numerous plastids. The middle zone comprises 4-8 layers of elongated, compactly arranged cells. The cells of the inner zone are large, parenchymatous, highly vacuolated, and loosely arranged. The presence of large numbers of stomata in the outer epidermis, and chloroplast-containing cells in the exocarp suggests that this zone of the pericarp is actively involved in photosynthesis (Sehgal and Gandhi, 1986).

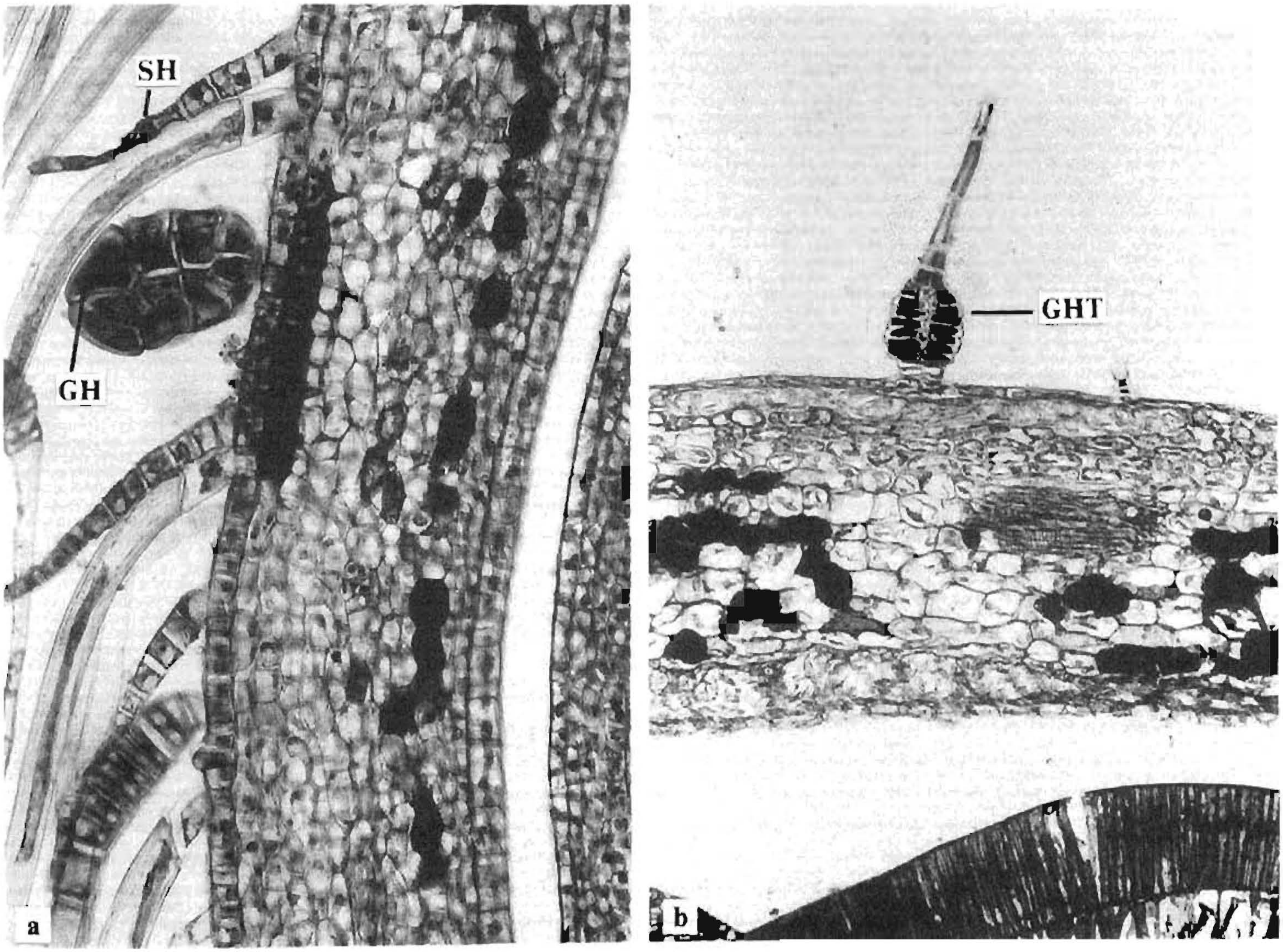


Figure 3.17. Transverse sections of a pigeonpea pod coat showing: a. Simple (SH) and glandular hairs (GH), × 215; and b. Glandular hairs with tubular neck (GHT), × 167.
Photo: ICRISAT.

The ovules are arranged in a row on a marginal placenta of the single carpellary ovary. At the time of anthesis, the ovules are in an undivided space within the carpel, but within the first week of pod development, cross-walls develop between the seeds, dividing the pod into locules. At the time of fertilization the ovules are anatropous, but they usually undergo a curvature later to become campylotropous.

During the first week after anthesis, the endosperm undergoes rapid development. The endosperm in pigeonpea, as in other members of the Leguminosae belongs to the nuclear type. In this type the first and subsequent divisions are not followed by wall formation, the nuclei usually take up a parietal position, and a large vacuole forms in the centre of the embryo sac. The embryo sac elongates at the chalazal region and forms the haustorium. The haustorium penetrates deep into the nucellar tissue and is instrumental in absorbing food material that is utilized by the developing embryo. By the end of the second week there are still large amounts of endospermous tissue, and within the embryo, distinct cotyledons are apparent. Further development of the seed involves rapid growth of the cotyledons, and almost complete degeneration of the endosperm. In the cotyledons, the synthesis of starch and protein starts about 17 days after pollination and continues for about 14 days (Sehgal *et al.*, 1987). The initiation of starch grains occur earlier than that of protein bodies. Only one type of large oval starch grains are observed in mature pigeonpea seeds, but small, spherical starch grains are present in the hypodermis and procambial tissue.

The pods of most pigeonpea varieties are non-shattering, except when they are left on the plant well beyond maturity.

Pod Shape, Size, and Colour

Pods are oblong, straight or sickle-shaped, laterally compressed, green when young, straw-coloured when ripe, often streaked to various degree with purple. Based on colour, pods are classified as dark purple, purple, mixed (green and purple), and green. In the world germplasm collections 90% of the accessions are of mixed pod colour (Remanandan *et al.*, 1988). Usually pod length varies from 2 to 8 cm, but rarely 13-cm pods have been observed (Figure 3.18). Pod width generally ranges from 0.4 to 1.0 cm and occasionally to 1.7 cm.

Morphological Variants

A large number of morphological variants that have arisen either as spontaneous mutations or due to hybridization or mutagen treatment are reported in pigeonpea. These variants may be described under two broad categories; vegetative variants, and reproductive variants.

Vegetative Variants

Vegetative variants include those of seedling, leaf, and stem. Several seedling abnormalities were observed by Reddy (1973) in interspecific crosses between *Cajanus cajan* and *C. lineatus*; and *C. sericeus* and *C. scarabaeoides* var. *scarabaeoides*. These include changes in the number and arrangement of the first pair of simple leaves, and various degrees of suppression of lateral leaflets of the first trifoliate leaf. He also observed twin seedlings and the "fasciata" type of seedlings. Such induced twin seedlings (Kim and Faris, 1987) and spontaneous fasciation of the shoot apex (P. Venkateswara Rao, unpublished) have also been observed by other workers. Rajagopalan (1983) reported an abnormal seedling with two bifid or obscordate cotyledonary leaves.

A number of leaf variants have been reported. Singh *et al.* (1942) found a mutant with obcordate leaves in Uttar Pradesh, India. This mutant had free and filiform keel petals, symmetrical wings, and light yellow petals: Singh *et al.* (1942) erroneously described it as a new species. Kajjari (1956)

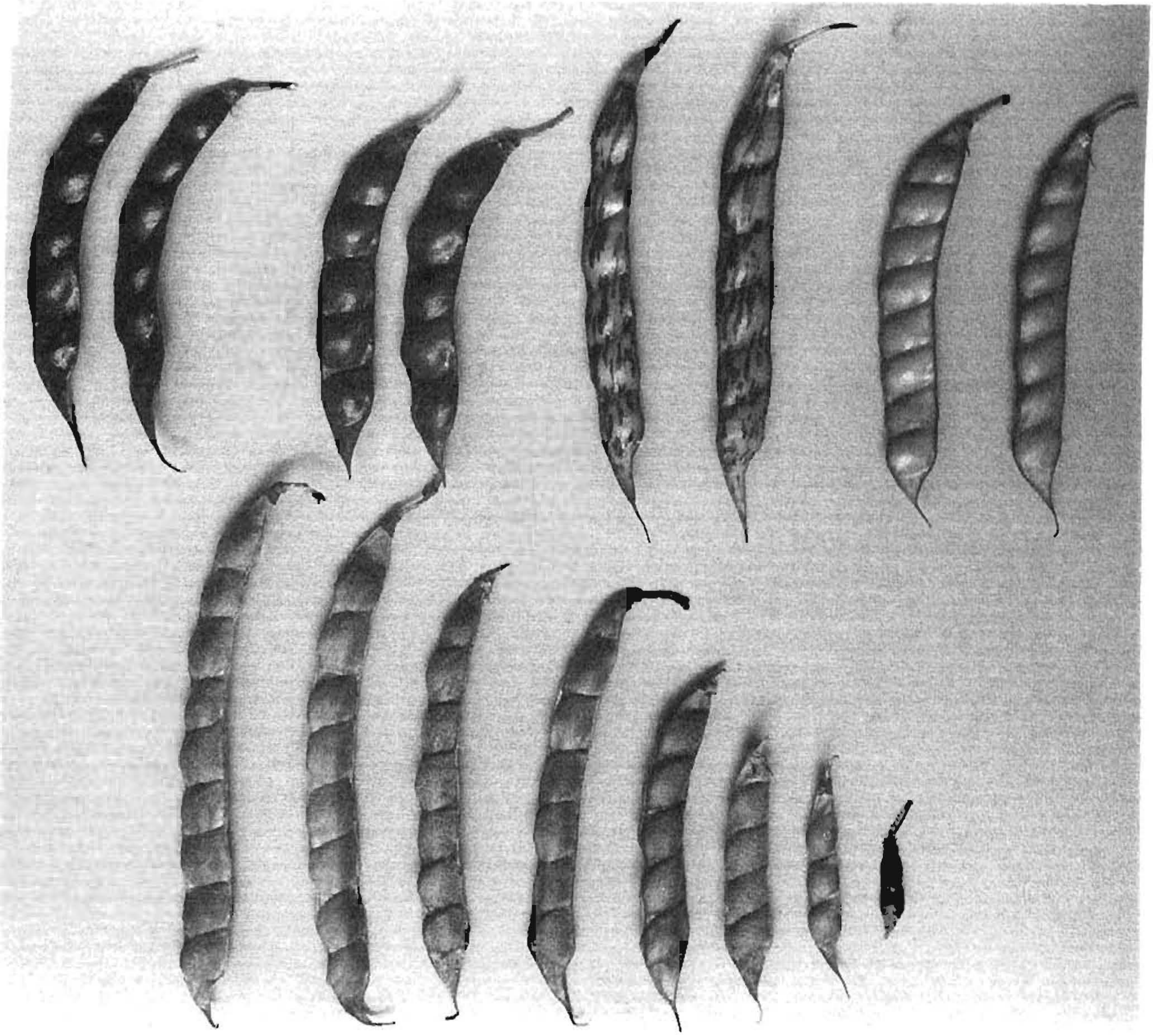


Figure 3.18. Variation in pigeonpea pod colour and size.
Source: Remanandan *et al.*, 1988.

found another mutant with obcordate leaflets with united keel petals in Karnataka, India. Patil (1959) also reported an obcordate-leaflet plant in which one of the wing petals protruded beyond the standard petal at the bud stage. Mutants with round and "tiny" leaflets (Pandya *et al.*, 1954), oblong-ovate leaflets (Divakaran and Ramabhadran, 1958), and oval-oblong leaflets (Joglekar and Deshmukh, 1958) have also been reported. Wanjari *et al.* (1978) described a "robust leaf variant" whose leaves were very thick, dark green, and robust with rounded apices.

Murthi and van der Maesen (1979) working on the world pigeonpea collections at ICRISAT Center observed two new leaf mutants with sesame-type leaves and minute leaves, in addition to the already reported obcordate and round-leaf (broad-elliptic) variants. The minute mutant

(Murthi and van der Maesen, 1979) differed from the tiny leaf mutant (Pandya *et al.*, 1954) because, in the minute mutant the internode length is not suppressed, the rachis is short i.e., matching the leaf size, flowering is not early, and leaf colour and epidermis do not differ from the normal pigeonpea. Later Marekar (1986) also reported such minute-leaf phenotypes in an intervarietal cross.

In interspecific crosses of pigeonpea, Reddy (1973) observed a low frequency of tetrafoliate to hexafoliate leaflets along with normal trifoliate leaves. Sengupta and Sen (1986) reported a variant with 5-7 leaflets per leaf. Unifoliate mutants have also been observed (Jeswani and Deshpande, 1962; Wanjari *et al.*, 1978). Desai *et al.* (1981) reported a genetic abnormality designated as "bracteomania", where affected plants were stunted, and had fewer branches. They possessed simple leaves with obtuse tips, and the flower buds on their inflorescences were clustered and remained undeveloped.

Jeswani and Deshpande (1962) observed a sepaloid mutant that had simple leaves and sepaloid flowers. They also observed another dwarf mutant with thin, wiry and straggling branches, and simple leaves on the lower part of the plant, but none on the upper part that bore only rudimentary floral organs.

Chlorophyll leaf mutants have frequently been observed in pigeonpea treated with mutagens, and the frequency of such mutants has been taken as an index of mutagenic efficiency. In general, chemical mutagens induced a wider spectrum of chlorophyll mutations than physical mutagens such as gamma rays (Venkateswarlu *et al.*, 1981b). The chlorophyll mutants observed in pigeonpea include, viridis, chlorina, xantha, and virescent (Venkateswarlu *et al.*, 1978, 1981b; Pawar *et al.*, 1978). The chlorina and virescent mutants usually survived to maturity, but the xantha seedlings only survived for a few days after emergence.

Prostrate-stem or creeping mutants have been reported (Deshpande and Jeswani, 1952; Chaudhari and Patil, 1953). Such true-breeding prostrate mutants have also been observed at ICRISAT Center. These were considered useful for soil conservation, and for cover and strip cropping. A corky-stem mutant characterized by dry, rough, brown-coloured bark with irregular cracks on the stem and branches has been found at ICRISAT Center (Saxena *et al.*, 1988a). Apart from its abnormal stem surface, this mutant had reduced height, fewer branches, and low pod set. Histological study revealed that the mutant possesses a prominent periderm layer, characteristic of many woody species, interior to the cortical fibre band. The periderm comprises three sections: the outermost phellum of 30-40 layers of dead, flattened, suberized cork cells; the pellogin with a single layer of cambial cells; and the innermost phellodum of 5-6 layers of large cells with deeply staining cytoplasm, adjacent to the cortical parenchyma.

Bhatnagar *et al.* (1967) observed a spontaneous, genetic, fasciated mutant where the branches were fused with the main stem at the point of emergence, and finally assumed a deformed and flattened look. This mutant had purple, curved stems, and the flowers showed about 11% pollen sterility. The flowers possessed bifid styles and usually developed two but rarely 3-4 fused pods (Sinha *et al.*, 1976). Such 2- to 3-fused, deformed and curved pods were also noticed by Shah *et al.* (1984).

Dahiya and Sidhu (1979) reported a nonbranching, spontaneous mutant that differed from its parent in leaf size, maturity, and plant height. A similar mutant associated with female sterility was earlier reported by Deshmukh (1959).

Saxena *et al.* (1984a) reported a nonflowering uniculm mutant that did not produce any primary or secondary branches, presumably due to apical dominance. Lack of floral induction in this mutant was supposed to be due either to a longer juvenile phase, or a shorter daylength requirement. Alternatively, hormonal imbalance might cause lack of flowering.

At ICRISAT Center, the following seven distinct genetic dwarfs (Figure 3.19) have been identified (D. Sharma *et al.*, MARIF, unpublished). Agronomically types D_2 and D_6 appear to be promising.

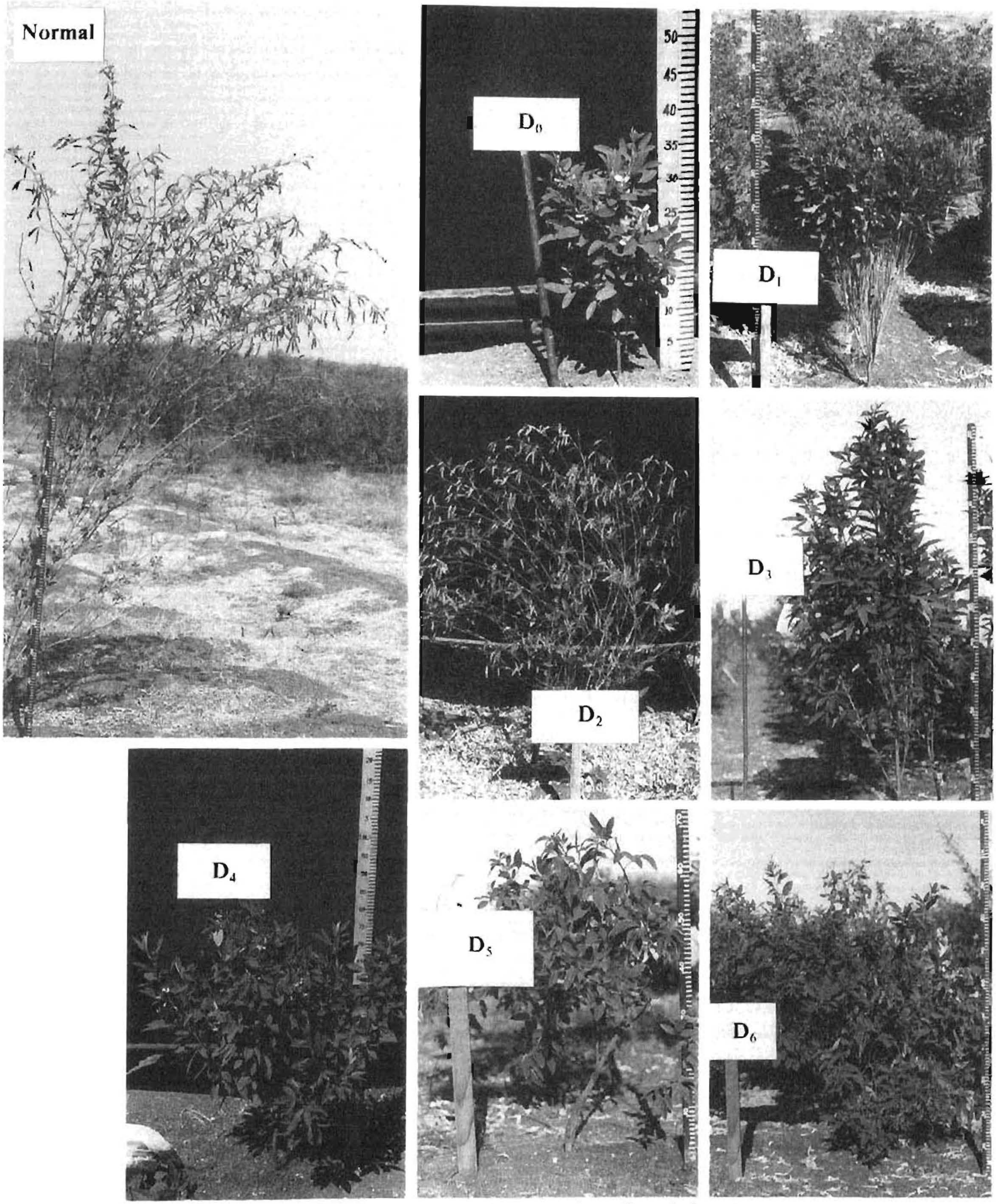


Figure 3.19. A normal pigeonpea plant (left) compared with various dwarf plant types.
Photo: ICRISAT.

D_0 Dwarf

Indeterminate, the shortest genetic dwarf with a height ranging from 25 to 40 cm, with uniformly shortened internodes. The plants produce only a small quantity of dry matter with 4-5 branches, and a few small pods.

D_1 Dwarf

Mid-late maturing, indeterminate plant type of plant height less than a metre (mean 82.0 ± 9.7 cm). Its internodes are very condensed, and the branches appear to radiate from a narrow region. Each plant has on average 7.5 ± 1.87 primary branches that form an acute angle with the main axis. The attachment of the primary branches to the main stem is very weak, and branches break easily at the nodes in very windy weather. Each primary branch bears several secondary and tertiary branches that have leafy and tender apical growth.

D_2 Dwarf

Medium-maturing, semi-spreading, indeterminate plant type. Plants grow 150-cm tall. Plant height is reduced because basal internodes are shortened. Unlike other dwarfs, the angle between the central axis and main branches of D_2 is obtuse, resulting in an open plant canopy.

D_3 Dwarf

Compact, medium-maturing plant type. In this dwarf, plant height (142 ± 6.9 cm) is reduced due to abnormal condensation of the internodes confined to the top 25-30 cm of the main stem. The rest of the plant stature resembles a typical compact type, with the primary branches attached to main axis at an acute angle.

D_4 Dwarf

Late-maturing, about 1m high with few branches.

D_5 Dwarf

Late-maturing, indeterminate dwarf with a distinct main stem, and few branches characterised by the presence of rough, dark-brown bark.

D_6 Dwarf

Medium-maturing indeterminate plant type, with a mean height of 1m. Plants produce many secondary and tertiary branches.

Reproductive Variants

From a thorough search of over 7000 germplasm accessions and over 120 interspecific derivatives of *Cajanus*, Reddy *et al.* (1977) identified the following five different types of reproductive variants.

Ordinary Male Steriles

The anthers are small, pale yellow, apparently empty, and scale-like in appearance. Pollen is scanty and pollen fertility ranges from 10 to 90%. Both pollen quantity and pollen sterility are factors affecting reduced pod setting in this group. The "sparse pollen" type reported by Saxena *et al.* (1981) falls under this category.

Translucent Male Steriles

The anthers are white-translucent in colour, small and scaly in appearance, and devoid of pollen. Such anthers do not dehisce, and die faster than normal ones. Histological study of these translucent types (Reddy *et al.*, 1978) revealed that the pollen tetrads were not released, and that they subsequently degenerated due to the persistent nature of the tapetum. Under selfing, the translucent types do not produce any seeds, but under open pollination pod setting is normal.

Long-styled Types

The style is longer than the stamens and most often a groove on the bud is seen, that does not occur in normal types. They are partially pollen sterile.

Short-styled Types

The style is shorter than in normal types, but there is no change in the length of the stamens. The stigma is completely enclosed inside the staminal column. Pollen is partially sterile, and seed setting is very poor. Such short-styled types have been reported earlier (Patil and Sheikh, 1957) and the "inserted stigma" variant reported by Wanjari *et al.* (1978) falls under this category.

Incompletely Short-styled Types

Plants show both normal and short-styled flowers. Pollen sterility ranges from 5 to 60%.

Although sterile mutants have been reported earlier (Deshmukh, 1959) , these were apparently also female sterile, so that the transluscent types reported by Reddy *et al.* (1977, 1978) constitute the first true genetic male steriles identified in pigeonpea. Following this discovery several other sources of male sterility have been identified. In Australia, Dundas *et al.* (1981) reported a male-sterile source characterised by brown, shrivelled, nondehiscent, and arrowhead-shaped anthers. Unlike transluscent-anthered male steriles, in this male sterile the anthers are completely devoid of pollen grains because the pollen mother cells degenerate at the young tetrad stage. Venkateswarlu *et al.* (1981a) reported a male sterile with obscordate leaf shape. The male sterility in this line is associated with a floral abnormality, wherein the keel petals are modified into thread-like structures, and pollen sterility ranges from 60 to 100%. A syngenesious male sterile in which all 10 fully developed, pale yellow anthers were tightly united into a tube surrounding the style with the filaments remaining free was reported by Gupta and Faris (1983). In this line, the anthers were nondehiscent.

Reddy and Faris (1981) reported a cytoplasmic-genetic male-sterile line from a cross, *C. scarabaeoides* var. *scarabaeoides* × [*C. cajan* (T 21) × *C. scarabaeoides* var. *scarabaeoides*]. The male sterility in this line is associated with two kinds of abnormalities. In one, the anthers are modified into petaloid structures, and male sterility is linked with female sterility. In the other, the male sterility is associated with free stamens and heterostyly, and the anthers appear morphologically normal. However, these normal-looking anthers are devoid of any viable pollen. Histological studies revealed early degeneration of pollen mother and tapetal cells. The latter type of flowers produce very few seeds, even if large numbers of pollinations are carried out.

None of the above-mentioned male steriles, except the translucent types are useful for developing commercial hybrids in pigeonpea.

A variant consistently observed at ICRISAT, and designated a "recurring monstrosity" has been reported by van der Maesen and Saxena (1984). In this variant the pedicels are very crowded, the floral parts are modified into ovate or lineate-ovate bracts, and crowded together giving an impression of a green capitulum similar to those found in Compositae. The bracts possess abundant glandular hairs and vesicles. The plants are almost completely sterile, but occasional flowers occur.

Wanjari *et al.* (1978) reported a petaloid variant where the androecium is petaloid giving a multipetalous appearance to the flower. The plant was completely sterile.

A modification of floral morphology called "wrapped" flower character is reported in a variety Royes and several other accessions in Australia by Byth *et al.* (1982). In the normal flower the margins of the standard petal are slightly convolute, and open with slight pressure. In contrast, the standard margins of the wrapped flower are strongly convolute. This expression is highly variable among genotypes, and to a lesser extent within plants of a line. In some lines, the margins overlap in opposite directions at the proximal and distal regions of the calyx, and appear to act in zipper-like manner. It was presumed that this character inhibits cross-fertilization, but later (Saxena *et al.*, 1987b) found it to be ineffective in preventing outcrossing in pigeonpea. Reddy (1973) isolated a true-breeding line with modified flower structure known as the "free stamen" line from *C. cajan* (T 21) × *C. lineatus*. In contrast to the normal condition where the anthers are diadelphous (9 + 1), all the stamens in this line are free. In addition, the tip of the standard and the wing petals are trapped by the keel. This results in a considerable delay in opening of the flower. Eventually, in an open flower the standard unwraps but the wings still remain enclosed within the keel and thereby almost complete self-fertilization is ensured. Studies at ICRISAT Center on the extent of outcrossing in this line for several seasons revealed only 0.54% outcrossing (K.B. Saxena *et al.*, ICRISAT, unpublished).

Wanjari *et al.* (1978) reported a plant with cleistogamous flowers with a cup-shaped calyx enclosing the complete flower. The flowers remained closed, were sterile, and did not set any pods. A similar weak-stemmed plant with large, thick, puckered leaves and cleistogamous flowers where the standard completely enveloped the keel petals was reported by Jeswani and Deshpande (1962).

From ICRISAT Center, Saxena *et al.* (1984b) reported a mutant that produces flowers with an open carpel similar to those found in primitive plants such as gymnosperms. Histological studies (Saxena *et al.*, 1988b) of the mutant revealed that initial development of the carpel primordium is normal, except that the margins of this horse shoe-shaped primordium are obliquely placed and do not fuse. This abnormality hampers the normal development of the ovule primordium, and results in gradual degeneration of the ovules. Finally, the carpel falls open due to nondevelopment of a ventral suture but does not form any ovules.

Correlation of Morphological Characters in Pigeonpea

Knowledge on the association between various morphological characters is essential to conceptualize, identify, and develop ideal plant types through effective planning of recombinations, and deployment of selection indices. Also, apart from its taxonomic significance, information on character association is important in the classification of varieties into cultivar groups, that help to properly identify and maintain cultivars. Such information is also helpful in grouping the germplasm into various gene pools that can be cheaply and effectively maintained as mass reservoirs. Various methods such as simple correlations, regression, and multiple and partial regression analyses, and path coefficient analyses have been employed to determine direct and indirect associations between various morphological characters including grain yield. Phenotypic, genotypic, and environmental correlation coefficients have been reported for various characters by several workers (Table 3.4). Data from various reports cannot be strictly compared because of the varying number and divergent nature of the material studied, and the different statistical methods employed. However, to gain broad impressions, the extent of correlations reported were classified into two classes; (a) strongly correlated (values ≥0.5), and (b) weakly to moderately correlated (values <0.5), and the following inferences are drawn:

1. Seed yield is strongly and positively correlated with pods per plant, plant height, primary and secondary branches, pod-bearing length, and number of pod clusters (racemes) per plant. Strong, positive genotypic correlations for the above traits are reported, indicating that the environment has relatively less influence on the above associations. Seed yield exhibits weak to moderate, mostly non-significant, negative associations with 100-seed mass, days to flowering and maturity, pod length, and angle of branching.
2. Plant height shows strong to weak positive associations with primary and secondary branches, plant width, days to flowering and maturity, pods per plant, seeds per pod, 100-seed mass, and number of pods per cluster. These associations show high genotypic correlation coefficients.
3. Plant width (spread) shows mostly weak to moderate positive associations with primary and secondary branches, pod bearing length, pods per plant, and 100-seed mass, and weak negative correlation with seeds per pod.
4. Primary branches show weak to strong correlations with secondary branches, pods per plant, pod-bearing length, and number of pod clusters per plant, and both positive and negative weak correlations with seeds per pod, 100-seed mass, and days to flowering and maturity.
5. Secondary branches show weak to strong positive correlations with pods per plant, pod-bearing length, days to flowering and maturity, and number of pod clusters per plant, and both positive and negative weak correlations with seeds per pod, and 100-seed mass.
6. Pod-bearing length shows weak to strong positive correlations with pods per plant, seeds per pod, 100-seed mass, days to flowering and maturity, and number of pod clusters per plant.
7. Pods per plant exhibits weak positive correlations with seeds per pod, 100-seed mass, days to maturity, internode length and leaf area, and both weak and strong positive association with days to flowering, and number of pod clusters per plant.
8. Seeds per pod shows both positive and negative weak associations with 100-seed mass, days to flowering and maturity, and number of pod clusters per plant.
9. 100-seed mass exhibits both positive and negative weak associations with days to flowering, and number of pod clusters per plant.
10. Days to flowering and maturity are highly associated with each other, and they show weak to strong positive correlations with number of pod clusters per plant, and internode length.

FUTURE

The cultivated species, *Cajanus cajan* shows a wide range of diversity for various morphological characters such as plant height, branching pattern, flowering habit, leaf, stem, flower, pod and seed shapes, sizes, and colours. In addition, several vegetative and reproductive variants that have arisen either spontaneously, or been induced through hybridization and mutagens have been described by various workers. Genetic, climatic, and edaphic factors exert profound influence on the expression of morphological characters, and the present knowledge on these factors is far from

Table 3.4. Correlation studies of seed yield with various morphological characters in pigeonpea.

	Phenotypic correlation				Genotypic correlation			
	Positive		Negative		Positive		Negative	
Character	< 0.5	≥ 0.5	< 0.5	≥ 0.5	< 0.5	≥ 0.5	< 0.5	≥ 0.5
Plant height	3[1],(11)[2],(16),17,19,20,(21),22	2,4,(6),7,9,10,12,15	(1),(8)			2,3,4,7,12,15,16,18,20,21,22	8	
Plant width (spread)	(1),(4),(7),(11),(21)	6,7			4	7,18,21		
Primary branches	1,2,3,4,(5),8,17,(19),(21),(22)	(6),7,9,12,15			2,4,5,8,21,22	3,7,12,15,18		
Secondary branches	2,5,(11),14,17,(22)	3,6,16,(19)	**(1)**		14	3,5,16	**22**	
Pod-bearing length	1,3,(11)	(6),7			3	7,18		
Pods plant^{-1}	2,17	1,3,4,5,(6),7,8,9,10,11,12,14,15,16,20,21			14	3,4,5,7,8,12,13,15,16,18,20,21		
Seeds pod^{-1}	(1),2,(3),(7),(12),(16),(19),20,(21),(22)	1[3]	**(1),(4)**		7,12,16,20,21	13,18	**3,4,22**	
100-seed mass	2,(4),(5),(6),(9),(14),(17),20,(21)		(3),(7),8,(13),(16),(19)		4,5,21	13,14,18,21	3,7,8,16	
Days to 50% or 75% flowering	(3),4,(7),(9),(10),12,15,(20),(22)	**21**	(8),(11),(19)		3,4,7,12,15,20,22	21	8	
Days to maturity	2,(3),4,5,(7),12,(20),(22)	21	(8),(11),(19)		3,5,7,20,22	2,4,12,13,18,21	8	

Table 3.4. Continued

Character	Phenotypic correlation				Genotypic correlation			
	Positive		Negative		Positive		Negative	
	<0.5	≥ 0.5	<0.5	≥ 0.5	<0.5	≥ 0.5	<0.5	≥ 0.5
Number of pod clusters plant^{-1}	3	7,14,15,16			3	7,14,15,16		
Pod length	(14),(17),(21)	8	12,(16)		8,14,22		12,16	
Angle of branching	17		(6),(11)					
Plant biomass		8				8		
Number of pods cluster^{-1}	(7)		(4)					
Pod breadth	(17)		8				8	
Internode length	(11)							

1. Numbers refer to the following references:
   1. Shrivastava *et al.*, 1977
   2. Balyan and Sudhakar, 1985a
   3. Kumar and Reddy, 1982
   4. Sinha *et al.*, 1987
   5. Asawa *et al.*, 1981
   6. Sharma *et al.*, 1971
   7. Malik *et al.*, 1981a
   8. Mukewar and Muley, 1974
   9. Gunaseelan and Rao, 1976
   10. Wagh *et al.*, 1983
   11. Tiwari *et al.*, 1978
   12. Patel *et al.*, 1988
   13. Balyan and Sudhakar, 1985b
   14. Singh and Malhotra, 1973
   15. Veeraswamy *et al.*, 1973
   16. Gupta *et al.*, 1975.
   17. Wakankar and Yadav, 1975
   18. Malik *et al.*, 1981b
   19. Remanandan *et al.*, 1988
   20. Sidhu *et al*,, 1985
   21. Dumbre *et al.*, 1985
   22. Bainiwal and Jatasra *et al.*, 1983
2. Figures in parentheses for phenotypic correlations indicate that values reported are not significant or significance was not reported.
3. Authors report different values separately for different maturity groups.

complete. Several statistical methods have been employed to study both direct and indirect associations between various morphological traits. There is a need to continue studies in this direction by proper phenological stratification of the varieties, and by deployment of multilocational sites to gain a better understanding of the effect of genotype × environment interactions on the expression of various morphological traits.

So far, pigeonpea classification based on morphology has been directed towards satisfying the rather isolated interests of taxonomists and agronomists. In order to effectively and economically maintain and utilize the world germplasm accessions, that now amount to several thousands, but possibly include many duplicates, we need to develop a more comprehensive pigeonpea classification based on both morphological and agronomic characters. For this purpose numerical classification methods such as the MULTCLAS hierarchical program, and the Euclidean system of Burr (1968) merit consideration.

REFERENCES

Akinola, J.O. and Whiteman, P.C. (1972) A numerical classification of *Cajanus cajan* (L.) Millsp. accessions based on morphological and agronomic attributes. *Australian Journal of Agricultural Research* 23, 995-1005.

Ariyanayagam, R.P. (1975) Status of research on pigeonpeas in Trinidad. In: *International Workshop on Grain Legumes, 13-16 January 1975, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 131-139.

Arora, N. (1956) Morphological study of the root nodules on *Cajanus indicus*. *Proceedings of the Indian Science Congress* 43(3), 244-245 (abstract).

Asawa, B.M., Chandra, R.K. and Panday, R.L. (1981) Character correlations and divergence in pigeonpea. *Indian Journal of Agricultural Sciences* 51, 12-17.

Bahadur, B., Madhusudana Rao, M. and Lokendar Rao, K. (1981) Studies on dimorphic stamens and pollen (SEM) and its possible role in pollination biology of *Cajanus cajan* (L.) Millsp. *Indian Journal of Botany* 4, 122-129.

Bainiwal, C.R. and Jatasra, D.S. (1983) Component analysis in pigeonpea [*Cajanus cajan* (L.) Millsp.]. *Indian Journal of Heredity* 15, 1-7.

Baldev, B. (1988) Origin, distribution, taxonomy and morphology. In: Baldev, B., Ramanujam, S. and Jain, H.K. (eds), *Pulse Crops (Grain Legumes)*. Oxford and IBH, New Delhi, pp. 3-51.

Balyan, H.S. and Sudhakar, M.V. (1985a) Variability character association and path coefficient studies on genotypes of early maturity group in pigeonpea (*Cajanus cajan* (L.) Millsp.). *Madras Agricultural Journal* 72, 168-172.

Balyan, H.S. and Sudhakar, M.V. (1985b) Path coefficient studies in pigeonpea. *International Pigeonpea Newsletter* 4, 18-20.

Bhatia, G.K., Gupta, S.C., Green, J.M. and Sharma, D. (1981) Estimates of natural cross-pollination in *Cajanus cajan* (L.) Millsp.: several experimental approaches. In: *Proceedings of the International Workshop on Pigeonpeas, volume 2, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 129-136.

Bhatnagar, P.S., Sen Gupta, P.K., Gangwar, L.C., Saxena, J.K. and Kumar, V. (1967) A fasciated mutant in pigeonpea. *Science and Culture* 33, 120-121.

Bisen, S.S. and Sheldrake, A.R. (1981) *The Anatomy of the Pigeonpea. Research Bulletin no. 5*. Patancheru, A.P., India: ICRISAT, 24 pp.

Burr, E.J. (1968) Cluster sorting with mixed character types. I. Standardization of character values. *Australian Computer Journal* 1, 97-99.

Byth, D.E., Saxena, K.B., and Wallis, E.S. (1982) A mechanism for inhibiting cross-fertilization in pigeonpea (*Cajanus cajan* (L.) Millsp.). *Euphytica* 31, 405-408.

Chaudhari, B.B. and Patil, J.A. (1953) "Creeping" - a mutant in *Cajanus cajan* Millsp. *Current Science* 22, 153.

Dahiya, B.S. and Sidhu, P.S. (1979) Non-branching (single-stem) mutant in pigeonpea (*Cajanus cajan* (L.) Millsp.). *Tropical Grain Legume Bulletin* 15, 24-25.

Datta, P.C. and Deb, Arati (1970) Floral biology of *Cajanus cajan* (Linn.) Millsp. var. *bicolor* D.C. (Papilionaceae). *Bulletin of Botanical Society of Bengal* 24(1-2), 135-145.

De, D.N. (1974) Pigeonpea In: Hutchinson, J. (ed), *Evolutionary Studies in World Crops, Diversity and Change in the Indian Subcontinent*. Cambridge University Press, London, pp. 79-87.

de Candolle, A.P. (1813) *Catalogus Plantarum Horti Botanici Monspeliensis*. Paris and Strasbourg Montpellier, pp. 85-86.

de Jabrun, P.L.M., Byth, D.E. and Wallis, E.S. (1981) Imbibition by and effects of temperature on germination of mature seed of pigeonpea (*Cajanus cajan*). In: *Proceedings of the International Workshop on Pigeonpeas, volume 2, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 181-187.

Deodikar, G.B. and Thakar, C.V. (1956) Cyto-taxonomic evidence for the affinity between *Cajanus indicus* Spreng. and certain erect species of *Atylosia* W.&A. *Proceedings of the Indian Academy of Sciences, Section B* 43, 37-45.

Desai, B.G., Patel, J.C. and Vora, M.S. (1981) *Bracteomania*: a genetic abnormality giving a virus disease syndrome in pigeonpea. *International Pigeonpea Newsletter* 1, 20-21.

Deshmukh, N.Y. (1959) Sterile mutants in tur (*Cajanus cajan*). *Nagpur Agriculture College Magazine* 33, 20-21.

Deshpande, R.B. and Jeswani, L.M. (1952) A prostrate mutant in pigeonpea (*Cajanus cajan* (L.) Millsp.)–a possible soil conservation plant. *Indian Journal of Genetics and Plant Breeding* 12, 50-51.

Divakaran, K. and Ramabhadran, G. (1958) A marker gene for red gram (*Cajanus cajan* Millsp.). *Current Science* 27, 100-101.

Dumbre, A.D., Deshmukh, R.B. and Patil, J.V. (1985) Path analysis in pigeonpea. *Legumes Research* 8, 37-38.

Dundas, I.S., Saxena, K.B., Byth, D.E. and Wallis, E.S. (1981) Cytological aspects of a new male sterile source in pigeonpea. *International Pigeonpea Newletter* 1, 14-16.

Durga Prashad, M.M.K. and Narasimha Murthy, B.L. (1963) Some observations on anthesis and pollination in red gram (*Cajanus cajan*). *Andhra Agricultural Journal* 10, 161-167.

Gunaseelan, T. and Rao, H.K.H. (1976) Discriminant function and study of the correlated effects in pigeonpea. *Indian Journal of Agricultural Sciences* 46, 175-177.

Gunn, C.R. (1981) Seeds of Leguminosae. In: Polhill, R.M. and Raven, P.H. (eds), *Advances in Legume Systematics, Part* 2. Royal Botanic Gardens, Kew, UK. pp. 913-925.

Gupta, S.C. and Faris, D.G. (1983) New steriles in early pigeonpea. *International Pigeonpea Newsletter* 2, 21-22.

Gupta, V.P., Sethi, L.C. and Chandra, S. (1975) Variation, heritability and correlation among yield components in arhar (*Cajanus cajan* (L.) Millsp.). *Haryana Agricultural University Journal of Research* 5, 110-115.

Harms, H. (1915) Über eine neue Art der Gattung *Cajanus* Spreng. *Feddes Repert.* 14, 196.

Howard, A., Howard, G.L.C. and Khan, A.R. (1919) Studies in the pollination of Indian Crops-I. *Memoirs of the Department of Agriculture in India, Botanical Series* 10, 195-200.

IBPGR/ICRISAT (1981) *Descriptors for Pigeonpea*. International Board for Plant Genetic Resources (IBPGR) Secretariat, Rome, 15 pp.

ICRISAT (1978) *Annual Report 1977-1978*. Patancheru, A.P., India: ICRISAT, p. 100.

Jeswani, L.M. and Deshpande, R.B. (1962) Inheritance studies on some sterile mutants in pigeonpea. *Indian Journal of Genetics and Plant Breeding* 22, 236-240.

Joglekar, R.G. and Deshmukh, N.Y. (1958) Mutations in pigeonpea (*Cajanus cajan*). *Nagpur Agriculture College Magazine* 32, 23-29.

Kajjari, N.B. (1956) A new mutation in *Cajanus cajan* Millsp. *Current Science* 25, 333.

Kapil, R.N. and Kapil, N. (1971) Root nodules of *Cajanus cajan*: origin, structure and ontogeny. *Phytomorphology* 21, 192-202.

Khan, T.N., (1973) A new approach to the breeding of pigeonpea (*Cajanus cajan* (L.) Millsp.): formation of composites. *Euphytica* 22, 373-377.

Kim, T.S. and Faris, D.G. (1987) Inducing twin seedlings in pigeonpea. *International Pigeonpea Newsletter* 6, 16-17.

Kumar, A.S. and Reddy, T.P. (1982) Path coefficient analysis of yield attributes in pigeonpea (*Cajanus cajan* (L.) Millsp). *Genetica Agraria* 36, 63-72.

Kumar, L.S.S., Shama Rao, H.K. and Thombre, M.V. (1966) Interspecific and intergeneric hybridization in the breeding of crop plants. *Indian Journal of Genetics and Plant Breeding* 26A, 114-120.

Kumar, L.S.S. and Thombre, M.V. (1958) An intergeneric hybrid of *Cajanus cajan* (L.) Millsp. × *Atylosia lineata* W.&A. *Journal of the University of Poona* 12, 13-16.

Kumar, L.S.S., Thombre, M.V. and D'Cruz, R. (1958) Cytological studies of an intergeneric hybrid of *Cajanus cajan* (Linn.) Millsp. and *Atylosia lineata* W.&A. *Proceedings of the Indian Academy of Sciences, Section B* 47, 252-262.

Lord, E.M. (1981) Cleistogamy: a tool for the study of floral morphogenesis, function and evolution. *Botanical Review* 47, 421-449.

Madhusudana Rao, M., Lokendar Rao, K. and Bahadur, B. (1979) Corolla handedness in Papilionaceae. *Current Science* 48, 408-410.

Mahta, D.N. and Dave, B.B. (1931) Studies in *Cajanus indicus*. *Memoirs of the Department of Agriculture in India, Botanical Series* 19, 1-25.

Malik, B.P.S., Paroda, R.S. and Chaudhary, B.D. (1981a) Partial correlations and path coefficient analysis of seed yield characters in pigeonpea. In: *Proceedings of the International Workshop on Pigeonpeas, volume 2, 15-19 December 1980, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 109-115,

Malik, B.P.S., Singh, V.P., Paroda, R.S. and Gupta, S.C. (1981b) Correlation and path coefficient analysis in pigeonpea. *Crop Improvement* 8, 100-105.

Marekar, R.V. (1986) Spontaneous mutant in pigeonpea. *Punjabrao Krishi Vidyapeeth Research Journal* 10(2), 148-149.

Mukewar, A.M. and Muley, D.P. (1974) Correlation studies of some yield components in tur (*Cajanus cajan* (L.) Millsp.). *Nagpur Agriculture College Magazine* 47, 83-87.

Murthi, A.N. and van der Maesen, L.J.G. (1979) Leaf variants in pigeonpea [*Cajanus cajan* (L.) Millsp.]. *Tropical Agriculture (Trinidad)* 56, 81-83.

Nambiar, P.T.C., Rupela, O.P. and Kumar Rao, J.V.D.K. (1988) Nodulation and nitrogen fixation in groundnut (*Arachis hypogaea* L.), chickpea (*Cicer arietinum* L.) and pigeonpea (*Cajanus cajan* (L.) Millsp.). In: Subba Rao, N.S. (ed), *Biological Nitrogen Fixation–Recent Developments*. Oxford and IBH, New Delhi, pp. 21-52.

Narayanan, A., Saxena, N.P. and Sheldrake, A.R. (1981) Varietal differences in seed size and seedling growth of pigeonpea and chickpea. *Indian Journal of Agricultural Sciences* 51, 389-393.

Narayanan, A. and Sheldrake, A.R. (1975) *Pulse Physiology Annual Report 1974-75, Part 1–Pigeonpea Physiology.* Patancheru, A.P., India: Legumes Program, ICRISAT (Limited distribution).

Natarajan, M. and Willey, R.W. (1980) Sorghum-pigeonpea intercropping and the effects of plant population density. 1. Growth and yield. *Journal of Agricultural Sciences, Cambridge* 95, 51-58.

Onim, J.F.M. (1981) Pigeonpea improvement research in Kenya. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 427-436,

Pandey, R.K. and Singh, V.B. (1981) Influence of source and sink size on flower drop and seed yield of pigeonpea. *Indian Journal of Agricultural Sciences* 51, 185-188.

Pandya, P.S., Patil, J.A. and Chaudhary, B.B. (1954) "Round and Tiny" leaf mutants in *Cajanus cajan* Millsp. *Poona Agricultural College Magazine* 45, 18.

Patel, J.A., Patel, D.B., Zaveri, P.P. and Pathak, A.R. (1988) Path coefficient studies in pigeonpea. *International Pigeonpea Newsletter* 7, 5-6.

Pathak, G.N. (1970) Red gram. In: *Pulse Crops of India*. Indian Council of Agricultural Research, New Delhi, India, pp. 14-53.

Patil, J.A. (1959) A mutation in *Cajanus cajan* (Linn.) Millsp. *Poona Agricultural College Magazine* 49, 264.

Patil, J.A. and Sheikh, Y.N. (1957) Short stigma off type plant in pigeonpea (*Cajanus cajan* Millsp.). *Current Science* 26, 253-254.

Pawar, S.E., Thakare, R.G. and Joshua, D.C. (1978) Relative biological effectiveness and mutagenic efficiency of fast neutrons in *Cajanus cajan*. *Indian Journal of Experimental Biology* 16, 656-659.

Prasad, S., Prakash, R. and Haque, Md. F. (1977) Floral biology of pigeonpea. *Tropical Grain Legume Bulletin* 7, 12-13.

Purseglove, J.W. (1968) *Tropical Crops–Dicotyledons 1*. Longmans, London, pp.236-241.

Rachie, K.O. and Roberts, L.M. (1974) Grain legumes of the lowland tropics. *Advances in Agronomy* 26, 1-132.

Rajagopalan, C.K. (1983) Two abnormal morphological variations in pigeonpea seedlings. *International Pigeonpea Newsletter* 2, 10-11.

Reddy, B.V.S., Green, J.M. and Bisen, S.S. (1978) Genetic male sterility in pigeonpea. *Crop Science* 18, 362-364.

Reddy, B.V.S., Reddy, L.J. and Murthi, A.N. (1977) Reproductive variants in *Cajanus cajan* (L.) Millsp. *Tropical Grain Legume Bulletin* 7, 11.

Reddy, L.J. (1973) Interrelationship of *Cajanus* and *Atylosia* species as revealed by hybridization and pachytene analysis. PhD thesis, Indian Institute of Technology, Kharagpur, India.

Reddy, L.J. and Faris, D.G. (1981) A cytoplasmic-genetic male sterile line in pigeonpea. *International Pigeonpea Newsletter* 1, 16-17.

Reddy, L.J., Green, J.M. and Sharma, D. (1981a) Genetics of *Cajanus cajan* (L.) Millsp. × *Atylosia* spp. In: *Proceedings of the International Workshop on Pigeonpeas, volume 2, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 39-50.

Reddy, L.J. and Mishra, A.K. (1981) Is emasculation necessary for pigeonpea hybridization? *International Pigeonpea Newsletter* 1, 12-13.

Reddy, L.J., Saxena, K.B., Sharma, D. and Green, J.M. (1981b) Some combining ability analyses in pigeonpea (*Cajanus cajan* (L.) Millsp.). In: *Proceedings of the International Workshop on Pigeonpeas, volume 2, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 93-104.

Reddy, R.P. and Rao, N.G.P. (1975) Somatic variation in *Cajanus cajan*. *Current Science* 44, 816-817.

Remanandan, P., Sastry, D.V.S.S.R. and Mengesha, M.H. (1988) *ICRISAT Pigeonpea Germplasm Catalog: Evaluation and Analysis*. Patancheru, A.P., India: ICRISAT, 90 pp.

Roy, A. and De, D.N. (1965) Intergeneric hybridization of *Cajanus* and *Atylosia*. *Science and Culture* 31, 93-95.

Saxena, K.B., Byth, D.E., Dundas, I.S. and Wallis, E.S. (1981) Genetic control of sparse pollen production in pigeonpea. *International Pigeonpea Newsletter* 1, 17-18.

Saxena, K.B., Dundas, I.S., Faris, D.G. and Gupta, S.C. (1988a) Genetics and histology of a corky-stem mutant in pigeonpea. *Journal of Heredity* 79, 221-222.

Saxena, K.B., Durga, B.K. and Laxman Singh (1987a) A case of cross-incompatability in pigeonpea. *International Pigeonpea Newsletter* 6, 33-34.

Saxena, K.B., Gupta, M.D. and Faris, D.G. (1984a) A nonflowering uniculm mutant of pigeonpea. *International Pigeonpea Newsletter* 3, 11-12.

Saxena, K.B., Sharma, D. and Faris, D.G. (1984b) An open carpellary mutant in pigeonpea. *International Pigeonpea Newsletter* 3, 10-11.

Saxena, K.B., Sharma, D. and Faris, D.G. (1987b) Ineffectiveness of wrapped flower in inhibiting cross-fertilization in pigeonpea. *Euphytica* 36, 295-297.

Saxena, K.B., Singh, A.K. and Faris, D.G. (1988b) The morphogenesis and inheritance of an open carpel mutant *cd1* in pigeonpea. *Journal of Heredity* 79, 75-76.

Sehgal, C.B. and Gandhi, V. (1986) Histology and histochemistry of pericarp of grain legumes: *Cajanus cajan*, *Vigna mungo* and *Vigna radiata*. *Cytologia* 51, 333-339.

Sehgal, C.B., Gandhi, V. and Varma, B. (1987) Histological and histochemical studies on the cotyledons of some legumes II. Reserve metabolites during seed development. *Cytologia* 52, 847-858.

Sengupta, K. and Sen, B.K. (1986) A multileaflet pigeonpea variant. *International Pigeonpea Newsletter* 5, 17-18.

Shah, R.M., Pathak, A.R., Zaveri, P.P., Patel, J.A., Sharma, A.N. and Patel, R.S. (1984) A fused pod variant in pigeonpea. *International Pigeonpea Newsletter* 3, 10.

Sharma, D., Laxman Singh, Sharma, H.K. and Parashar, R.R. (1971) Plant types in arhar (*Cajanus cajan* (L.) Millsp.) and their bearing on varietal improvement. *SABRAO Newsletter* 3, 109-112.

Sharma, D., Reddy, L.J., Green, J.M. and Jain, K.C. (1981) International adaptation of pigeonpeas. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 71-81.

Shaw, F.J.F., Khan, A.R. and Singh, H. (1933) Studies in Indian pulses. 3. The type of *Cajanus indicus* Spreng. *Indian Journal of Agricultural Sciences* 3, 1-36.

Sheldrake, A.R. (1984) Pigeonpea. In: Goldsworthy, R. and Fisher, N.M. (eds), *The Physiology of Tropical Field Crops.* John Wiley and Sons Ltd., Chichester, pp. 385-417.

Sheldrake, A.R. and Narayanan, A. (1979) Growth, development and nutrient uptake in pigeonpeas *(Cajanus cajan). Journal of Agricultural Science, Cambridge* 92, 513-526.

Sheldrake, A.R., Narayanan, A., and Venkataratnam, N. (1979) The effects of flower removal on the seed yield of pigeonpeas *(Cajanus cajan). Annals of Applied Biology* 91, 383-390.

Shrivastava, M.P., Singh, R.P. and Laxman Singh (1977) Intra-group correlations in three maturity groups of pigeonpea. *Indian Journal of Genetics and Plant Breeding* 37, 124-129.

Sidhu, P.S., Verma, M.M., Cheema, H.S. and Sra, S.S. (1985) Genetic relationships among yield components in pigeonpea. *Indian Journal of Agricultural Sciences* 55, 232-235.

Singh, D.N., Bansal, R.K. and Mital, S.P. (1942) *Cajanus obcordifolia* Singh–A new species of *Cajanus. Indian Journal of Agricultural Sciences* 12, 779-784.

Singh, K.B. and Malhotra, R.S. (1973) Yield components in pigeonpea (*Cajanus cajan* L.). *Madras Agricultural Journal* 60, 364-366.

Sinha, S.C., Saxena, J.K. and Lakhan, R. (1976) Note on the breeding behaviour of a fasciated mutant in *Cajanus cajan. Indian Journal of Agricultural Research* 10, 203-204.

Sinha, S.C., Srivastava, A.N. and Singh, K.N. (1987) Interrelationship of some quantitative traits in pigeonpea. *International Pigeonpea Newsletter* 6, 21-24.

Srivastava, V. (1978) Pollen morphology of *Cajanus cajan* (L.) Willd. (Leguminosae) cultivars and their hybrids. *Grana* 17, 107-109.

Tayo, T.O. (1980) Compensatory growth and yield of pigeonpea *(Cajanus cajan)* following pod removal at different stages of reproductive growth. *Journal of Agricultural Science, Cambridge* 95, 487-491.

Thompson, J.A., Kumar Rao, J.V.D.K. and Dart, P.J. (1981) Measurement of inoculation response in pigeonpea. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 249-253.

Tiwari, A.S., Singh, B.R. and Asawa, B.M. (1978) Character correlations in pigeonpea [*Cajanus cajan* (L.) Millsp.]. *Tropical Grain Legume Bulletin* 13/14, 25-27.

van der Maesen, L.J.G. (1986) *Cajanus DC. and Atylosia W.&A. (Leguminosae). Agricultural University Wageningen Papers 85-4 (1985).* Agricultural University, Wageningen, the Netherlands, 225 pp.

van der Maesen, L.J.G. and Saxena, K.B. (1984) A recurring monstrosity. *International Pigeonpea Newsletter* 3, 12.

Veeraswamy, R., Rathnaswamy, R., Ragupathy, A. and Palaniswamy, G.A. (1973) Genotypic and phenotypic correlations in *Cajanus cajan* (L.) Millsp. *Madras Agricultural Journal* 60, 1823-1825.

Venkateswarlu, S., Reddy, A.R., Nandan, R., Singh, O.N. and Singh, R.N. (1981a) Male sterility associated with obcordate leaf shape in pigeonpea. *International Pigeonpea Newsletter* 1, 16.

Venkateswarlu, S., Singh, R.M. and Reddy, L.J. (1981b) Induced mutagenesis in pigeonpea with gamma rays, ethyl methane sulfonate (EMS) and hydroxylamine (HA). In: *Proceedings of the*

International Workshop on Pigeonpeas, volume 2, 15-19 December 1980, ICRISAT Center, India. Patancheru, A.P., India: ICRISAT, pp. 67-73.

Venkateswarlu, S., Singh, R.M., Singh, R.B. and Singh, B.D. (1978) Radiosensitivity and frequency of chlorophyll mutations in pigeonpea. *Indian Journal of Genetics and Plant Breeding* 38, 90-94.

Wagh, U.R., Deshmukh, R.B., More, D.C. and Mehetre, S.S. (1983) Correlations in pigeonpea IV. Standard partial regression coefficients. *Pulse Crops Newsletter* 3, 5-6.

Wakankar, S.M. and Yadav, L.N. (1975) Path analysis of yield components in arhar *Cajanus cajan*. *Indian Journal of Agricultural Research* 9, 182-186.

Wanjari, K.B., Khadilkar, B.T. and Kutarekar, D.R. (1978) Spontaneous variants in tur. *Nagpur Agriculture College Magazine* 50, 41-42.

Westphal, E. (1974) Pulses in Ethiopia, their taxonomy and agricultural significance. *Agricultural Research Reports* 815. PUDOC, Wageningen, pp. 64-71.

Whiteman, P.C., Byth, D.E. and Wallis, E.S. (1985) Pigeonpea (*Cajanus cajan* (L.) Millsp.). In: Summerfield, R.J. and Roberts, E.H. (eds), *Grain Legume Crops*. Collins Professional and Technical Books, London, pp. 658-698.

Williams, I.H. (1977) Behaviour of insects foraging on pigeonpea (*Cajanus cajan* (L.) Millsp.) in India. *Tropical Agriculture (Trinidad)* 54, 353-363.

Wilsie, C.P. and Takahashi, M. (1934) Natural crossing in the pigeonpea. *Journal of Agricultural Research* 49, 923-927.

Chapter 4

PIGEONPEA: GENETIC RESOURCES

P. REMANANDAN

Botanist, Genetic Resources Unit, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Andhra Pradesh 502 324, India.

INTRODUCTION

Success in crop improvement work largely depends on access to well-classified and diverse genetic resources. The world's largest collection of pigeonpea germplasm is conserved in the ICRISAT gene bank. This collection consists of 11,171 accessions from 52 countries and is freely available to scientists all over the world. Small collections are maintained at various research centres of the Indian Council of Agricultural Research (ICAR), a number of agricultural universities in India, and at national research centres in several other countries.

THE PLANT

Pigeonpea belongs to the genus *Cajanus* of the subtribe Cajaninae, tribe Phaseoleae of the sub-family Papilionoideae, family Leguminosae. The plant is a perennial shrub but is often cultivated as an

Table 4.1. Number of accessions in the world collection of pigeonpea held in the gene bank, ICRISAT Center, by country, 1 April 1989.

Country	Number of accessions	Country	Number of accessions
Antigua	2	Nepal	116
Australia[1]	60	Nigeria	43
Bangladesh	73	Pakistan	14
Barbados	25	People's Republic of China	1
Belgium[1]	2		
Brazil	17	Peru	5
Cape Verde	6	Philippines	58
Colombia	5	Puerto Rico	78
Dominican Republic	63	Rwanda	5
Ethiopia	14	Senegal	10
German Democratic Republic[1]	2	Sierra Leone	3
		South Africa	4
Ghana	2	Sri Lanka	71
Grenada	15	St. Kitts/Nevis/Anguilla	6
Guadeloupe	22		
Guyana	28	St. Lucia	17
India	9 136	St. Vincent	22
Indonesia	12	Taiwan	3
Italy[1]	14	Tanzania	221
Jamaica	64	Thailand	17
Kenya	332	Trinidad and Tobago	112
Malagasy Republic	1	Uganda	1
Malawi	245	UK[1]	3
Martinique	1	USA	3
Mexico	2	USSR	2
Montserrat	4	Venezuela	47
Mozambique	10	Zambia	74
Myanmar (Burma)	68	Unknown	10
		Total	11 171

1. Secondary source, original source not known.

annual crop. When sown at ICRISAT Center (18°N) soon after the longest day (23 June), the maturity of different cultivars ranges from 3 to 9 months, and their height from 50cm to over 2m. Pigeonpea is slowgrowing for the first 45 days after sowing. It grows well during the rainy season, and yields best when flowering and podding coincide with receding rainfall patterns. The plant has a deep root system and produces a relatively high biomass with a low harvest index that varies from 15 to 30% in most of the traditionally grown cultivars. Pigeonpea has a C_3 pathway for carbon fixation, and it interacts with cowpea strains of *Rhizobium* to fix atmospheric nitrogen. Most traditionally grown pigeonpeas have an indeterminate flowering habit. However, there are determinate genotypes that are often the products of plant breeding. The flowering period of pigeonpea is usually prolonged, enabling the plant to recover from various stresses to which it may be exposed. Pigeonpea is a quantitative short-day plant with a critical daylength of 13 h (Sharma *et al.*, 1981).

India is considered to be the primary centre of origin and diversification of pigeonpea (van der Maesen, 1980). Other important areas of cultivation include eastern Africa, the Caribbean Islands, parts of South and Central America, and South and Southeast Asia. The crop's evolution through natural hybridization, selection for adaptation to a wide range of agro-ecosystems, and selection by man has resulted in numerous locally adapted landraces with a wide genetic base.

COLLECTION

The world collection of pigeonpea, consisting of 11,171 accessions from 52 countries (Table 4.1), is conserved in the ICRISAT gene bank. The initial ICRISAT collection consisted of germplasm donated by the Indian Council for Agricultural Research (ICAR) and various institutions in India. Based on the centre of diversity, crop statistics, and representation in the collection, priority areas for collection were identified. ICRISAT then embarked on a phase of systematic germplasm assembly, and Tables 4.1 and 4.2 present the current status. The collection includes different categories of germplasm such as landraces, established cultivars, breeding stocks with specific characters, gene pools, etc. Special attention is given to the closely related wild species which form the secondary gene pool of pigeonpea. In 1989 ICRISAT gene bank held 270 accessions of 47 wild species belonging to six genera.

Table 4.2. Pigeonpea accessions in ICRISAT gene bank originating from Indian states, and developed at ICRISAT, 1 April 1989.

State	Number of accessions	State	Number of accessions
Andhra Pradesh	2 135	Orissa	322
Assam	102	Punjab	12
Bihar	675	Rajasthan	90
Daman	1	Sikkim	4
Gujarat	136	Tamil Nadu	383
Haryana	12	Uttar Pradesh	2 137
Himachal Pradesh	4	West Bengal	107
Karnataka	265	Developed at ICRISAT	887
Kerala	47	Unknown	406
Madhya Pradesh	653		
Maharashtra	628		
Meghalaya	2		
New Delhi (Union territory)	128		
		Total	9 136

MAINTENANCE

Maintenance of pigeonpea is a difficult and expensive operation. Though pigeonpea's floral biology favours self-pollination, some hybrid seed is usually produced as a result of bee visits. *Megachile* spp are considered responsible for most of the cross-pollination in pigeonpea (Williams, 1977). Pigeonpea outcrosses to varying degrees under field conditions (Howard *et al.*, 1919; Mahta and Dave, 1931; Deshmukh and Rekhi, 1963; Abrams, 1967; Ariyanayagam, 1976; Khan and Rachie, 1972; Onim, 1981). The outcrossing mechanism helps in the production of hybrid seed and in population-improvement breeding schemes, but it makes maintenance of the genetic purity of cultivars difficult and expensive.

To preserve their genetic purity it is essential to multiply accessions under controlled pollination. This can be achieved by covering the whole plant or individual branches with muslin or nylon bags. Selfed seeds from about 30 plants per accession are bulked to constitute the next generation, and to reconstitute the original population as closely as possible. Sowing pigeonpea close to the shortest day of the year results in reduced plant height, and thus allows whole plants to be conveniently covered with muslin bags. It is also possible to control pollination by covering the whole plot using dismantleable frames covered with nets. When small numbers of cultivars are to be multiplied for large-scale seed production, geographic isolation of about 100 m is desirable. Acccessions are rejuvenated by resowing selfed seed. However, it is desirable to restrict the number of rejuvenations to the bare minimum to minimize the risk of genetic drift.

Harvested pods are sun dried before threshing and the moisture level of cleaned seed reduced to 6% before storage in the gene bank. Airtight moisture-proof aluminium cans are used at ICRISAT to store seed in medium-term cold storage at +4°C and 25% relative humidity. Plastic cans can also be used to store seed. Periodic germination tests are carried out to monitor the viability of stored seed, that generally remains above 90% for about 15 years under medium-term cold storage conditions.

The entire world collection is presently maintained in medium-term cold storage at ICRISAT, seed from this store is used for general distribution. Long-term cold storage at -20°C is currently under test in the ICRISAT gene bank. A set of the world collection will be conserved in long-term cold storage as a base collection. It is further planned to conserve a duplicate set of the world collection at another location.

CHARACTERIZATION AND EVALUATION

Characterization is the recording of distinctly identifiable, heritable, characteristics; while preliminary evaluation involves recording a limited number of agronomic traits that are important in pigeonpea improvement. Characterization data of the world pigeonpea collection, and the preliminary evaluation data of a limited number of accessions have been subjected to statistical analysis and a catalogue has been published (Remanandan *et al.*, 1988a).

Systematic description of the accessions will eventually lead to classification into small and well-defined sectors that will facilitate enhanced utilization of the germplasm.

The major objectives of characterization are:

- to describe accessions, establish their diagnostic characteristics and identify duplicates;
- to classify groups of accessions using sound criteria;
- to identify accessions with desired agronomic traits and select entries for further evaluation;
- to study interrelationships between or among traits, and between geographic groups of cultivars (Chang, 1976); and
- to estimate the extent of variation in the collection.

ICRISAT follows a multidisciplinary approach to accomplish these objectives.

The major exercise of characterization is carried out at ICRISAT Center, Patancheru, Andhra Pradesh, India (latitude 18°N). Sowing dates, climatological details, and descriptions of soil type are recorded. The location is ideal for characterizing medium-maturing genotypes. However, because early- and late-maturing accessions do not express their full potential at this location, in addition to ICRISAT Center, early-maturing accesions are characterized at Hisar, Haryana, India (29°N) and late-maturing accessions at Gwalior, Madhya Pradesh, India (26°N).

At ICRISAT Center, characterization is carried out on Vertisols (black soils), classified as fine montmorillonitic, isohyperthermic, Typic, Pellustert (Swindale, 1982).

Characterization is done in precision fields under adequate cultural conditions and insecticide protection. Seeds are sown by hand in holes spaced 50 cm apart on ridges 75 cm apart. Two to three seeds are sown per hole and the stand is reduced to one plant per hole by thinning. Reference cultivars of matching maturity are grown at regular intervals (Table 3.3).

For each accession 40 morphoagronomic traits are recorded, of which 22 are entered in the computer-based catalogue (Table 4.3). The characterization data are recorded from unreplicated plots which are subject to a variety of environmental factors. Therefore, the quantitative traits, particularly yield, harvest index, shelling ratio, etc., are no more than rough indicators of the genetic potential. However, such data are generally useful if compared with the nearest control of similar maturity.

Table 4.3 details the various descriptors and descriptor states used in the characterization. Elaboration of these are given in the ICRISAT Pigeonpea Germplasm Catalog (Remanandan *et al.*, 1988a) and Pigeonpea Descriptors (IBPGR/ICRISAT, 1981). Salient features of the more important characteristics in pigeonpea improvement are highlighted below.

Days to 50% Flowering

This term refers to the number of days from the effective date of sowing to the date when 50% of the plants in a given plot have at least one open flower. This is directly related to the days to maturity of the accession. A wide range of duration to maturity exists in pigeonpea and is very important in the adaptation of cultivars to various agroclimatic areas and cropping systems. Pigeonpea breeders at ICRISAT have developed a scale of maturity groups with reference cultivars for each group (see Table 3.3).

As mentioned earlier, pigeonpea is a quantitative short-day plant, and genotypes within a maturity class vary in their duration depending on the sowing date, latitude and altitude, and the climatic and other environmental conditions of a given location (Sharma *et al.*, 1981). The data are summarized in Figure 4.1 and Table 4.8.

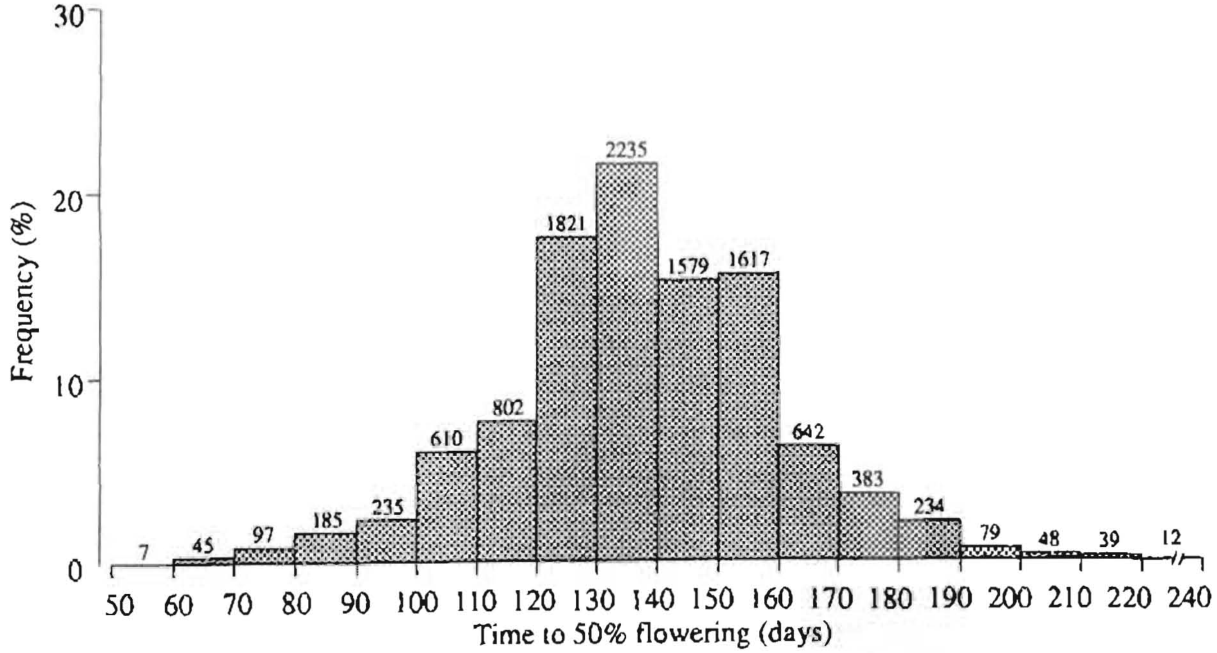


Figure 4.1. Frequency distribution for time to 50% flowering (days).
Figures on top of bars indicate number of gene bank accessions in that class interval.

Table 4.3. Characterization descriptors and descriptor states used in ICRISAT Pigeonpea Germplasm Catalog.

Descriptor[1]	Descriptor states	Descriptor[1]	Descriptor states
1. Days to 50% flowering	Number of days	13. Pod colour	DP = Dark purple
[FLOW50%]		[PDBASCOL]	G = Green
2. Days to 75% maturity	Number of days		M = Mixed, green and purple
[MATURITY]			P = Purple
3. Base flower colour	I = Ivory	14. Number of seeds pod^{-1}	Count (number)
[BASFLCOL]	LY = Light yellow	[SEEDNR]	
	OY = Orange yellow	15. Seed colour pattern	M = Mottled
	Y = Yellow	[SEEDPATT]	MS = Mottled and speckled
4. Second flower colour	NO = None		P = Plain
[SECFLCOL]	Pu = Purple		R = Ringed
	R = Red		S = Speckled
5. Pattern of streaks	DS = Dense streaks	16. Base colour of seed	B = Brown
[STRKPATT]	FS = Few streaks	[SBASCOL]	BL = Black
	MS = Medium amount of streaks		C = Cream
	NO = None		DB = Dark brown
	P = Plain, uniform coverage		DG = Dark grey
6. Flowering pattern	DT = Determinate		DP = Dark purple
[FLOWPATT]	NDT= Indeterminate		G = Grey
	SDT = Semi-determinate		LB = Light brown
7. Growth habit	C = Compact		LC = Light cream
[GROWHAB]	S = Spreading		LG = Light grey
	SS = Semi-spreading		O = Orange
8. Plant height at maturity	Measurement (cm)		P = Purple
[PLHTMAT]			RB = Reddish-brown
			W = White

Table 4.3. continued

Descriptor[1]	Descriptor states	Descriptor[1]	Descriptor states
9. Number of primary branches [NRPRBR]	Count (number)	17. Seed shape [SEEDSHPE]	E = Elongate O = Oval P = Pea S = Square
10. Number of secondary branches [NRSECBR]	Count (number)	18. Seed mass [SEEDWT]	100-seed mass (g)
11. Stem colour [STEMCOL]	D = Dark purple G = Green P = Purple R = Sun red	19. Harvest index [HI]	Grain yield:biological yield ratio (%)
		20. Shelling ratio [SHRAT]	Dry seed:pod ratio (%)
12. Number of racemes [RACEMNR]	Count (number)	21. Protein percentage [PROTEIN]	Proportion of protein in whole seed (%)
		22. Yield per plant [YLDPERPT]	Grain yield (g)

[1] To measure descriptors 3, 4, 5, 6, 7, 11, 13, 15, 16, and 17 (qualitative traits) the whole plot is considered; descriptors 1, 2, 8, 9, 10, 12, 14, 18, 19, 20, 21, and 22 are recorded from three randomly chosen plants.

In addition to the above the following descriptors are also recorded; being of less-immediate utility, these are not yet entered in the computer-based catalogue.

Vigour at 50% flowering (visually scored)
Days to flower initiation
Duration of flowering (days)
Leaf colour
Leaf size (cm)
Leaf shape
Leaf texture
Number of tertiary branches
Raceme length (cm)
Stem thickness (visually scored)
Pod length (cm)
Pod form
Pod texture
Seed second colour
Seed eye colour
Eye colour width (visually recorded)
Presence of hilum
Plant stand (number)

Source: Remanandan *et al.*, 1988.

Days to 75% Maturity

This refers to the number of days taken by 75% of the plants in a given plot to reach maturity. A plant is considered to have reached maturity when about 75% of its pods are dry. Days to 75% maturity is a difficult character to determine accurately, and is highly influenced by such environmental factors as soil moisture and temperature.

Flowering Pattern

Most traditionally grown pigeonpeas have an indeterminate flowering habit (Table 4.4). The inflorescences develop as axillary racemes from all over the branches, and flowering proceeds acropetally from base to apex, both within the racemes and on the branches. The flowering period is often prolonged enabling the plant to recover from various stresses such as terminal drought, insect attack, etc. to which the pigeonpea plant is exposed.

Table 4.4. Distribution of pigeonpea flowering pattern, ICRISAT Center, 1974-1978.

Code	Flowering pattern	Number of accessions	Frequency (%)
DT	Determinate	341	3.19
NDT	Indeterminate	10 220	95.81
SDT	Semi-determinate	105	0.98

Some genotypes are morphologically determinate; i.e., the apical buds of the main shoots develop into inflorescences. In these genotypes the sequence of inflorescence production is basipetal.

There are genotypes intermediate between the two types described above, these are semi-determinate. In semi-determinate genotypes flowering starts at nodes below the apex and proceeds both acropetally and basipetally.

Most of the determinate genotypes have been genetically improved and are the products of breeding programmes. They are generally short in stature and bear clusters of pods more or less at the same height, at the top of the plant canopy, that mature at the same time. Hence, they are easier to spray and mechanically harvest. However, they are prone to severe insect attacks and therefore have a definite disadvantage when they are not heavily protected by insecticides (ICRISAT, 1976). The determinate habit confers no advantage in yield, or in the partitioning of dry matter into seeds (ICRISAT, 1980).

Growth Habit

Pigeonpea cultivars differ markedly in growth habit and plant canopy characteristics. The growth habit mainly depends upon the numbers of primary and secondary branches, and the angle of branches on the stem on which they are borne – resulting in a continuous variety of forms, from upright compact to spreading types. Plant habit is an important factor that influences optimum plant population, which varies from 6000 to over 300,000 plants ha^{-1} (Abrams and Julia, 1973; Ariyanayagam, 1975; Saxena and Yadav, 1975). This character is also of critical importance in various intercrop situations.

Pigeonpea accessions are classified into three categories of growth habit (Table 4.5).

Compact	Accessions generally have few branches, borne at narrow angles to the stem, resulting in a compact plant habit.
Spreading	Accessions usually have many branches, resulting in a broad plant canopy. Such types are often preferred in some intercropping situations where they will cover the area vacated by a companion crop. However, they often fail to make optimum use of solar radiation.
Semi-spreading	Most accessions belong to this group, which is intermediate between the above two types.

Since landraces are not pure lines, there are often variations among individual plants in an accession. For example, some accessions have both compact and semi-spreading plants.

Table 4.5. Distribution of pigeonpea growth habit, ICRISAT Center, 1974-1978.

Code[1]	Number of accessions	Frequency (%)
C	1 291	12.10
C+SS	16	0.14
S	244	2.28
S+SS	1	0.01
SS	9 097	85.27
SS+C	19	0.17

1. C=Compact, S=Spreading, SS=Semi-spreading.

Plant Height at Maturity

This trait is related to maturity, photoperiod sensitivity, and environment, and has low heritability (Sharma, 1981). Long-duration pigeonpeas are generally tall because of their prolonged vegetative phase. However, their height will be substantially reduced if they are forced to flower early by photoinduction. Similarly, short-duration pigeonpeas are comparatively short in stature because of their short vegetative phase. Their height can be increased by prolongation of the vegetative phase if they are exposed to long-day conditions. Thus, this character varies according to location and time of sowing. But there are genetic dwarfs which retain their dwarfness when grown over a wide range of environments. The classification presented here (Figure 4.2 and Table 4.8) is based on measurements taken from June/July sowings at ICRISAT Center.

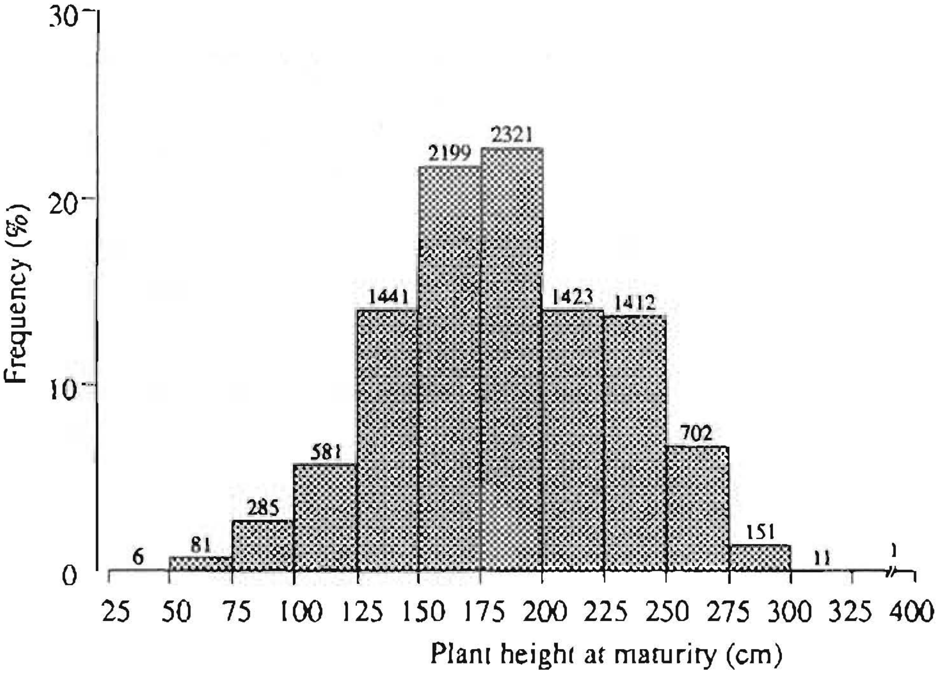


Figure 4.2. Frequency distribution for plant height at maturity (cm).
Figures on top of bars indicate number of gene bank accessions in that class interval.

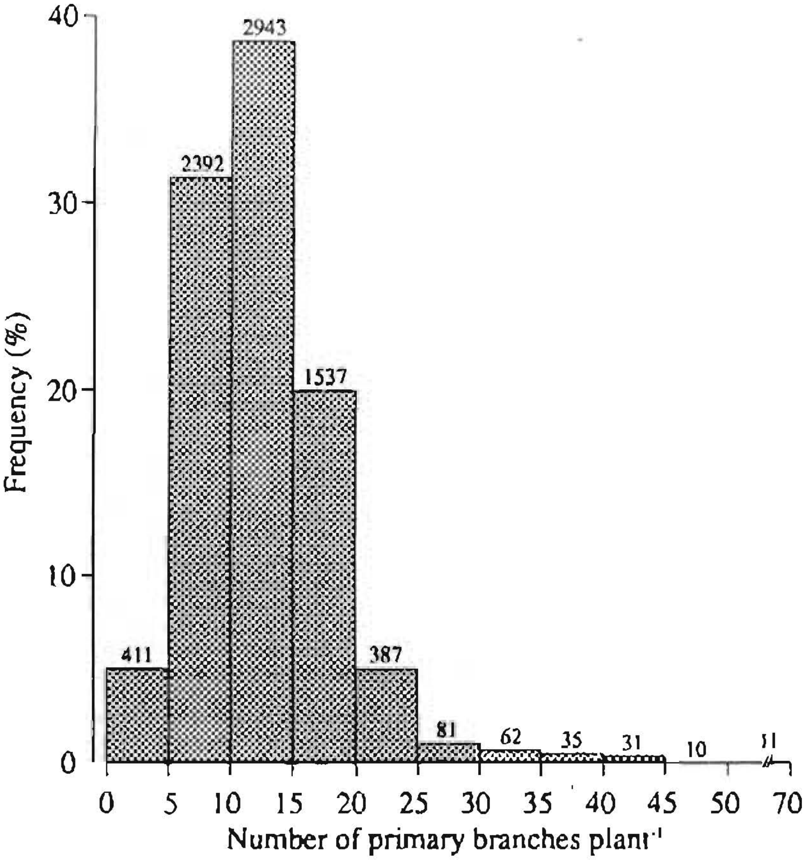


Figure 4.3. Frequency distribution of number of primary branches plant^{-1}.
Figures on top of bars indicate number of gene bank accessions in that class interval.

Number of Primary Branches

This trait is highly heritable (Govinda Raju and Sharat Chandra, 1972) and has a highly positive correlation with yield (Beohar and Nigam, 1972). It is strongly correlated with other yield components such as the numbers of secondary branches and racemes (Remanandan *et al.*, 1988a). The data are summarized in Figure 4.3 and Table 4.8.

Number of Secondary Branches

This refers to the total number of branches borne on all the primary branches. More secondary branches occur on the primary branches of plants with a spreading habit, than on compact or semi-spreading types. A high degree of plant spread is regarded as an effective attribute to grain yield (Dasappa and Mahadevappa, 1970). Most of the profusely branching accessions belong to medium to mid-late maturity groups.

In all cultivars, branching is greatly reduced in dense plantings and in intercropping systems where pigeonpeas are shaded by companion crops (Sheldrake, 1984).

The data on this trait are summarized in Figure 4.4 and Table 4.8.

Number of Racemes

Pigeonpea produces many flowers, of which about 90% are shed without setting pods (Pathak, 1970; Ariyanayagam, 1975; Sheldrake *et al.*, 1979; Tayo, 1980; Pandey and Singh, 1981). Therefore, the number of flowers produced cannot be regarded as a major yield component. The data on this trait are summarized in Figure 4.5 and Table 4.8. In general, medium to mid-late maturing cultivars produce large numbers of racemes.

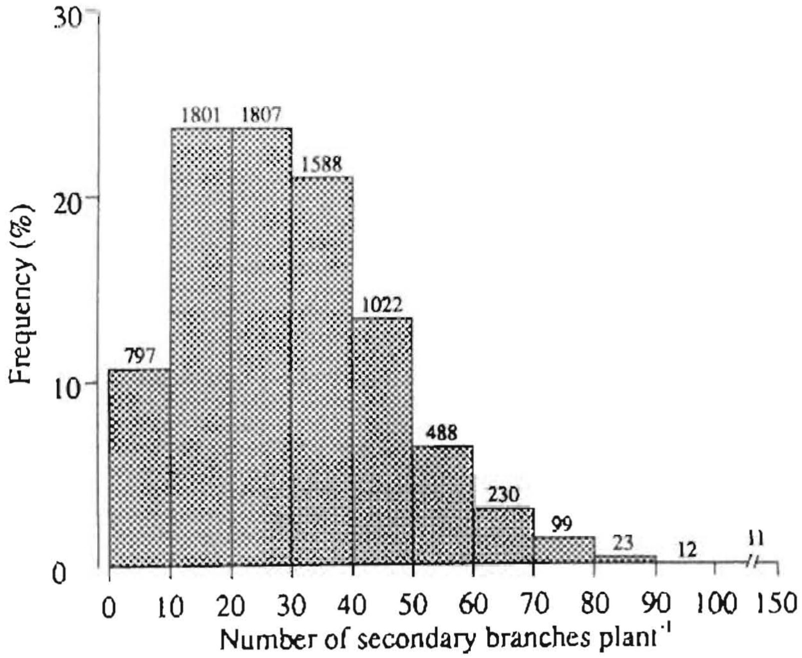


Figure 4.4. Frequency distribution for number of secondary branches plant^{-1}. Figures on top of bars indicate number of gene bank accessions in that class interval.

During flowering, pigeonpea is attacked by many insects and the plant has the inherent ability to compensate at least partially for the resulting loss of flowers by producing more. However, there are strong genotypic differences for this trait.

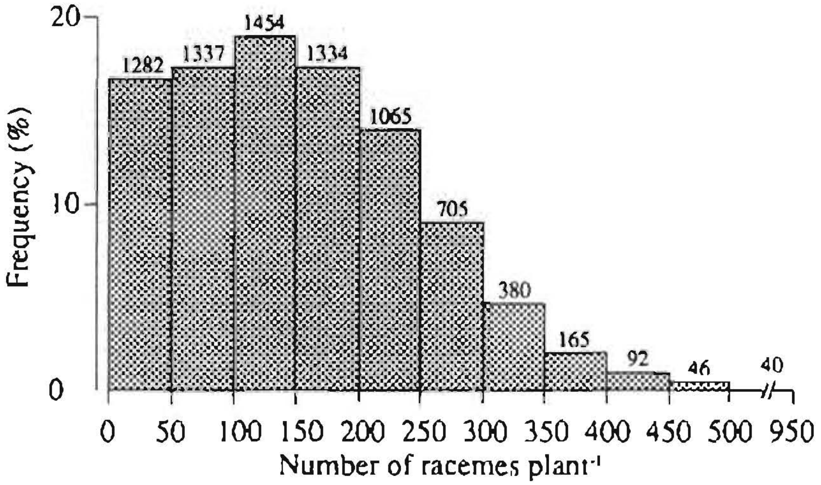


Figure 4.5. Frequency distribution for number of racemes plant^{-1}.
Figures on top of bars indicate number of gene bank accessions in that class interval.

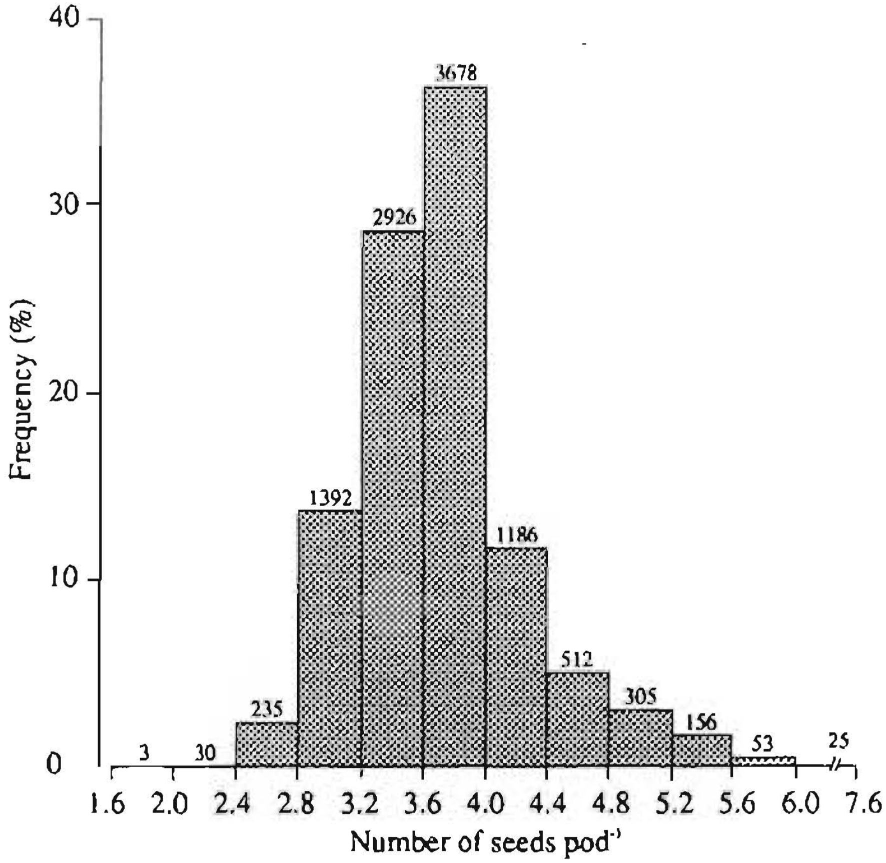


Figure 4.6. Frequency distribution for number of seeds pod^{-1}.
Figures on top of bars indicate number of gene bank accessions in that class interval.

Number of Seeds per Pod

Although there are large variations between genotypes in seed number per pod and also in seed size, these are remarkably constant within a given genotype (Sheldrake, 1984). The number of seeds per pod is considered an important yield component (ICRISAT, 1975). However, genotypes that produce as many as seven seeds per pod have a reduced ability to fill their seeds.

In regions where pigeonpea is used as a vegetable, there is a strong consumer preference for cultivars with many seeds per pod. The distribution of this trait is presented in Figure 4.6 and Table 4.8.

Base Colour of Seed

Base colour refers to the main colour of the seed coat. Over 50% of pigeonpeas have orange seed coats. Various shades of red and brown are predominant, and that is why pigeonpea is known as red gram in India. The seed-coat colour does not affect the colour of the dhal (dry, split, decorticated seeds). However, for some reason cultivars with light seed-coat colour are preferred even in areas where pigeonpea is mainly consumed as dhal. In areas where the undecorticated dry seeds or green peas are cooked whole, the consumer preference for light-coloured or white seeds is fairly strong. The light-coloured seeds, are generally bright green at the pod-filling stage and hence this trait is an advantage in vegetable-type pigeonpeas. In the Caribbean Islands, vegetable types with broad pods (Figure 4.7) containing many green seeds are popular because they are conveniently easy to shell.

Seed Shape

The most common shape is oval. The other shapes are elongate, pea (globular), and square. The pea-shaped trait is preferred where pigeonpea is used as a green vegetable, but this trait is rare in early-maturing types.

Seed Mass

Seed mass (weight) is an important yield component (ICRISAT, 1975). Cultivars vary widely in this trait. Large-seeded types are generally poor pod setters. Most large-seeded types belong to late-maturing groups. Large seeds are preferred by consumers (Gupta *et al.*, 1981) possibly because the pericarp percentage reduces with increase in seed size (ICRISAT, 1975). For vegetable-type pigeonpeas, large pods with large seeds are strongly preferred (Figure 4.7) and pods are harvested before they reach physiological maturity. Data on seed mass are summarized in Figure 4.8 and Table 4.8.

Seedlings from large seeds (100-seed mass about 16 g) are usually larger and often grow faster than seedlings from small seeds. However, there is no significant effect of seed-grading within a genotype on yield (ICRISAT, 1976).

Harvest Index

The harvest index of pigeonpeas grown in traditional cropping systems is generally low (Sheldrake, 1984). Because it is strongly influenced by environmental conditions, harvest index alone is not a dependable selection criterion. It varies markedly under different cropping systems, spacing, growing seasons, and availability of moisture. Nevertheless, repeated evaluations in different agroclimatic regions have helped to identify accessions in landraces with comparatively high harvest indexes (Figure 4.9). The data on harvest index are summarized in Figure 4.10 and Table 4.8.

Shelling Ratio

Shelling ratio refers to the seed:pod ratio, expressed as a percentage based on mass, taken after harvesting and drying. Shelling ratio data are summarized in Figure 4.11 and Table 4.8. In general, when evaluated at ICRISAT Center, early-maturing and late-maturing accessions have low shelling ratios compared to medium to mid-late maturing types.

Figure 4.7. Broad pods that are an advantage in 'vegetable type' pigeonpea since they are easy to shell.
Photo: ICRISAT.

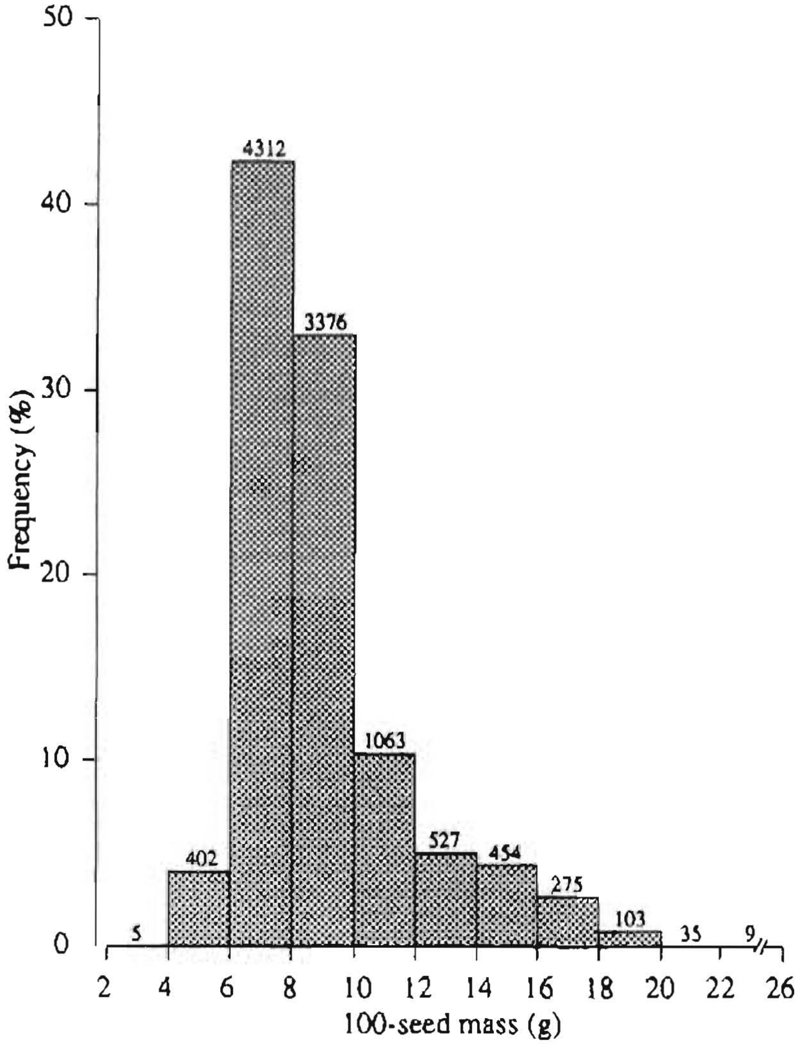


Figure 4.8. Frequency distribution for 100-seed mass (g).
Figures on top of bars indicate number of gene bank accessions in that class interval.

Protein Percentage

Analysis of the world collection for the percentage of protein in mature whole seed has revealed that there are genotypic differences in this trait (Figure 4.12 and Table 4.8). This analysis has identified many sources of high seed protein useful in improving the nutritional quality of pigeonpeas. In recent years, pigeonpea has become increasingly important in agroindustries to meet the protein/calorie requirement of poultry and animal feed, especially in regions where the cultivation of soybean is not successful.

Some of the closely related wild species have still higher percentages of seed protein (up to 33%). This trait has already been successfully transferred to pigeonpea and stable lines with high seed protein are now available at ICRISAT Center (ICRISAT, 1984).

Figure 4.9. An elite accession with a high harvest index identified during evaluation trials at Katumani, Kenya.
Photo: ICRISAT.

CORRELATION MATRIX OF CHARACTERS

A correlation matrix of 12 agronomically important traits is given in Table 4.6.

The relationship of yield components to seed yield and amongst themselves is a subject of great interest to the plant breeder. The correlation matrix aids the effective querying of the database, and helps to select accessions with a desired combination of traits from the collection. When requesting germplasm with a specific trait, users can also acquire an indication of the other traits likely to be associated with the one under consideration.

There has been considerable work on this subject using a limited number of genotypes. However, for the first time a large (8582 accessions) and diverse collection has recently been subjected to this analysis and the results and discussions of them presented (Remanandan *et al.*, 1988a). It was concluded that the numbers of primary branches, secondary branches, and racemes are prime contributors to seed yield, although plant height contributes significantly by increasing all these traits, which are themselves positively correlated.

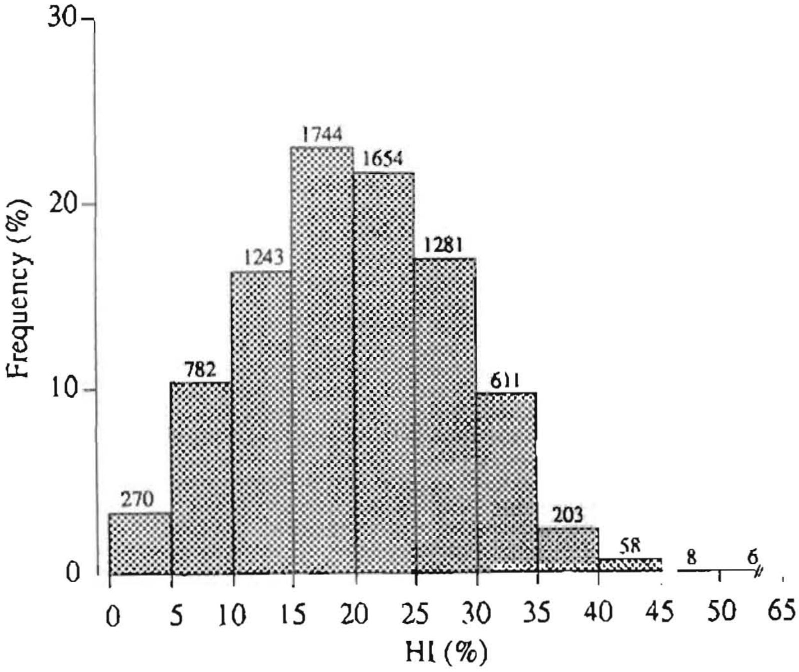


Figure 4.10. Frequency distribution for harvest index (HI) (%).
Figures on top of bars indicate number of gene bank accessions in that class interval.

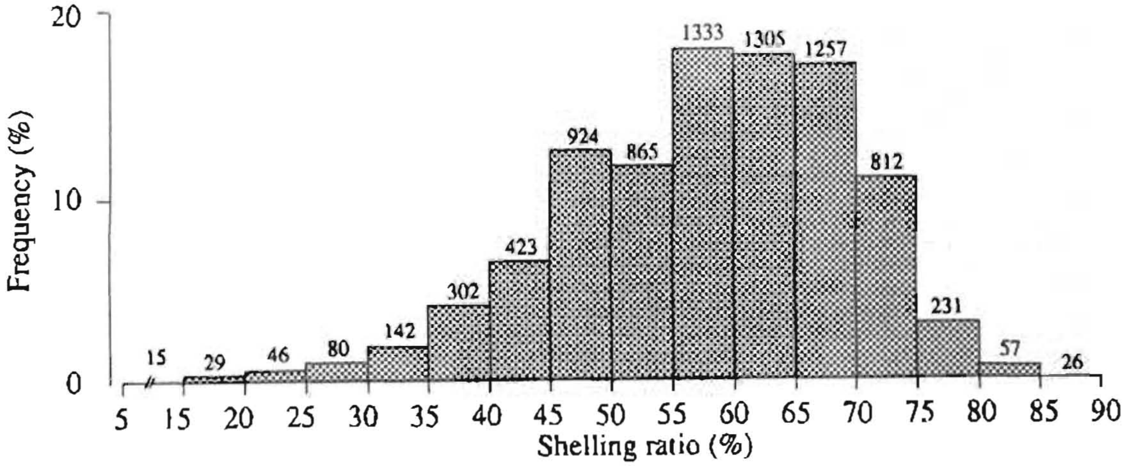


Figure 4.11. Frequency distribution for shelling ratio (%).
Figures on top of bars indicate number of gene bank accessions in that class interval.

Table 4.6. Correlation matrix of the important agronomic characters of 10 670 pigeonpea accessions evaluated from 1975/76 to 1987/88 at ICRISAT Center.

	FLOW 50%	MATU RITY	PLHT MAT	NRPR BR	NRSEC BR	RACEM NR	SEED NR	SEED WT	HI	SH RAT	PRO TEIN
MATURITY[1]	**0.91**[2]										
PLHTMAT	**0.41**	**0.40**									
NRPRBR	−0.20	−0.16	0.17								
NRSECBR	−0.08	−0.08	0.19	**0.47**							
RACEMNR	−0.28	−0.23	0.09	**0.42**	**0.70**						
SEEDNR	0.22	0.17	0.26	−0.21	−0.27	−0.25					
SEEDWT	**0.40**	**0.37**	**0.31**	−0.26	**−0.41**	**−0.50**	**0.50**				
HI	**−0.53**	**−0.55**	**−0.41**	0.05	0.15	**0.38**	−0.23	**−0.42**			
SHRAT	**−0.39**	**−0.45**	0.00	0.21	0.24	0.29	−0.09	−0.21	**0.63**		
PROTEIN	0.14	0.20	0.01	−0.08	0.01	−0.04	−0.17	−0.14	−0.10	−0.17	
YLDPERPT	**−0.30**	−0.29	0.12	**0.37**	**0.59**	**0.79**	−0.09	**−0.31**	**0.50**	**0.45**	−0.19

1. See Table 4.3 for descriptor details.
2. Values of ±0.3 or more are indicated in bold face. Significant value at 1% is 0.155.

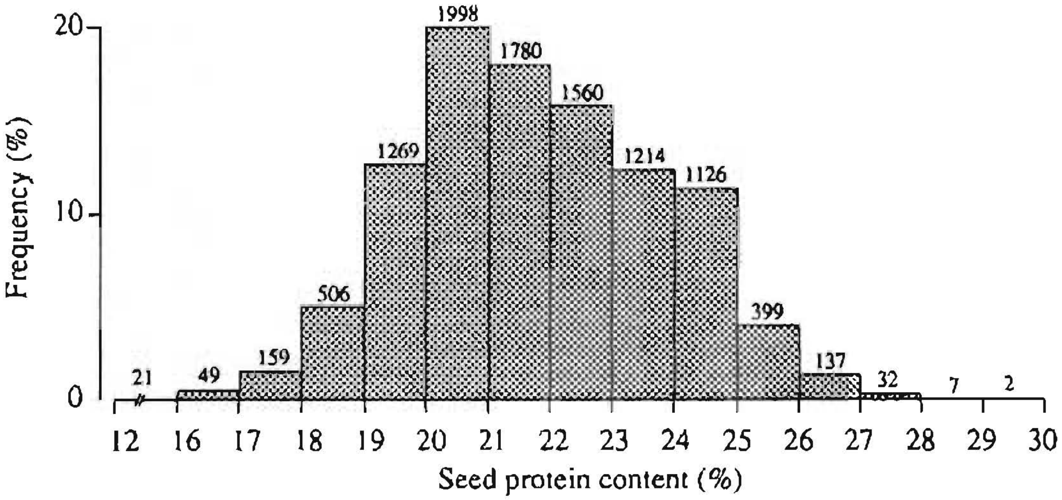


Figure 4.12. Frequency distribution for seed protein content (%).
Figures on top of bars indicate number of gene bank accessions in that class interval.

WILD SPECIES

Pigeonpea belongs to the genus *Cajanus* of the subtribe Cajaninae. *Cajanus cajanifolius* is the most probable progenitor of pigeonpea. Many species of *Cajanus* readily cross with pigeonpea. Introgressed and backcrossed progenies of the following *Cajanus* species with various elite pigeonpea parents are now held in the collection at ICRISAT:

Cajanus acutifolius
C. albicans
C. cajanifolius
C. confertiflorus
C. lanceolatus
C. latisepalus
C. lineatus
C. reticulatus var. *reticulatus*
C. scarabaeoides var. *scarabaeoides*
C. sericeus
C. trinervius

The present collection of wild relatives consists of 270 accessions of 47 species belonging to six genera (Figure 4.13 and Table 4.7). Evaluation of the secondary gene pool of pigeonpea has resulted in the identification of several desirable traits such as resistance to diseases and pests, and superior nutritional qualities (Remanandan, 1981). The wild relatives have also been evaluated for a few important traits and have been subjected to screening against diseases and pests. *Cajanus albicans*, *C. lineatus*, *C. sericeus*, and *C. crassus* var. *crassus* are resistant to sterility mosaic (SM). *Cajanus platycarpus* is resistant to phytophthora blight *(Phytophthora drechsleri* f.sp. *cajani)* and it flowers in 48 days. *Cajanus sericeus* is resistant to both blight and SM. A remarkable trait of these wild species is that most of them have a high seed protein percentage (Remanandan, 1981). The maximum recorded is 33.4% for *C. mollis*, while the mean seed protein percentage in pigeonpea is 21.8%. The list of wild species in the present collection is given in Table 4.7 and includes some species that are not readily crossable with *Cajanus*.

Figure 4.13. Wild relatives of pigeonpea: a. *Cajanus cinereus*; and b. *Rhynchosia malacophylla*.
Photo: ICRISAT.

Table 4.7. List of wild species related to pigeonpea conserved in the ICRISAT gene bank.

Species	Number of accessions
Cajanus acutifolius (F. von Muell.) van der Maesen	12
Cajanus albicans (W. & A.) van der Maesen	15
Cajanus cajanifolius (Haines) van der Maesen	4
Cajanus cinereus (F. von Muell.) F. von Muell.	5
Cajanus confertiflorus F. von Muell	1
Cajanus crassus (Prain ex King) van der Maesen var. *crassus*	10
Cajanus goensis Dalz.	1
Cajanus lanceolatus (W.V. Fitzg.) van der Maesen	1
Cajanus latisepalus (Reynolds & Pedley) van der Maesen	1
Cajanus lineatus (W. & A.) van der Maesen	10
Cajanus marmoratus (R. Br. ex Benth.) F. von Muell.	2
Cajanus mollis (Benth.) van der Maesen	8
Cajanus platycarpus (Benth.) van der Maesen	13
Cajanus reticulatus var. *grandifolius* (F. von Muell.) van der Maesen	5
Cajanus reticulatus (Dryander) F. von Muell. var. *grandifolius* (F. von Muell.) van der Maesen	5
Cajanus reticulatus (Dryander) F. von Muell. var *reticulatus*	3
Cajanus rugosus (W. & A.) van der Maesen	5
Cajanus scarabaeoides (L.) Thouars var. *scarabaeoides*	77
Cajanus sericeus (Benth. ex Bak.) van der Maesen	4
Cajanus trinervius (DC.) van der Maesen	3
Dunbaria ferruginea W. & A.	7
Dunbaria heynei W. & A.	5
Eriosema glomeratum (Fuill & Pen.) Hook F.	1
Eriosema sporaleoides (Lam.) G. Don	2
Flemingia bracteata (Roxb.) Wight	2
Flemingia macrophylla (Willd.) Prain. ex Merrill	6
Flemingia nana Roxb.	1
Flemingia paniculata Wall. ex Benth.	1
Flemingia semialata Roxb.	1
Flemingia stricta Roxb.	1
Flemingia strobilifera (L.) Aiton	3
Paracalyx scariosa (Roxb.) Ali	2
Rhynchosia aurea DC.	6
Rhynchosia bracteata Benth. ex Bak.	3
Rhynchosia cana DC.	5
Rhynchosia densiflora DC.	4
Rhynchosia filipes Benth. ex Bak.	2
Rhynchosia heynei W. & A.	1
Rhynchosia himalensis Benth. ex Bak.	1
Rhynchosia hirta (Andr.) Meikle & Verdc.	3
Rhynchosia malacophylla (Spreng.) Boj.	1
Rhynchosia minima DC.	15
Rhynchosia rothii Benth. ex Aitch.	10
Rhynchosia rufescens DC.	5
Rhynchosia suaveolens DC.	2
Rhynchosia sublobata (Schumach.) Meikle	2
Rhynchosia venulosa (Hiern) Schum.	1
Rhynchosia viscosa DC.	1
Total	270

DOCUMENTATION

Passport information and characterization data of the world collection of pigeonpea have been documented and computerized using descriptors and descriptor states jointly developed by

ICRISAT and the International Board for Plant Genetic Resources (IBPGR) in consultation with crop scientists (IBPGR/ICRISAT, 1981). The passport information consists of accession identifiers, information on origin, and other data recorded by collectors. Characterization data includes 40 descriptors on morpho-agronomic traits, of which 22 are entered in the computer-based catalogue. A computer programme, ICRISAT Data Management and Retrieval System (IDMRS) programmed in the VAX-11 BASIC programming language under the VMS operating system on a VAX-11/780 computer system is used at ICRISAT to store and retrieve data. This serves as a live catalogue which is frequently revised and updated as new information becomes available. IDMRS is an integrated set of procedures that can record, store, process, and retrieve information. The system allows data entry and editing, printing the entire or specific required descriptors, retrieving information on a few selected descriptors, retrieving information on a desired set of accessions (either with all the data on these accessions, or with information on only a few descriptors), and retrieving information on the number of accessions belonging to a particular class (Estes and Ramanatha Rao, 1989). It also facilitates manipulation of the stored data for statistical analysis to examine patterns of variation.

To store and retrieve data on seed distribution a dBase III programme on microcomputers is used. This facilitates keeping track of the distribution of germplasm within and outside ICRISAT, and is also used to follow up the utilization of distributed germplasm. The same system is used to store and retrieve data on seed viability.

GERMPLASM CATALOGUE

Genetic resources cannot be effectively used if the information needed by crop improvement programmes cannot be readily supplied. Although the live catalogue maintained in the main-frame computer at ICRISAT Center contains easily retrievable information, its physical availability does not stretch beyond ICRISAT Center. The utility of the stored information largely depends upon its accessability to germplasm users all over the world. To achieve this, ICRISAT recently published and distributed the Pigeonpea Germplasm Catalog in two parts: Evaluation and Analysis, and Passport Information (Remanandan *et al.*, 1988 a, b). In this catalogue, an attempt has been made to classify the world collection into a number of natural and artificial groups together with several short lists of accessions that have frequently required combinations of morpho-agronomic traits.

WORKING COLLECTION

To utilize the germplasm effectively an attempt has been made to classify the world collection according to several criteria. These include; phenology, flowering pattern, growth habit, pod and seed characteristics, quality traits, resistance to diseases and pests, and origin from diverse ecological zones. These are well-defined groups that contain few or many desirable traits. This led to the constitution of a working collection of a limited number of accessions that contain most of the genetic diversity available in the entire collection.

The working collection includes widely used landraces, released cultivars, lines developed at ICRISAT, disease-resistant accessions, insect-tolerant accessions, partially day-neutral genotypes, accessions originating from arid areas, acid soils, and high altitudes, accessions with specific traits (e.g., determinate flowering habit) or a combination of traits (e.g., mid-late maturing, determinate with large and white seed). In addition, there are gene pools composed of several landraces.

Multilocational evaluations carried out in different regions have resulted in the identification of several elite accessions. Analysis of such experiments along with agroclimatological considerations of the sites has helped to improve the predictive value of the performance of a given accession at a specific agroclimatic region or location. Some of the elite lines identified during evaluation in Kenya were found to perform well in Venezuela (Figure 4.14). The working collection includes several such accessions.

Other important constituents of the working collection are genetic stocks with such unique traits such as dwarfs, markers (Figure 4.15), modified determinate flowering, modified flowers (cleistogamous and/or wrapped flowers), mutants, and genetic male steriles.

The working collection is maintained at ICRISAT Center as a dynamic unit. Based on the availability of new data this collection is frequently reviewed and reconstituted.

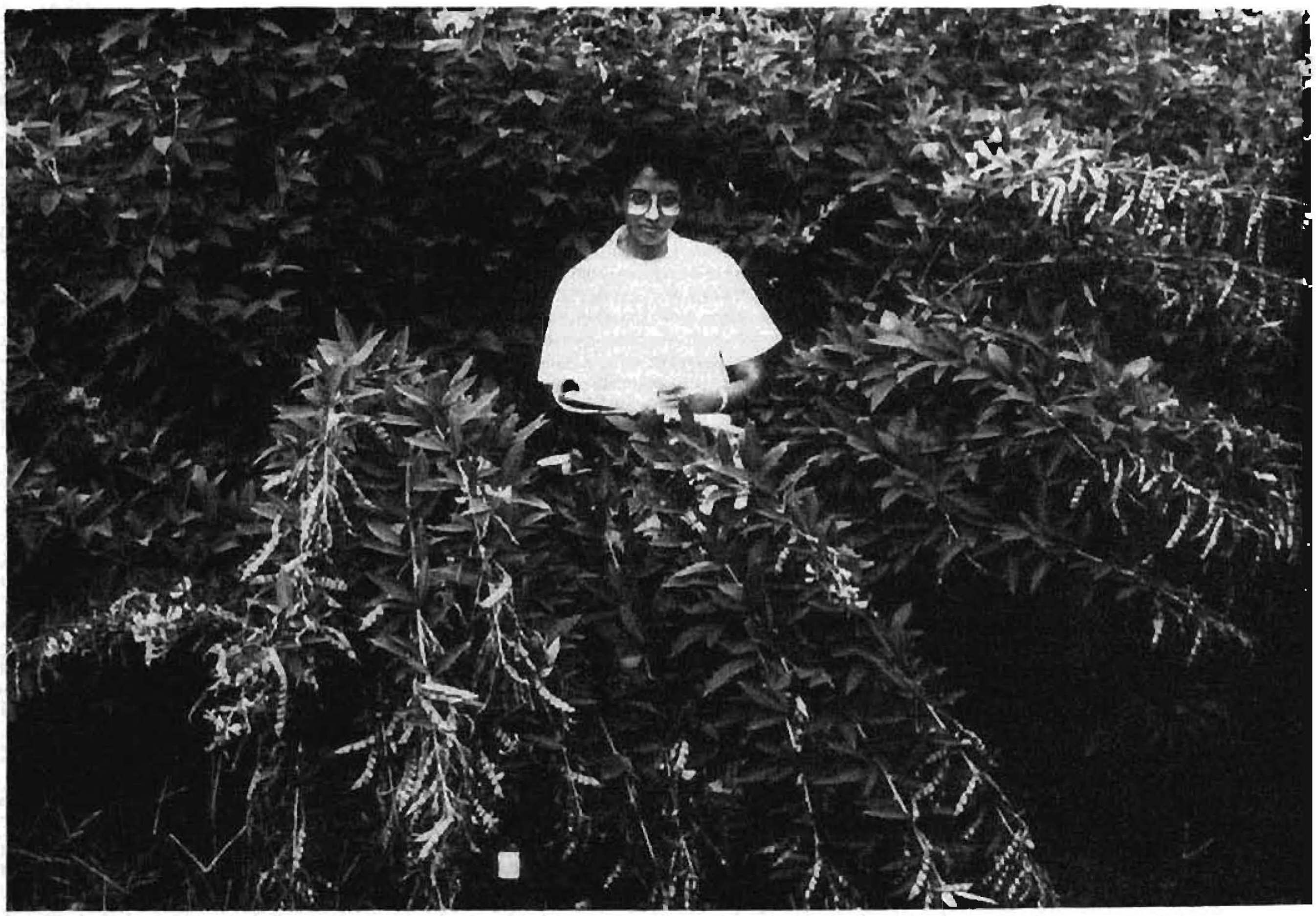


Figure 4.14. An elite pigeonpea line identified during evaluation trials in Kenya that was recently found to be well-adapted to conditions in Venezuela.
Photo: ICRISAT.

EXPLOITATION

The ultimate purpose of genetic resources activities is to support present and future crop improvement work that aims to improve the productivity and quality of crops grown by farmers.

Pigeonpea improvement started in India in the 1920s. Many lines have since been developed and released, mainly through selections from landraces. Since 1972, ICRISAT has made considerable efforts through its multidisciplinary approach to systematically improve pigeonpea and strengthen national programmes by the free flow and exchange of germplasm and elite breeding lines, and information exchange between ICRISAT and national centres. There has been a concerted effort to mobilize, evaluate, and utilize germplasm by employing conventional breeding procedures. Between 1972 and 1989, a total of 54,042 germplasm samples were used by various disciplines within ICRISAT and 33,316 germplasm samples were distributed to institutions in 97 countries.

However, the efforts to improve pigeonpea are yet to result in a substantial increase in total production. While in experimental fields yields over 5.0 t ha^{-1} have been demonstrated, the average yield in farmers' fields in India is only 830 kg ha^{-1} (Government of India, Ministry of Agriculture, 1985). Most of the world's pigeonpea is produced in India, and Indian farmers continue to grow traditional landraces in the majority of the pigeonpea-growing areas. The gap between present-day farm yields and potentially attainable yield is incredibly wide. The reasons for this need to be critically investigated. A major reason has been attributed to the limited use of available germplasm (Ramanujam and Singh, 1981) but this is now being corrected (Lal *et al.*, 1989). Intensive plant breeding leads to a narrowing of the genetic base of a cultivar (de Wet, 1989), so many developed lines do not have stability of yield across years, and have only a narrow range of adaptation. The ability of cultivars to adapt to a wide range of agro-ecosystems thus needs to be strengthened by enlarging their genetic base.

Landraces are endowed with enormous variation created through natural hybridization, mutation, and selection by nature and man. The pigeonpea plant which probably evolved under severe pressure for survival due to various biotic and abiotic stresses, has developed several adaptive measures such as the ability to produce a huge biomass, prolong flowering, and over-produce

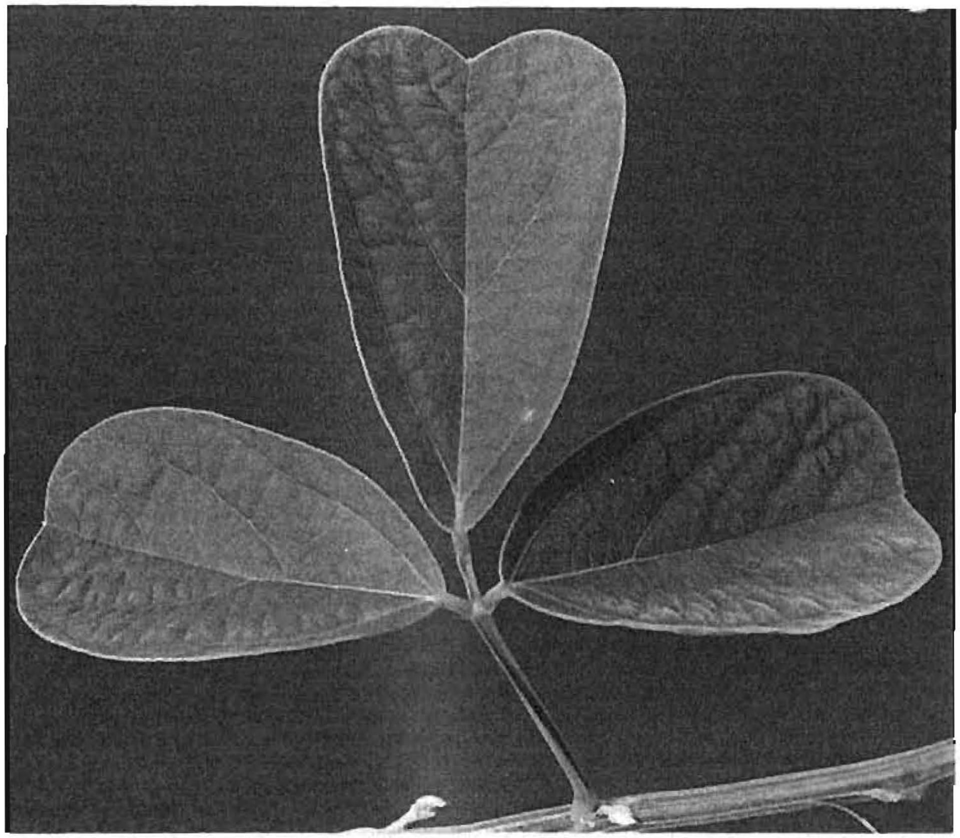


Figure 4.15. Retuse leaflet (recessive over normal) a genetic marker in pigeonpea.
Photo: ICRISAT.

flowers, etc. As a result the present-day pigeonpea landrace is a primitive crop with a low harvest index and perennial habit, but with a wide range of adaptation and survival mechanisms due to its broad genetic base. The plant, therefore, offers tremendous opportunity for genetic improvement.

The potential for improvement certainly exists within the germplasm as evidenced by the yields attained in experimental fields. The contribution of germplasm to crop improvement falls under two major categories: direct use as released cultivars; or as a source for a specific character such as a yield component, resistance to a biotic or abiotic stress, a quality trait, adaptation etc.

Many germplasm accessions have been directly released as cultivars. Almost all the breeding lines and released cultivars are selections from traditional landraces (Chandra *et al.*, 1983). Recently ICP 7035, a field collection from India, was released for cultivation in Fiji. ICP 8863, a wilt (*Fusarium udum*)-resistant selection from ICRISAT, has been released in Karnataka, India, and the Government of Malawi released ICP 9145, a landrace from Kenya.

As source of specific traits, the pigeonpea germplasm offers a wide range of variation (Table 4.8) for practically all yield components, quality traits, and adaptation. This variability needs to be utilized in crop improvement programmes (Paroda, 1989). Genetic male sterility is now available in many converted germplasm lines, and many centres have begun using these in hybrid pigeonpea breeding programmes (Lal *et al.*, 1989). The availability of multiple-disease resistance and insect tolerance can substantially contribute to yield stability.

Characterization, followed by preliminary evaluation and further evaluation by multidisciplinary teams has resulted in the identification of several desirable traits and their pattern of distribution across the germplasm. We now have the world collection classified into well-defined groups with several combinations of desirable traits. Imaginative use of these could result in a breakthrough in pigeonpea improvement.

Table 4.8. Range of variability in the pigeonpea germplasm held in ICRISAT gene bank.

Character	Minimum	Maximum	Number of observations[1]
50% flowering (days)	55.0	237.0	10 670
75% maturity (days)	97.0	299.0	10 649
Plant height (cm)	39.0	385.0	10 614
Primary branches (number)	2.0	66.0	7 900
Secondary branches (number)	0.3	145.3	7 878
Racemes (number)	6.0	915.0	7 900
Seeds pod^{-1} (number)	1.6	7.6	10 501
100-seed mass (g)	2.8	25.8	10 561
Harvest index (%)	0.6	62.7	7 860
Shelling ratio (%)	5.3	87.5	7 847
Seed protein percentage (%)	12.4	29.5	10 259

1. This indicates the number of accessions on which a specific trait has been measured.

FUTURE

The world collection conserved at ICRISAT has a fair representation from the primary and secondary centres of origin and diversification. Gaps in the collection include India, Bangladesh, Indonesia, Myanmar, the Philippines, and Uganda. Wild species from India and Australia need to be secured. Based on new information, pointed collections may be required to secure specific traits.

Characterization and preliminary evaluation of new accessions need to continue, and further evaluation should be organized with multidisciplinary participation. Efforts to identify and purify accessions with less sensitivity to photoperiod need to be further strengthened. Multidisciplinary efforts should be organized to screen germplasm accessions against such complex phenomena as flower drop, and tolerance to abiotic stresses. Based on new data, the distributional pattern of different agronomic traits across the germplasm needs to be re-examined. Constitution of gene pools for specific traits will enhance the utilization of a larger number of accessions. Existing gene pools need to be reviewed, and large gene pools need to be constituted in close collaboration with breeders.

The database has to be expanded, and statistical analysis will continue–resulting in review of the existing classification and the constitution of working collections. The new advancements in microcomputer-based data management systems and the availability of compact disc (CD) technology may allow us to shift our vast germplasm data and its management to microcomputers, thus increasing the availability of a computer-based catalogue to users.

REFERENCES

Abrams, R. (1967) Studies on natural cross pollination in pigeonpeas *(Cajanus cajan). Journal of Agriculture of the University of Puerto Rico* 51, 1-21.

Abrams, R. and Julia, F.J. (1973) Effect of planting time, plant population, and row spacing on yield, and other characteristics of pigeonpeas, *Cajanus cajan* (L.) Millsp. *Journal of Agriculture of the University of Puerto Rico* 57, 275-285.

Ariyanayagam, R.P. (1975) Status of research on pigeonpeas in Trinidad. In: *International Workshop on Grain Legumes, 13-16 January 1975, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 131-139.

Ariyanayagam, R.P. (1976) Outcrossing and isolation in pigeonpeas. *Tropical Grain Legume Bulletin* 5, 14-17.

Beohar, A.R.L. and Nigam, P.K. (1972) Correlation studies in arhar, *Cajanus cajan* (L.) Millsp. *JNKVV Research Journal* 6, 58.

Chandra, S., Asthana, A.N., Ali, M., Sachan, J.N., Lal, S.S., Singh, R.A. and Gangal, L.K. (1983) *Pigeonpea Cultivation in India–A Package of Practices.* Project Directorate Pulses, Kanpur, India, 41 pp.

Chang, T.T. (1976) *Manual on Genetic Conservation of Rice Germplasm for Evaluation and Utilization.* International Rice Research Institute, Los Baños, Philippines, 77 pp.

Dasappa and Mahadevappa, M. (1970) Investigations on grain yield and related characters of some tur varieties. *Mysore Journal of Agricultural Science* 4, 212-215.

Deshmukh, N.Y. and Rekhi, S.S. (1963) Study of natural cross-pollination in pigeonpea (*Cajanus cajan* (L.) Millsp.). *Proceedings of the Bihar Academy of Agricultural Sciences* 8-9, 135-139.

de Wet, J.M.J. (1989) Inaugural address. In: *Collaboration on Genetic Resources: Summary Proceedings of a Joint ICRISAT/NBPGR (ICAR) Workshop on Germplasm Exploration and Evaluation in India, 14-15 November 1988, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 5-6.

Estes, J.W. and Ramanatha Rao, V. (1989) Computerized documentation and retrieval systems for genetic resources work at ICRISAT — present and future. In: *Collaboration on Genetic Resources: Summary Proceedings of a Joint ICRISAT/NBPGR (ICAR) Workshop on Germplasm Exploration and Evaluation in India, 14-15 November 1988, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 71-74.

Government of India (Ministry of Agriculture) (1985) *Bulletin on Food Statistics.* Directorate of Economics and Statistics, Ministry of Agriculture, Government of India, New Delhi, India.

Govinda Raju, D.R. and Sharat Chandra, H.C. (1972) Studies on variability in tur. *Andhra Agricultural Journal* 9 (5-6), 155-156.

Gupta, S.C., Saxena, K.B. and Sharma, D. (1981). Inheritance of days to flower and of seed size in pigeonpea. In: *Proceedings of the International Workshop on Pigeonpeas, volume 2, 15-19 December 1980, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 61-66.

Howard, A., Howard, G.L.C and Khan, A.R. (1919) Studies in the pollination of Indian crops–I. *Memoirs of the Department of Agriculture in India, Botanical Series* 10, 195-200.

IBPGR/ICRISAT (1981) *Descriptors for Pigeonpea.* International Board for Plant Genetic Resources (IBPGR) Secretariat, Rome, 15 pp.

ICRISAT (1975) *Annual Report 1974-75.* Patancheru, A.P., India: ICRISAT, p. 40.

ICRISAT (1976) *Annual Report 1975-76.* Patancheru, A.P., India: ICRISAT, pp. 101-105.

ICRISAT (1980) *Annual Report 1978-79.* Patancheru, A.P., India: ICRISAT, p. 95.

ICRISAT (1984) *Annual Report 1983.* Patancheru, A.P., India: ICRISAT, p. 171.

Khan, T.N. and Rachie, K.O. (1972) Preliminary evaluation and utilization of pigeonpea germplasm in Uganda. *East African Agricultural and Forestry Journal* 38, 78-82.

Lal, S., Asthana, A.N. and Gowda, C.L.L. (1989) Use of chickpea and pigeonpea germplasm and their impact on crop improvement in India. In: *Collaboration on Genetic Resources: Summary Proceedings of a Joint ICRISAT/NBPGR (ICAR) Workshop on Germplasm Exploration and Evaluation in India, 14-15 November 1988, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 101-103.

Mahta, D.N. and Dave, B.B. (1931) Studies in *Cajanus indicus. Memoirs of the Department of Agriculture in India, Botanical Series* 19, 1-25.

Onim, J.F.M. (1981) Pigeonpea improvement research in Kenya. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 427-436.

Pandey, R.K. and Singh, V.B. (1981) Influence of source and sink size on flower drop and seed yield of pigeonpea. *Indian Journal of Agricultural Sciences* 51, 185-188.

Paroda, R.S. (1989) Keynote address: collaborative efforts on plant genetic resources by ICRISAT and ICAR. In: *Collaboration on Genetic Resources: Summary Proceedings of a Joint ICRISAT/NBPGR (ICAR) Workshop on Germplasm Exploration and Evaluation in India, 14-15 November 1988, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 7-10.

Pathak, G.N. (1970) Red gram. In: *Pulse crops of India.* Indian Council of Agricultural Research, New Delhi, India, pp. 14-53.

Ramanujam, S. and Singh, S.P. (1981) Pigeonpea breeding in the All India Coordinated Programme. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 403-414.

Remanandan, P. (1981) The wild gene pool of *Cajanus* at ICRISAT, present and future. In: *Proceedings of the International Workshop on Pigeonpeas, volume 2, 15-19 December 1980, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 29-38.

Remanandan, P., Sastry, D.V.S.S.R. and Mengesha, M.H. (1988a) *ICRISAT Pigeonpea Germplasm Catalog: Evaluation and Analysis.* Patancheru, A.P., India: ICRISAT, 90 pp.

Remanandan, P., Sastry, D.V.S.S.R. and Mengesha, M.H. (1988b) *ICRISAT Pigeonpea Germplasm Catalog: Passport Information.* Patancheru, A.P., India: ICRISAT, 368 pp.

Saxena, M.C. and Yadav, D.S. (1975) Some agronomic considerations of pigeonpeas and chickpeas. In: *International Workshop on Grain Legumes, 13-16 January 1975, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 31-61.

Sharma, D., Reddy, L.J., Green, J.M. and Jain, K.C. (1981) International adaptation of pigeonpeas. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 71-81.

Sharma, H.K. (1981) Genetic analysis of plant height in pigeonpea. In: *Proceedings of the International Workshop on Pigeonpeas, volume 2, 15-19 December 1980, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 55-59.

Sheldrake, A.R. (1984) Pigeonpea. In: Goldsworthy, P.R. and Fisher, M.M. (eds), *The Physiology of Tropical Field Crops*. John Wiley and Sons Ltd., Chichester, pp. 385-417.

Sheldrake, A.R., Narayanan, A. and Venkataratnam, N. (1979) The effects of flower removal on the seed yield of pigeonpeas *(Cajanus cajan)*. *Annals of Applied Biology* 91, 383-390.

Swindale, L.D. (1982) Distribution and use of arable soils in the semi-arid tropics. In: *Managing Soil Resources*. Pleanary Session Papers, 12th International Congress of Soil Science, New Delhi, India, 8-16 February 1982. Indian Society of Soil Science, New Delhi, India, pp. 67-100.

Tayo, T.O. (1980) Compensatory growth and yield of pigeonpea *(Cajanus cajan)* following pod removal at different stages of reproductive growth. *Journal of Agricultural Science, Cambridge* 95, 487-491.

van der Maesen, L.J.G. (1980) India is the native home of pigeonpea. In: Arends, J.C., Boelema, G., de Groot, C.T. and Leeuwenberg, A.J.M. (eds), *Libergratulatorius in honerem H.C.D. de Wit. Landbouwhogeschool, Miscellaneous Paper no. 19*. Wageningen, Netherlands: H.Veenman and B.V. Zonen, pp. 257-262.

Williams, I.H. (1977) Behaviour of insects foraging on pigeonpea (*Cajanus cajan* (L.) Millsp.) in India. *Tropical Agriculture (Trinidad)* 54, 353-363.

Chapter 5

PIGEONPEA: CYTOLOGY AND CYTOGENETICS – PERSPECTIVES AND PROSPECTS

I.S. DUNDAS

Research Associate, Department of Agronomy, University of Adelaide, Waite Agricultural Research Institute, Glen Osmond, SA 5064, Australia.

INTRODUCTION

Cytological investigation of a species involves the study of the number, morphology, and behaviour of its chromosomes and of any sites for extra-chromosonal gene location. The relationships of these gene sites to the transmission, inheritance, and expression of characters is termed cytogenetics (Schulz-Schaeffer, 1980). This information is important in understanding the process of gene transfer within or between species. Cytogenetic studies also encompass the development of techniques required to study the chromosomes, combine genomes, and manipulate whole or parts of chromosomes.

The cytogenetic study of a species may progress through the following stages,

(a) Exploratory: This initial phase involves the acquisition of basic information on the chromosomes of a species, namely the number and the morphology (karyotypes) of mitotic and meiotic chromosomes. The potential role of any wild relatives as gene donors for agronomic improvement of the cultivated type may also be assessed.

(b) Developmental: Studies include clarification of affinities with wild relatives through; hybridization, examination of chromosome behaviour in the hybrids, and determination of causes of any crossability barriers and ways to overcome them. The mapping of genes into linkage groups and the assignment of these linkage groups to chromosomes facilitates later manipulation of selected chromosomes or their segments. Development of tissue culture techniques may be required to complete the above goals, i.e., embryo rescue to obtain interspecific crosses, and anther culture to produce haploids and subsequent aneuploids for use in gene mapping.

(c) Implementary: This phase involves purposeful gene transfer, usually from the wild to the cultivated species, to solve defined problems, e.g., breeding for disease resistance. These procedures may employ transfer of entire genomes, single chromosomes, or chromosome segments.

Cytological investigation of pigeonpea began in the 1930s. However, it has only been in the last 10-15 years that the bulk of information on pigeonpea chromosomes and their behaviour has been gathered. At present, pigeonpea cytogenetics could be considered to be in the "developmental stage". Details of somatic and meiotic chromosomes and their morphologies have been reported, while studies of cytogenetic relationships of this crop with the wild species in *Cajanus* are presently being clarified.

This chapter provides a history of studies into the cytology of pigeonpea and the relationship of this important pulse crop to its wild relatives. Future directions for pigeonpea cytogenetical research are indicated. In a recent taxonomic revision, van der Maesen (1986) merged many of the wild relatives of the pigeonpea *(Cajanus cajan)*, formerly in *Atylosia* W. & A. into *Cajanus* DC. In this chapter the new names proposed by van der Maesen (1986) have been used and the former names have been included in parentheses where first mentioned.

CHROMOSOMES

Number

Roy (1933) was the first to report the chromosome number of pigeonpea (n=11), surprisingly using female gametophytic tissue. Roy also provided a detailed description of the development of the pigeonpea embryo sac. Krishnaswamy and Ayyangar (1935), working with sections of pollen mother cells, confirmed the count of Roy (1933), and suggested that 11 was the basic number of the entire tribe. Naithani (1941) later reported the somatic chromosome number to be 2n=22. He mentioned pairs of chromosomes lying close to each other, and the existence of prochromosomes (chromocentres) at interphase. These early studies were on Indian varieties of pigeonpea. More recently, Akinola *et al.* (1972) conducted the most extensive cytological survey of the genus to date, examining 95 accessions from around the world, but failing to find any variation from previously reported somatic counts.

Wild relatives of pigeonpea have been generally found to have the same chromosome number as the cultivated type. According to van der Maesen (1986) there are 32 species in *Cajanus*, the majority of these species being found in India and Australia. Reports indicate that n=11 and 2n=22 exist for most wild species examined to date (Table 5.1). One notable exception is that of the African species *C. kertsingii* that was found to have n=16 (Gill and Hussaini, 1986). Lackey (1980) had previously reported 2n=22 for this species.

Table 5.1. First reports of chromosome counts involving wild species of *Cajanus*.

Species	Origin	Meiotic count	Mitotic count	Source
Cajanus acutifolius (F. von Muell.) van der Maesen *comb. nov.*				
(*Atylosia acutifolia* Reynolds & Pedley)	Australia	n=11	2n=22	Dundas, 1984; Dundas *et al.*, 1987, 1988
C. albicans (W. & A.) van der Maesen *comb. nov.*				
(*A. albicans* (W. & A.) Benth.)	India	n=11		Gajapathy, 1962
(*A. albicans* (W. & A.) Benth.)			2n=22	Pundir and Singh, 1978, 1986
(*A. albicans* (W. & A.) Benth.)		n=11		Rao, 1978
C. cajanifolius (Haines) van der Maesen *comb. nov.*				
(*A. cajanifolia* Haines)	India	n=11		Rao, 1978
(*A. cajanifolia* Haines)			2n=22	Pundir and Singh, 1978, 1986
C. cinereus (F. von Muell.) F. von Muell.				
(*A. cinerea* F. von Muell. ex Benth.)	Australia	n=11		Keighery, 1978
C. confertiflorus F. von Muell.				
(*A. pluriflora* F. von Muell. ex Benth.)	Australia	n=11	2n=22	Dundas *et al.*, 1987, 1988
C. crassus (Prain ex King) van der Maesen var. *crassus*				
(*A. volubilis* (Blanco) Gamble)	India	n=11		Rao, 1978
(*A. volubilis* (Blanco) Gamble)			2n=22	Pundir and Singh, 1978, 1986
C. goensis Dalz.				
(*A. barbata* (Benth.) Bak.)	India		2n=22	Tschechow and Kartaschowa, 1932 in Darlington and Wylie, 1955
C. heynei (W. & A.) van der Maesen *comb. nov.*				
(*A. kulnensis* (Dalz.)	India	n=11		Bir and Kumari, 1973, 1977
(*A. kulnensis* (Dalz.)			2n=22	Bir and Kumari, 1977
C. kerstingii Harms	Africa		2n=22	Lackey, 1980
C. kerstingii Harms		n=16		Gill and Husaini, 1986
C. lanceolatus (W. V. Fitzg.) van der Maesen *comb. nov.*				
(*A. lanceolata* W. V. Fitzg.)	Australia	n=11	2n=22	Kumar, 1985
C. latisepalus (Reynolds & Pedley) van der Maesen *comb. nov.*				
(*A. latisepala* Reynolds & Pedley)	Australia	n=11	2n=22	Kumar, 1985
C. lineatus (W. & A.) van der Maesen *comb. nov.*				
(*A. lineata* (W. & A.)	India	n=11	2n=22	Deodikar and Thakar, 1956
(*A. lineata* (W. & A.)		n=11	2n=22	Kumar *et al.*, 1958

Table 5.1. continued.

Species	Origin	Meiotic count	Mitotic count	Source
C. platycarpus (Benth.) van der Maesen *comb. nov.*				
(*A. platycarpa* Benth.)	India	n=11		Bir and Kumari, 1973, 1977
(*A. platycarpa* Benth.)			2n=22	Bir and Kumari, 1977
(*A. platycarpa* Benth.)			2n=22	Pundir and Singh, 1978, 1986
C. reticulatus var. *grandifolius* (F. von Muell.) van der Maesen *comb. et stat. nov.*				
(*A. grandifolia* (F.v.Muell.) Benth.)	Australia	n=11		Kumar, 1985
C. rugosus (W. & A.) van der Maesen *comb. nov.*				
(*A. rugosa* W. & A.)	India	n=11		Sanjappa and Sathyananda, 1979
C. scarabaeoides var. *scarabaeoides* van der Maesen				
(*A. scarabaeoides* (L.) Benth.)	India	n=11		Bir and Sidhu, 1966, 1967
(*A. scarabaeoides* (L.) Benth.)		n=11		Kumar *et al.*, 1966
(*A. scarabaeoides* (L.) Benth.)			2n=22	Roy and De, 1965
(*A. scarabaeoides* (L.) Benth.)			2n=22	Pundir and Singh, 1978, 1986
C. sericeus (Benth. ex. Bak.) van der Maesen *comb. nov.*)				
(*A. sericea* Benth. ex Bak.)	India	n=11	2n=22	Deodikar and Thakar, 1956
(*A. sericea* Benth. ex Bak.)		n=11		Kumar *et al.*, 1966
(*A. sericea* Benth. ex Bak.)			2n=22	Pundir and Singh, 1978, 1986
C. trinervius (DC.) van der Maesen *comb. nov.*				
(*A. trinervia* (DC.) Gamble)	India		2n=22	Pundir and Singh, 1978

Polyploidy and Aneuploidy

Spontaneous polyploid formation is a rare occurrence in pigeonpea. There have been only three reports of spontaneous polyploids including tetraploids (n=22—Pathak, 1948; Pathak and Yadava, 1951; 2n=44—Saxena *et al.*, 1982), and a hexaploid (n=33—Pathak and Yadava, 1951). These types were first identified in the field on the basis of their morphological features and poor pod set. Pathak and Yadava (1951) suggested that cold shock following a heavy hailstorm may have induced polyploidy in their material.

Tetraploids have also been induced by colchicine treatment (Kumar *et al.*, 1945; Bhattacharjee, 1956; Shrivastava *et al.*, 1972; Tewari *et al.*, 1981). Chopde *et al.* (1979) reported a tetraploid arising from X-ray treated material but did not comment on the possible role that this form of irradiation may have had on polyploid induction.

Meiosis in tetraploids has revealed varying degrees of multivalent formation (Kumar *et al.*, 1945; Pathak, 1948; Bhattacharjee, 1956; Joshi, 1966; Khamankar, 1966; Tewari *et al.*, 1981; Tewari and Singh, 1986) followed by irregular disjunction in second division (Pathak, 1948; Bhattacharjee, 1956; Shrivastava *et al.*, 1972; Chopde *et al.*, 1979). Consequently, pollen fertility and pod set on tetraploid plants has been very low.

Two cases of aneuploidy have been reported in pigeonpea. D'Cruz and Jadhav (1972) recovered a plant with 2n=23, while in anther-derived callus, chromosome numbers from 2n=8 to 2n=28 were noted by Bajaj *et al.* (1980). These latter workers were unable to raise plantlets from their material. It is believed that no identified stocks of aneuploids presently exist.

Meiotic Behaviour and Pollen Formation

Reports of metaphase I behaviour in pigeonpea pollen mother cells generally mention "normal pairing" with 11 bivalents (Kumar *et al.*, 1945, 1966; Bhattacharjee, 1956; Dundas *et al.*, 1987) or "perfect pairing" (Reddy and De, 1983). Krishnaswamy and Ayyangar (1935) described the larger metaphase I chromosomes of the pigeonpea as having more than four chiasmata, with the rest of the complement showing 2 or 3 chiasmata. Mukhopadhyay (1986) reported that chiasma frequency per bivalent to be 1.46.

No cell walls are laid down after the first division in pigeonpea pollen mother cells, and the four microspores form a tetrahedral shape at the end of meiosis (Dundas *et al.*, 1987). Pigeonpea pollen grains are bi-nucleate at maturity (Dundas *et al.*, 1981). Srivastava (1978) reported that pigeonpea pollen grains were 3-colporate and the exine areolate (negatively reticulate).

CYTOLOGICAL METHODS

Mitosis

Early studies of somatic pigeonpea chromosomes utilized root sections (Naithani, 1941; Singh *et al.*, 1942; Kumar *et al.*, 1958). This process is known for its tedious preparations and likelihood of chromosome loss. More recent methods employ squashes of root tips. Processing root material generally involves three steps; (a) pretreatment to arrest cell division through the use of chemicals or temperature shock for periods of up to 24 h, (b) fixation in an organic acid-alcohol mixture, and (c) staining in an acid-based dye solution. Sharma and Sharma (1980) have published a number of schedules for handling plant chromosomes.

Procedures for pigeonpea root squashes have stressed the need to use such pretreatment chemicals such as paradichlorobenzene (Akinola *et al.*, 1972; Sinha and Kumar, 1979; Sharma and Gupta, 1982; Lavania and Lavania, 1982), monobromonaphthalene (Shrivastava and Joshi, 1972; Shrivastava *et al.*, 1973), and 8-hydroxyquinoline (Pundir and Singh, 1983a, 1986). These chemicals act as spindle inhibitors and tend to result in the occurrence of higher frequencies of cells at metaphase. Stains such as Feulgen (Akinola *et al.*, 1972; Shrivastava and Joshi, 1972; Shrivastava *et al.*, 1973; Pundir and Singh, 1983a, 1986), and aceto-carmine (Singh *et al.*, 1942; Sinha and Kumar, 1979; Sharma and Gupta, 1982) have given satisfactory results. Shrivastava and Joshi (1972) compared several pretreatments, fixatives, and stains, and published a recommended schedule for the study of somatic chromosomes.

C-banding of pigeonpea chromosomes was first achieved by Lavania and Lavania (1982). Their technique involved de-naturing air-dried slides in a saturated barium hydroxide solution for 1.5 min, re-annealing in a standard saline-citrate bath for 45 min, and staining in a Giemsa solution for about 10 min.

Meiosis

Early meiotic studies involved sectioning flower buds and staining with Heidenhain's iron-alumhaematoxylin (Roy, 1933; Krishnaswamy and Ayyangar, 1935). Singh *et al.* (1942) appears to have been the first to use aceto-carmine smears on pigeonpea pollen mother cells. Several recent workers have emphasized the need for ferric salts to be present in the acid-alcoholic fixing solution (Reddy, 1981a; Dundas *et al.*, 1983; Kumar and Sinha, 1983). The likely role for the ferrous ion is that of a mordant in assisting binding of the stain to the chromosomes. Propionic-carmine stain has been found to produce excellent results in the study of all stages of meiosis, including pachytene (Reddy, 1981a, b, c; Dundas *et al.*, 1983, 1988).

Pollen Tubes, Pollen Viability

Confirmation of pollen viability is best achieved through *in vivo* germination tests on stigmatic tissue. This can be observed using fluorescence or conventional staining methods. Pundir and Singh (1985a) stained pistillate tissue of wild relatives of pigeonpea with toluidine blue stain and observed pollen tube development under ultra-violet (UV) irradiation. An alternative staining method is the use of a dilute solution of aceto-carmine (about 2%) for a quick check of pollen germination on stigmatic tissue. With this latter method, pollen tubes are readily visible until they enter the stigma and style, whereafter a fluorescence staining technique is required.

Quicker tests for pollen viability are *in vitro* germination and aceto-carmine staining of anthers. Pigeonpea pollen germinated *in vitro* on a 30% Davis' gelatine base containing 40% sucrose, 0.01% H_3BO_3, and 2.0mM $Ca(NO_3)_2.4H_20$ after incubating at 25°C for 3h (I.S. Dundas, unpublished). The simplest method of assessing pollen viability is by gently spreading mature anthers in a 2% solution of aceto-carmine. With this method, empty pollen grains (sterile) fail to stain owing to the absence of cytoplasm. This technique can not detect the proportion of grains which do stain that are also nonviable, although Kaul and Singh (1969) found that this test compared well with results of pollen germination and nitro-BT viability staining on pigeonpea.

General Histology

An extensive investigation of pigeonpea anatomy has been published by Bisen and Sheldrake (1981). They used paraffin wax embedded material and employed five different staining procedures. Reddy *et al.* (1978) and Dundas *et al.* (1981, 1982) also sectioned embedded flowers in their study of another wall and pollen mother cell development in fertile and male-sterile material.

KARYOTYPE ANALYSIS

Descriptions of the morphologies of both mitotic (somatic) and meiotic (pachytene) chromosomes have been published. In spite of numerous attempts at karyotype analysis of pigeonpea somatic chromosomes, reliable identification of these chromosomes remains difficult owing to their small size and the lack of distinguishing features. Reports of lengths and arm ratios vary according to study, limiting the usefulness of these parameters. Pigeonpea cytology awaits a method of uniquely characterizing each of the mitotic chromosomes. Chromomere patterns of pachytene chromosomes are presently the most useful features by which to recognize pigeonpea chromosomes.

Pachytene Chromosomes

The best available means of identifying pigeonpea chromosomes is with pachytene material (Figure 5.1). The advantages of studying this stage are, firstly, that the chromosomes are large and show

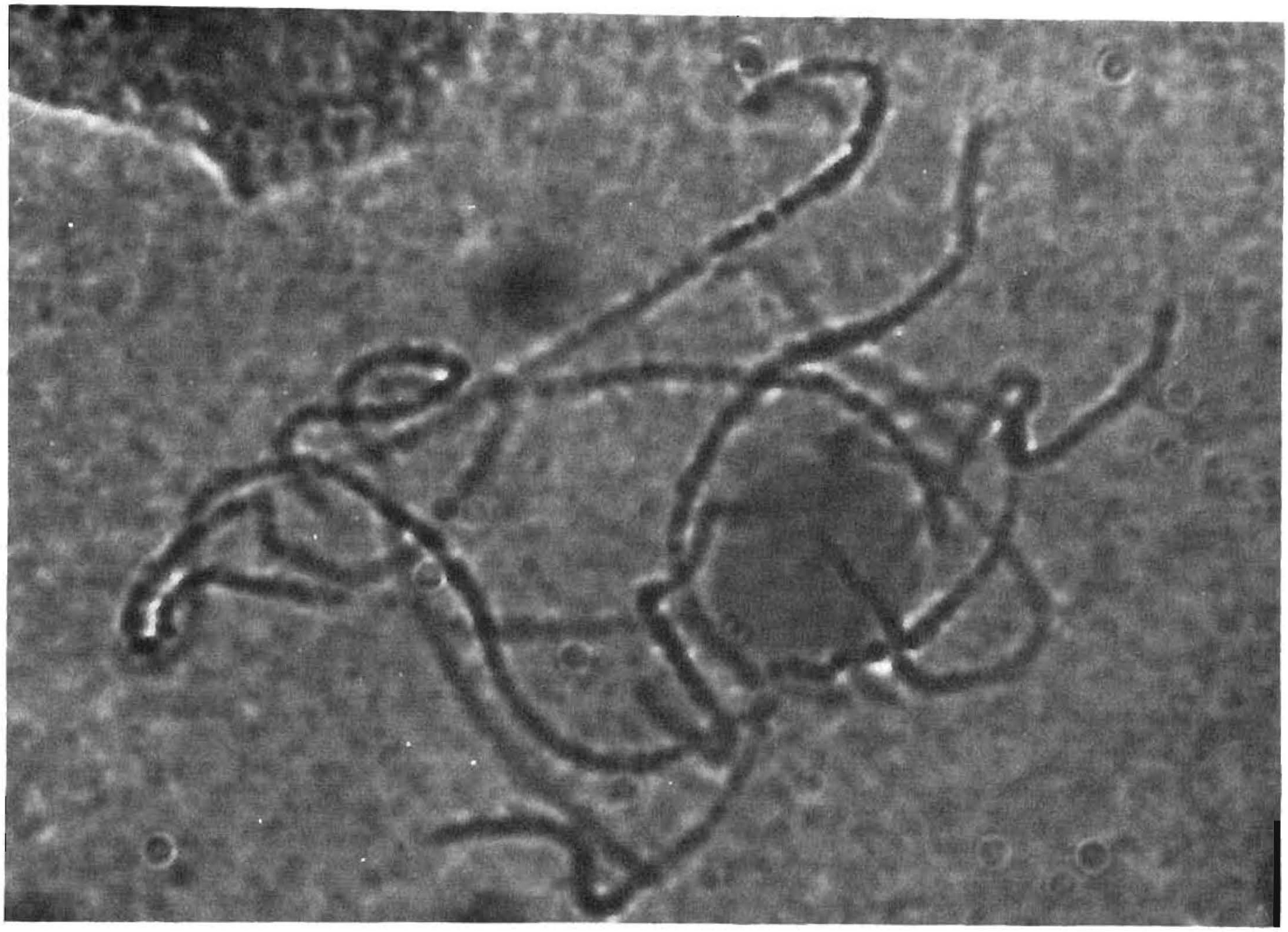


Figure 5.1. The eleven bivalent pachytene chromosomes, × 2600, of pigeonpea (Prabhat). Note the prominent chromomeres adjacent to the centromeres.

characteristic chromomere patterns, and secondly, only half the number of chromosomes are visible as compared to mitotic cells. Pachytene karyotypes were developed with the view to identifying synapsing homologous chromosomes in interspecific hybrids of pigeonpea with its wild relatives.

Reddy (1981a) was the first to study pachytene chromosomes of pigeonpea. His karyotype was prepared from 10 well-spread cells and chromosomes were arranged on the basis of relative length, arm length, nucleolar association, and the amount and distribution of heterochromatin. Reddy identified chromosomes of pigeonpea as they paired with those of wild species (Reddy, 1981 a, b, c).

Dundas *et al.* (1983) encountered the common cytological problem of tangling of pachytene chromosomes. They tried a different approach to karyotype preparation using 196 chromosomes in 79 cells and characterized chromosomes on the basis of nucleolar association, and then chromomere distribution and structure. Dundas *et al.* (1983) also prepared a key (Table 5.2) and idiogram (Figure 5.2) for the rapid identification of chromosomes under the microscope. This method of karyotype analysis was applied to the wild species *Cajanus acutifolius (Atylosia acutifolia)*, and *C. confertiflorus (A. pluriflora)* (Dundas *et al.*, 1988). Identification of some chromosomes of the pigeonpea and of *C. acutifolius* in interspecific hybrids has also been achieved (Dundas, 1984).

The major disavantages with pachytene study are, firstly, the inconvenience of waiting several weeks or months for the material to flower, and secondly, the tangling nature of the chromosomes.

Table 5.2. Key to the pachytene chromosomes of pigeonpea (*Cajanus cajan*) cv Prabhat[1].

Item		
1.	Nucleolus present	chr 11
	Nucleolus absent	item 2
2.	Major chromomeres distributed approximately equally between chromosome arms	item 3
	Major chromomeres distributed markedly unequally between chromosome arms	item 7
3.	Triple-chromomeres[2] present	chr 1
	Triple-chromomeres absent	item 4
4.	Double-chromomeres[2] on both sides of centromere	chr 2
	Double-chromomere(s) on one side of centromere only	item 5
5.	Three double-chromomeres in sequence	chr 3
	One double-chromomere present	item 6
6.	Prominent single-chromomere adjacent to centromere followed by three less prominent single chromomeres	chr 4
	Single-chromomere adjacent to centromere followed by lightly staining region	chr 5
7.	Four-part[2] chromomere present	chr 6
	No four-part chromomeres present	item 8
8.	Triple chromomere present	chr 7
	No triple chromomeres present	item 9
9.	Double-chromomeres on both arms	chr 8
	Double-chromomeres on one arm only	item 10
10.	Two double-chromomeres in sequence on one arm	chr 9
	One double-chromomere only present	chr 10

1. From Dundas *et al.*, 1983. Reprinted with permission of Journal of Heredity, Washington. © 1983 by the American Genetic Association.
2. Refers to sub-structure of the major chromomeres visible with light microscope, see Dundas *et al.*, 1983.

Somatic Chromosomes

Naithani (1941) described pigeonpea somatic chromosomes as "very small" (longest 2.7μ, shortest 1.35μ). Deodikar and Thakar (1956) made the first detailed attempt at karyotype analysis reporting the total length (75.4μ), the length of each chromosome, and positions of primary and secondary constrictions. Later workers have found considerable varietal difference with respect to total chromatin length (e.g., 27.6μ - 44.9μ by Shrivastava *et al.*, 1973; 44.4 - 63.5μ by Mukhopadhyay, 1986). Sinha and Kumar (1979) attempted to group 13 varieties on the basis of karyotype similarity. Seven groups emerged from this study and the authors inferred that chromosome structural change was associated with varietal development. Pundir and Singh (1983a, 1986) and Sharma and Gupta (1982) have also published somatic karyotypes of pigeonpea.

Mukhopadhyay (1986) calculated the total mean volume of chromosomes of nine varieties of pigeonpea and found it to be 28.76μm^3. The DNA content was estimated to be 9.9 pg cell^{-1} for root meristem tissue, and 8.37 pg cell^{-1} for shoot meristem.

Lavania and Lavania (1982) recognized the limitations of characterizing chromosomes solely on the basis of conventional length measurements and successfully applied C-banding methods to pigeonpea somatic chromosomes. They found that seven chromosomes had centromeric bands, three chromosomes showed a telomeric band on the short arm only, while one chromosome had telomeric bands on both arms. Hence, only one pigeonpea chromosome could be uniquely distinguished on the basis of C-bands thus limiting the usefulness of this technique as a tool in identification studies.

Reports of the number of satellited chromosomes in pigeonpea vary from zero for some varieties (Shrivastava *et al.*, 1973; Sinha and Kumar, 1979; Sharma and Gupta, 1982), to one pair (Deodikar and Thakar, 1956; Kumar *et al.*, 1958; Roy and De, 1965; Shrivastava *et al.*, 1973; Sinha and Kumar, 1979; Sharma and Gupta, 1982), or two pairs (Pundir and Singh, 1986; Mukhopadhyay, 1986). Secondary constrictions on metaphase chromosomes are regarded as sites for nucleolar-organizer activity at prophase (Rieger *et al.*, 1976). Pachytene studies by Reddy (1981a) and Dundas *et al.* (1983) have shown one chromosome bivalent attached to the nucleolus. More recent investigations by Kumar *et al.* (1987) indicated that pigeonpea and some of its wild relatives have two sites for nucleolar organization. Kumar *et al.* (1987) confirmed this discovery with studies on tetraploid

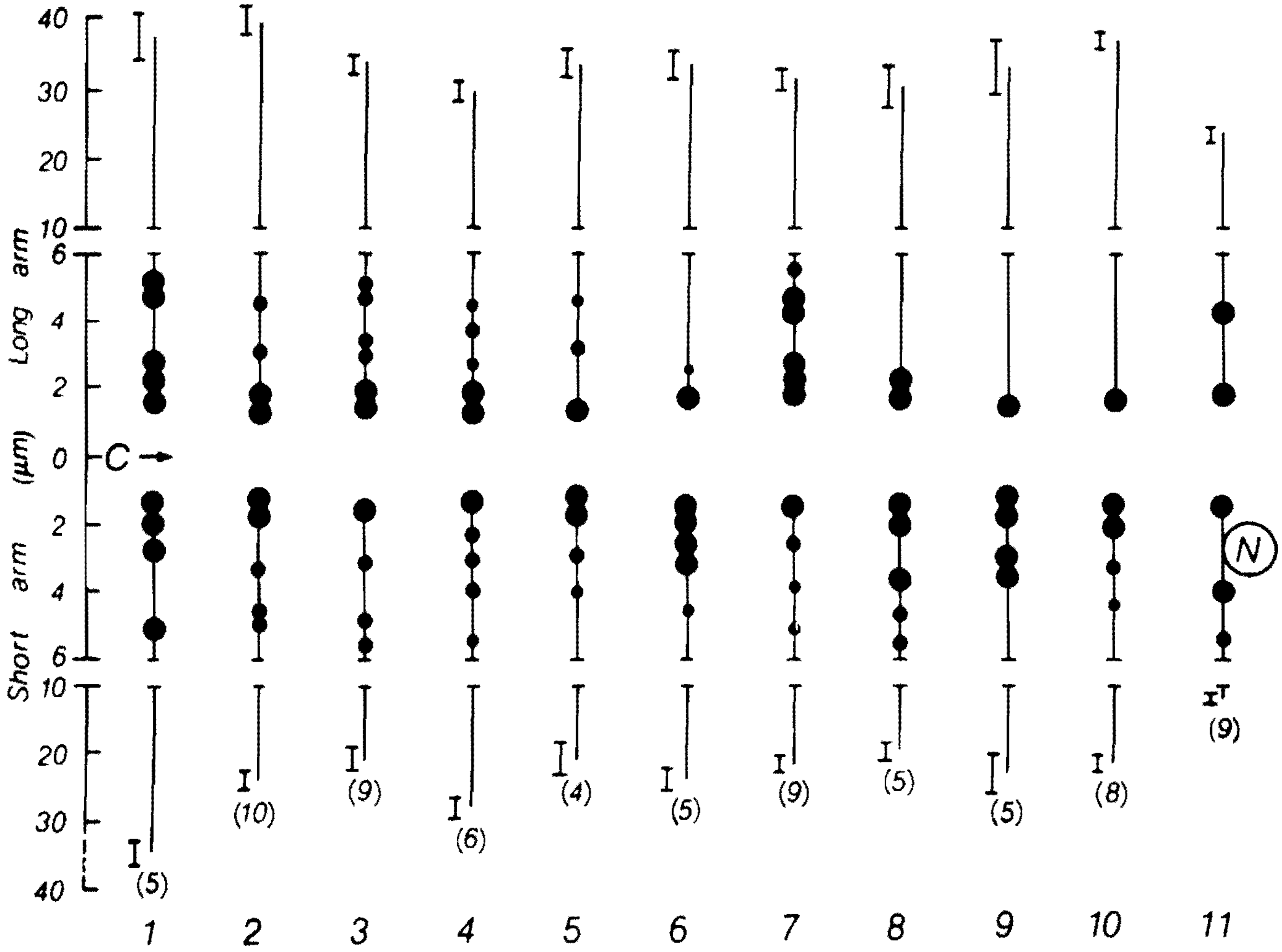


Figure 5.2. Idiogram of pachytene chromosomes of pigeonpea (Prabhat) showing major chromomeres. Numbers in parentheses refer to the number of chromosomes measured for determination of mean chromosome arm lengths, standard errors, and position of chromomeres, centromere (C), and nucleolus (N).

Source: Dundas *et al.*, 1983. Reprinted with permission of the Journal of Heredity, Washington. ©1983 by the American Genetic Association.

pigeonpeas. Variations in the number of secondary constrictions (nucleolar-organizer regions) on somatic chromosomes in previous reports may be related to techniques employed by former workers (Kumar *et al.*, 1987). The development of staining methods specific for nucleolar-organizer regions (e.g., Sharma and Sharma, 1980) may help clarify the locations of these sections in the pigeonpea genome.

INTERSPECIFIC HYBRIDIZATION

Crosses between pigeonpea and related wild species have included species both from Asia and Australia (Table 5.3). The wild *Cajanus* species used most frequently in hybridization have been *C. lineatus (A. lineata), C. sericeus (A. sericea)*, and *C. scarabaeoides* var. *scarabaeoides (A. scarabaeoides)*. Hybridizations have been most successful using pigeonpea as the female, but some reciprocal crosses have also been achieved, viz., *C. cajanifolius (A. cajanifolia)* (Pundir and Singh, 1985a), *C. lineatus* (Pundir and Singh, 1985a), and *C. scarabaeoides* var. *scarabaeoides* (Ariyanayagam and Spence, 1978). The rate of pod set and the number of seeds per pod after interspecific cross-pollination has been shown to increase after application of gibberellic acid (GA_3) or kinetin (Kumar, P.S. *et al.*, 1985a; Dhanju and Gill, 1985).

Apart from interspecific hybrids within the *Cajanus* genus, there have been two reports of crosses between pigeonpea and other members of the tribe Phaseoleae. Hybrids between *Lablab purpurea (Dolichos lablab)* and pigeonpea were obtained by Datta and Saha (1972). Mohamed *et al.* (1979) were able to cross *Phaseolus vulgaris* with pigeonpea. The recovery of these hybrids indicates the close relationships between members of the tribe.

Chromosome Behaviour, and Fertility

The extent of homology between diverse genomes in interspecific hybrids is best determined through evidence of crossing-over between synapsing chromosomes rather than by simply comparing morphologies of the chromosomes. Genetic recombination at meiotic prophase is visually revealed in metaphase I by chiasmata that hold the separating chromosomes together until anaphase (Rieger *et al.*, 1976). Chiasmata on both arms of the pairing chromosomes results in "ring bivalents", while chiasmata occuring on only one arm gives rise to "rod bivalents". Multivalents may arise when homologous segments involve several chromosomes.

Both ring and rod bivalents and multivalents have been found in metaphase I cells of hybrids of pigeonpea with wild *Cajanus* species. The higher frequency of rod bivalents and univalents in these hybrids compared with parents is indicative of incomplete homology between pairing genomes (Kumar *et al.*, 1966; Reddy and De, 1983; Dundas, 1984; Dhanju and Gill, 1985; Kumar, 1985; Pundir and Singh, 1985b; Dundas *et al.*, 1987). The occurrence of multivalents also indicates the presence of duplicated segments on the chromosomes, or evidence of heterozygous translocations.

Features at meiotic prophase and anaphases can also indicate levels of homology between genomes. Pachytene studies by Reddy (1981a, b, c) with Indian wild relatives, and Dundas (1984) with Australian wild species have shown close association between homologous chromosomes with occasional unpaired sections. Furthermore, Dundas (1984) reported inversion loops in hybrids of pigeonpea with the Australian species *C. acutifolius*. Other abnormal features included translocation cruciform configurations (Reddy, 1981c; Dundas, 1984), duplication/deletion loops (Dundas, 1984) and "star formations" caused by sticking centromeres (Reddy, 1984). Kumar, P.S. *et al.* (1984a) presented evidence of recombination between nucleolar-organizer chromosomes and non-nucleolar chromosomes in pigeonpea × *C. albicans (A. albicans)* hybrids by examining variation in nucleolar

Table 5.3. Wild species in *Cajanus* successfully crossed with pigeonpea.

Wild species	Reference
Cajanus acutifolius (*Atylosia acutifolia*)	Dundas, 1984 Dundas *et al.*, 1986, 1987, 1988
C. albicans (*A. albicans*)	Reddy *et* al., 1981 Kumar, P.S. *et al.*, 1984a, 1985b Pundir and Singh, 1983b, 1985a, b
C. cajanifolius (*A. cajanifolia*)	Reddy *et al.*, 1981 Tripathi *et al.*, 1984 Kumar, P.S. *et al.*, 1985a Pundir and Singh, 1983b, 1985a, b
C. confertiflorus (*A. pluriflora*)	Dundas, 1984 Dundas *et al.*, 1986, 1987, 1988
C. lanceolatus (*A. lanceolata*)	Kumar, 1985
C. latisepalus (*A. latisepala*)	Kumar, 1985
C. lineatus (*A. lineata*)	Deodikar and Thakar, 1956 Kumar *et al.*, 1958 Kumar and Thombre, 1958 Reddy *et al.*, 1981 Reddy and De, 1983 Pundir and Singh, 1983b, 1985a
C. platycarpus (*A. platycarpa*)	Dhanju and Gill, 1985
C. reticulatus var. *reticulatus* (A. *reticulata*)	Dundas, 1984 Dundas *et al.*, 1986 Kumar, 1985 Kumar, P.S. *et al.*, 1985a
C. scarabaeoides var. *scarabaeoides* (*A. scarabaeoides*)	Roy and De, 1965 Kumar *et al.*, 1966 Reddy *et al.*, 1981 Pundir and Singh, 1983b, 1985a, b
C. sericeus (*A. sericea*)	Kumar *et al.*, 1966 Reddy *et al.*, 1981 Kumar, P.S. *et al.*, 1985a
C. trinervius (*A. trinervia*)	Reddy *et al.*, 1981 Pundir and Singh, 1983b, 1985a, b

distribution. Anaphases I and II in interspecific hybrids have shown chromatin bridges and fragments (Dundas, 1984; Kumar, 1985; Dundas *et al.*, 1987) and laggards (Reddy and De, 1983; Dundas *et al.*, 1987). Dundas *et al.* (1987) interpreted the occurrence of chromatin bridges and fragments at anaphases as arising from cross-overs within inversion loops.

As a consequence of chromosomal abnormalities at meiosis in interspecific *Cajanus* crosses, the fertility of the F_1 plants has been lower than that found in parental material. High levels of abnormal pollen in hybrids have been reported by Kumar *et al.* (1958), Reddy and De (1983), Dhanju and Gill (1985), and Dundas *et al.* (1987) while pod set and seed content were lower in hybrids than parents (Kumar *et al.*, 1958; Reddy and De, 1983; Dundas *et al.*, 1987).

Inheritance and Morphology

Kumar and Thombre (1958) were the first to report on the morphology of, and the inheritance of characters in interspecific hybrids. Characters from the wild species such as the "presence of strophioles" and "perenniality" appeared to be dominant while some characters were under polygenic control (Kumar *et al.*, 1966). Other workers who have successfully crossed pigeonpea with its wild relatives have reported the morphology of the resulting hybrids to be intermediate to that of the parents (e.g., Pundir and Singh, 1983c; Dundas *et al.*, 1986).

The most extensive report on the inheritance of characters in interspecific hybrids has been that of Reddy *et al.* (1981). Inheritance of characters such as hairy pods, strophiolate seeds, and seed mottling indicated differences of one or two genes between pigeonpea and wild types from India (Reddy *et al.*, 1981; Pundir and Singh, 1983c; Kumar, P. S. *et al.*, 1985b) but larger genetic differences have been reported between pigeonpea and its Australian wild relatives (Dundas, 1984; Kumar, 1985).

Species Affinities

Several workers have attempted to rank the wild relatives of pigeonpea according to the closeness of their relationship to the cultivated type. Pundir and Singh (1985c) assessed details of plant morphology, karyotype, crossability, meiotic behaviour, and seed protein profiles of nine related species. Seed proteins have also been studied by Ladizinsky and Hamel (1980), while indices of similarity between pigeonpea and its wild relatives have also been produced by comparing patterns of esterase isozymes (Krishna and Reddy, 1982). Pundir and Singh (1985c) indicated that *C. cajanifolius* is the most closely related species to pigeonpea, followed by *C. lineatus*.

Australian wild relatives of pigeonpea were not included in the above studies. Investigations by Dundas (1984), Dundas *et al.* (1987), and Kumar (1985) have indicated that the Australian species *C. acutifolius*, *C. confertiflorus*, *C. lanceolatus* (*A. lanceolata*), *C. latisepalus* (*A. latisepala*), and *C. reticulatus* (*A. reticulata*, *A. grandifolia*) are less closely related to pigeonpea than are the Indian species. Hybrids of pigeonpea with Australian species tended to have higher levels of meiotic abnormalities, and greater genetic differences for heritable characters than reported in hybrids between pigeonpea and Indian species.

Despite the genetic and chromosomal differences between pigeonpea and its wild relatives, there is enough conclusive evidence to show that wild species in *Cajanus* are sufficiently closely related to the cultivated type to allow the transfer of useful genes.

TISSUE CULTURE

Activities with sterile culture of pigeonpea tissue have aimed to develop techniques for raising plants from callus, rescuing immature embryos, and producing haploids. One of the major problems affecting the culture of pigeonpea tissue has been necrosis of the material after several weeks' growth (Kumar, P.S. *et al.*, 1983). This feature has been attributed to the secretion of phenolic compounds from the tissue into the medium until toxic levels are reached (Mehta and Mohan

Ram, 1980). These latter workers reduced the problem by adding the absorbant polyvinylpyrrolidone (PVP) to the medium at a rate of 1000 ppm.

Explant Subculture

Methods for culture of leaf, epicotyl, cotyledon, or root tissue have been reported by several workers (Mehta and Mohan Ram, 1980; Sinha *et al.*, 1983; Kumar, A.S. *et al.*, 1983, 1984; Kumar, P.S. *et al.*, 1984b). In a complex diallel style investigation, Kumar, A.S. *et al.* (1985) found that genotypic differences existed for response to artificial medium culture and they calculated genetic parameters based on dry mass yields of callus tissue. Plantlets regenerated from explant cultures by Kumar, A.S. *et al.* (1983, 1984) were successfully established in potted soil.

Embryos

The first study to include culturing immature pigeonpea embryos was that of Kumar, P.S. *et al.* (1985c) who raised callus and plantlets from embryos 11-14 days old. Previous investigations had been concerned with mature whole embryos (Sen and Mukhopadhyay, 1961) or embryo segments (Kanta and Padmanabhan, 1964). Immature embryos from interspecific hybrids of pigeonpea × *C. scarabaeoides* var. *scarabaeoides* have been raised to plants by Dhanju *et al.* (1985) and × *C. platycarpus (A. platycarpa)* by Dhanju and Gill (1985). Moss *et al.*(1988) reported that interspecific embryos of *C. platycarpus* × *C. acutifolius*, *C. cajanifolius*, and *C. scarabaeoides* var. *scarabaeoides* as small as 0.7-1.0 mm long could be cultured into plantlets by using B5 medium with hormones, together with nurse tissue and dark treatment. A method for raising younger pigeonpea embryos (< 11 days) may be a great asset for future studies with haploids, triploids, and incompatible crosses.

Anthers

Activities with pigeonpea anther material have been attempted with the view to producing haploid plants. Bajaj *et al.* (1980) cultured pollen grains on Murashige and Skoog (MS) medium and obtained callus and embryoids. Chromosome counts indicated numbers from 2n=8 to 2n=28 and no plants were raised from this study. Kumar, P.S. *et al.* (1983) on the other hand, cultured whole anthers on MS medium + 2,4-D and callus resulted. This callus later degenerated. True haploids of pigeonpea are yet to be produced.

Protoplasts

Techniques have been achieved to isolate protoplasts from pigeonpea leaves (Shohet and Strange, 1987), radicles (Xu *et al.*, 1985), and pollen tetrads (Deka *et al.*, 1977). These methods utilize enzymatic digestion of the tissue. Production of pigeonpea protoplasts may find application in the hybridization of this crop with presently cross-incompatible species of *Cajanus*.

FUTURE STUDIES

To date investigations into pigeonpea cytology and cytogenetics have covered a wide range of fields. Future cytogenetical studies on this crop must be aimed at two principal areas, firstly, continuing the introduction of useful characters from related wild species, and secondly, assisting the efficiency of selection in existing breeding programmes.

Wide Hybridization

The transfer of new genes from wild relatives is well advanced with 11 wild species successfully crossed with pigeonpea. High seed protein content has already been transferred to the cultivated type from *C. albicans, C. sericeus,* and *C. scarabaeoides* var. *scarabaeoides* (ICRISAT, 1987). Pundir and Singh (1987) and Moss *et al.* (1988) have listed other potentially useful characters found in wild relatives. Introduction of new genes in future may continue to employ whole genome transfer (hybridization), and eventually single chromosome manipulation.

Difficulty in producing hybrids between pigeonpea and wild species has been encountered especially with *C. platycarpus,* and *C. crassus* var. *crassus (A. volubilis)* although Dhanju and Gill (1985) claim to have successfully crossed *C. platycarpus* with pigeonpea. *Cajanus platycarpus* is of great potential value for pigeonpea improvement possessing such characters as resistance to fusarium wilt *(Fusarium udum)* and phytophthora blight *(Phytophthora drechsleri* f. sp *cajani),* early maturity, and annuality (Moss *et al.*, 1988), and high pod set and large seed size (Pundir and Singh, 1987). It is possible that some bridge-cross combinations may be devised to allow gene transfer from these two species to pigeonpea (Moss *et al.*, 1988). Embryo culture techniques already exist that can be used to rescue immature hybrids from interspecific crosses and raise them to the plantlet stage (Moss *et al.*, 1988).

It should be noted that the majority of the known wild species in *Cajanus* have not yet been crossed with pigeonpea. This hybridization work should first be completed so that a clearer understanding of inter-relationships between *Cajanus* species can be obtained.

Selection Efficiency

The efficiency of selection in pigeonpea breeding programmes will be improved by; increasing our knowledge of the composition of the pigeonpea genome and those of related species, and by the development of new techniques to reduce the number of generations of selection before cultivar release, i.e., by haploid production. For the above goals to be achieved, investigations need to be initiated in the following areas; (i) preparation of linkage maps of pigeonpea and other *Cajanus* species, (ii) production of aneuploids and chromosome addition lines involving wild species for allocation of genes to chromosomes, (iii) development of haploid culture, and (iv) development of a staining technique to uniquely characterize somatic chromosomes.

Linkage Mapping and Laboratory Selection

The establishment of a comprehensive linkage map showing morphological, isozyme, and DNA markers (Restriction Fragment Length Polymorphisms – RFLPs) will be a major tool in the improvement of selection efficiency of present breeding programmes. It would also help to understand the pigeonpea genome, and its relationships to wild species' genomes. Present breeding methods are based on the recognition of superior phenotypes using field evaluation procedures. Recent studies on other major crops have shown the potential value of biochemical and RFLP markers for laboratory selection activities. These markers are useful in situations when they are closely linked with important agronomic characters, e.g., the RFLP marker with virus resistance in tomato (Young *et al.*, 1988), and isozymes with fusarium wilt resistance in peas (Hunt and Barnes, 1982). Laboratory selection procedures have two advantages, firstly, only a small amount of tissue is required, and secondly, plants can be screened at the seedling stage, or even as pre-germinated seed.

Chromosome Manipulation, Aneuploids, and Haploids

The handling of individual chromosomes is a more efficient means of moving a useful character across species boundaries rather than the normal process of whole genome transfer. Interspecific hybridization involves the transfer of large numbers of undesirable characters from the wild type together with the useful gene(s). Many generations of back-crossing are then required to reduce unwanted levels of alien chromatin in the cultivated type. A pre-requisite to single-chromosome manipulation is the allocation of linkage groups to recognizable chromosomes. This is achieved through the study of aneuploids.

Aneuploid lines of pigeonpea (nullisomic/monosomic/trisomic) are essential for mapping marker characteristics, be they isozymes or RFLPs. Monosomics may be produced by crossing haploid pigeonpeas with normal diploids. Selfing these types may result in nullisomics. Methods for routine haploid production do not presently exist although unsuccessful attempts have been made to culture pollen grains (Bajaj *et al.*, 1980) and anthers (Kumar, P.S. *et al.*, 1983). Another possible source of haploids may be the screening of spontaneously arising seed from bagged male-sterile plants, a proportion of which may have arisen parthenogenetically (P.S. Kumar, personal communication). Trisomic lines of pigeonpea may be produced by crossing triploid pigeonpeas with normal diploids. However, production of triploids (tetraploids × diploids) has been unsuccessful (I.S. Dundas, unpublished observations). Perhaps use of isolation plots of male-sterile diploid lines and male-fertile tetraploids in the presence of cross-pollinating insects would allow sufficient crosses to occur, and lead to the recovery of rare hybrids.

A further use of haploids is in the reduction of time for cultivar development. Large numbers of homozygous lines can be produced by doubling the chromosome numbers of haploids. This reduces the number of generations required to cover homozygous lines from five or six to only one. Selection work with doubled haploids also has the advantage of enabling recognition of recessive characters that may be concealed in heterozygous breeding populations.

In the absence of methods for producing aneuploids by way of haploids, mapping the genetic content of pigeonpea chromosomes may be possible using pigeonpea addition lines in the background of wild relatives. These can be achieved by selfing progeny of crosses between tetraploid types of the wild species, e.g., *C. albicans*, *C. lineatus*, with normal diploid pigeonpea. A range of addition lines would be expected and could be screened for marker characters and maintained with a low chance of crossing-over between homologous chromosomes. Conversely, addition or substituion lines with chromosomes of the wild species could be produced by crossing tetraploid pigeonpea × wild species. This technique may be routinely used in future when gene transfer between selected chromosomes of the wild species and pigeonpea is required.

Chromosome Identification

A reliable and convenient method of distinguishing chromosomes would allow faster classification of aneuploid stocks. Presently, the best means of identifying pigeonpea chromosomes is based on chromomere patterns of pachytene chromosomes (Reddy, 1981a; Dundas *et al.*, 1983). However, drawbacks to this method are; the occurrence of chromosome tangling, and the inconvenience of waiting for material to flower. Identification of somatic chromosomes would be more convenient, but present methods based on length measurements or C-bands are unsatisfactory. The development of a procedure showing more complex banding patterns (e.g., N- or G-bands) may allow distinctive charaterization of each of the pigeonpea mitotic chromosomes.

An expansion of research activity is expected to occur in the field of pigeonpea cytogenetics within the next few years. While applied research to solve specific problems affecting the pigeonpea should be a high priority in cytogenetical studies (e.g., breeding for disease resistance or drought tolerance), an investment of resources into basic research will expedite future transfer within the pigeonpea gene base and across species boundaries.

REFERENCES

Akinola, J.O., Pritchard, A.J. and Whiteman, P.C. (1972) Chromosome number in pigeonpea (*Cajanus cajan* (L.) Millsp.). *Journal of the Australian Institute of Agricultural Science* 38, 305-306.

Ariyanayagam, R.P. and Spence, J.A. (1978) A possible gene source for early, day-length neutral pigeonpeas, *Cajanus cajan* (L.) Millsp. *Euphytica* 27, 505-509.

Bajaj, Y.P.S., Singh, H. and Gosal, S.S. (1980) Haploid embryogenesis in anther cultures of pigeonpea *(Cajanus cajan). Theoretical and Applied Genetics* 58, 157-159.

Bhattacharjee, S.K. (1956) Study of autotetraploid *Cajanus cajan* (Linn.) Millsp. *Caryologia* 9, 149-159.

Bir, S.S. and Kumari, S. (1973) Fabaceae. In: Askell Love (ed), *IOPB Chromosome Number Reports XLI. Taxon* 22(4), 459-460.

Bir, S.S. and Kumari, S. (1977) Evolutionary status of Leguminosae from Pachmarhi, central India. *Nucleus* 20(1/2), 94-98.

Bir, S.S. and Sidhu, S. (1966) Fabaceae. In: Askell Love (ed), *IOPB Chromosome Number Reports VI. Taxon* 15(3), 119-121.

Bir, S.S. and Sidhu, S. (1967) Cytological observations on the Northern Indian members of family Leguminosae. *Nucleus* 10(1), 47-63.

Bisen, S.S. and Sheldrake, A.R. (1981) *The Anatomy of the Pigeonpea. Research Bulletin no. 5.* Patancheru, A.P., India: ICRISAT, 24 pp.

Chopde, P.R., Shinde, V.K. and Wanjari, K.B. (1979) A note on cytological studies in tetraploid pigeonpea (*Cajajus cajan* Millsp.). *Research Bulletin of the Marathwada Agricultural University* 3(3), 35-37.

Darlington, C.D. and Wylie, A.P. (1955) *Chromosome Atlas of Flowering Plants.* Second edition. George Allen and Unwin, London.

Datta, P.C. and Saha, N. (1972) A few trials of hybridization in Euphaseoleae and Cajaneae. *Castanea* 37(4), 294-297.

D'Cruz, R. and Jadhav, A.S. (1972) Aneuploidy in tur (*Cajanus cajan* (L.) Millsp.). *Research Journal of Mahatma Phule Agricultural University* 3(1), 61-62.

Deka, P.C., Mehra, A.K., Pathak, N.N. and Sen, S.K. (1977) Isolation and fusion studies on protoplasts from pollen tetrads. *Experientia* 33(2), 182-184.

Deodikar, G.B. and Thakar, C.V. (1956) Cyto-taxonomic evidence for the affinity between *Cajanus indicus* Spreng. and certain erect species of *Atylosia* W.&A. *Proceedings of the Indian Academy of Sciences, Section B* 43, 37-45.

Dhanju, M.S. and Gill, B.S. (1985) Integeneric hybridization between *Cajanus cajan* and *Atylosia platycarpa. Annals of Biology* 1, 229-231 (*Plant Breeding Abstracts* 57 Entry 2434, 1987).

Dhanju, M.S., Gill, B.S. and Sidhu, P.S. (1985) *In vitro* development of *Cajanus* x *Atylosia* hybrids. *Current Science* 54, 1284-1286.

Dundas, I.S. (1984) Cytogenetic investigations involving pigeonpea (*Cajanus cajan* (L.) Millsp.) and some Australian *Atylosia* species. Unpublished PhD thesis, Department of Agriculture, University of Queensland, Australia.

Dundas, I.S., Britten, E.J. and Byth, D.E. (1983) Pachytene chromosome identification by a key based on chromomeres in the pigeonpea. *Journal of Heredity* 74, 461-464.

Dundas, I.S., Britten E.J., Byth, D.E. and Gordon, G.H. (1986) Australian *Atylosia* species - a new gene source for pigeonpea breeders. In: Napompeth, B. and Subhadrabandhu, S. (eds), *New Frontiers in Breeding Researches. Proceedings of the Fifth International Congress Society for the Advancement of Breeding Researches in Asia and Oceania (SABRAO).* Kasetsart University, Bangkok, Thailand, pp. 389-395.

Dundas, I.S., Britten, E.J., Byth, D.E. and Gordon, G.H. (1987) Meiotic behavior of hybrids of pigeonpea and two Australian native *Atylosia* species. *Journal of Heredity* 78, 261-265.

Dundas I.S., Britten, E.J., Byth, D.E. and Gordon, G.H. (1988) The use of tangled pachytene chromosomes for karyotype analysis in *Atylosia. Journal of Heredity* 79, 175-178.

Dundas, I.S., Saxena, K.B. and Byth D.E. (1981) Microsporogenesis and anther wall development in male-sterile and fertile lines of pigeonpea (*Cajanus cajan* (L.) Millsp.). *Euphytica* 30, 431-435.

Dundas, I.S., Saxena, K.B. and Byth D.E. (1982) Pollen mother cell and anther wall development in a photoperiod-insensitive male-sterile mutant of pigeonpea (*Cajanus cajan* (L.) Millsp.). *Euphytica* 31, 371-375.

Gajapathy, C. (1962) Cytological observations in some dicotyledons. *Science and Culture* 28, 375-376.

Gill, L.S. and Husaini, S.W.H. (1986) Cytological observations in Leguminosae from Southern Nigeria. *Willdenowia* 15, 521-527.

Hunt, J.S. and Barnes, M.F. (1982) Molecular diversity and plant disease resistance: an electrophoretic comparison of near-isogenic lines of wilt-resistant or -susceptible *Pisum sativum* L. cv. William Massey. *Euphytica* 31, 341-348.

ICRISAT (1987) *Annual Report 1986*. Patancheru, A.P., India: ICRISAT, p. 201.

Joshi, K.S. (1966) Studies on autotetraploids of tur (*Cajanus cajan* (L.) Millsp.) with special reference to their utilization in breeding. *Nagpur Agriculture College Magazine (Special Research Number)*. Nagpur Agricultural College, Nagpur, India, p. 111.

Kanta, K. and Padmanabhan, D. (1964) *In vitro* culture of embryo segments of *Cajanus cajan* (L.) Millsp. *Current Science* 33, 704-706.

Kaul, C.L. and Singh, S.P. (1969) Validity of stain tests in determining pollen viability of some Papilionaceous plants. *Indian Journal of Agricultural Sciences* 39, 1050-1056.

Keighery, G.J. (1978) Chromosome numbers in Western Australian plants I. *Journal of Proceedings of the Royal Society of Western Australia* 60(4), 105-106.

Khamankar, Y.G. (1966) Induction of polyploidy by colchicine treatment in some of the crop plants. *Nagpur Agriculture College Magazine (Special Research Number)*. Nagpur Agriculture College, Nagpur, India, pp. 101-102.

Krishna, T.G. and Reddy, L.J. (1982) Species affinities between *Cajanus cajan* and some *Atylosia* species based on esterase isoenzymes. *Euphytica* 31, 709-713.

Krishnaswamy, N. and Ayyangar, G.N.R. (1935) Chromosome number in *Cajanus indicus* Spreng. *Current Science* 3, 614-615.

Kumar, A.S., Reddy, T.P. and Reddy, G.M. (1983) Plantlet regeneration from different callus cultures of pigeonpea (*Cajanus cajan* L.). *Plant Science Letters* 32, 271-278.

Kumar, A.S., Reddy, T.P. and Reddy, G.M. (1984) Adventitious shoot formation and plantlet regeneration in pigeonpea. *International Pigeonpea Newsletter* 3, 12-15.

Kumar, A.S., Reddy, T.P. and Reddy, G.M. (1985) Genetic analysis of certain *in vitro* and *in vivo* parameters in pigeonpea (*Cajanus cajan* L.). *Theoretical and Applied Genetics* 70, 151-156.

Kumar, L.S.S., Abraham, A. and Srinivasan, V.K. (1945) Preliminary note on autotetraploidy in *Cajanus indicus* Spreng. *Proceedings of the Indian Academy of Sciences, Section B*, 21, 301-306.

Kumar, L.S.S., Shama Rao, H.K. and Thombre, M.V. (1966) Interspecific and intergeneric hybridization in the breeding of crop plants. *Indian Journal of Genetics and Plant Breeding* 26A, 114-120.

Kumar, L.S.S. and Thombre, M.V. (1958) An intergeneric hybrid of *Cajanus cajan* (L.) Millsp. x *Atylosia lineata* W.&A. *Journal of the University of Poona* 12, 13-16.

Kumar, L.S.S., Thombre, M.V. and D'Cruz, R. (1958) Cytological studies of an intergeneric hybrid of *Cajanus cajan* (Linn.) Millsp. and *Atylosia lineata* W.&A. *Proceedings of the Indian Academy of Sciences, Section B* 47, 252-262.

Kumar, P. and Sinha, S.S.N. (1983) Meiotic analysis in thirteen varieties of *Cajanus cajan* Linn. (Millsp.). *Genetica Iberica* 35 (1/2), 39-48.

Kumar, P.S. (1985) Crossability, genome relationships and inheritance studies in intergeneric hybrids of pigeonpea. Unpublished PhD thesis, University of Hyderabad, India.

Kumar, P.S, Subrahmanyam, N.C. and Faris, D.G. (1983) Studies on developing pigeonpea haploids. *International Pigeonpea Newsletter* 2, 14-15.

Kumar, P.S., Subrahmanyam, N.C. and Faris, D.G. (1984a) Nucleolar variation in a pigeonpea intergeneric hybrid: evidence for allosyndetic recombination. *Canadian Journal of Genetics and*

Cytology 25, 499-505.

Kumar, P.S., Subrahmanyam, N.C. and Faris, D.G. (1984b) *In vitro* regeneration of *Cajanus* and *Atylosia* plants. *International Pigeonpea Newsletter* 3, 15-16.

Kumar, P.S., Subrahmanyam, N.C. and Faris, D.G. (1985a) Intergeneric hybridization in pigeonpea. I. Effect of hormone treatments. *Field Crops Research* 10, 315-322.

Kumar, P.S., Subrahmanyam, N.C. and Faris, D.G. (1985b) Morphological variation and inheritance in a pigeonpea intergeneric hybrid. *Current Science* 54, 346-348.

Kumar, P.S., Subrahmanyam, N.C. and Faris, D.G. (1985c) Plantlet regeneration from immature embryos of pigeonpea. *International Pigeonpea Newsletter* 4, 11-13.

Kumar, P.S., Subrahmanyam, N.C. and Faris, D.G. (1987) Nucleolar behavior in pollen mother cells in the pigeonpea. *Journal of Heredity* 78, 366-368.

Lackey, J.A. (1980) Chromosome numbers in the Phaseoleae (Fabaceae:Faboideae) and their relation to taxonomy. *American Journal of Botany* 67, 595-602.

Ladizinsky, G. and Hamel, A. (1980) Seed protein profiles of pigeonpea (*Cajanus cajan*) and some *Atylosia* species. *Euphytica* 29, 313-317.

Lavania, U.C. and Lavania, S. (1982) Chromosome banding patterns in some Indian pulses. *Annals of Botany* 49, 235-239.

Mehta, U. and Mohan Ram, H.Y. (1980) Regeneration of plantlets from the cotyledons of *Cajanus cajan*. *Indian Journal of Experimental Biology* 18, 800-802.

Mohamed, A.A.H., Ali, A.M. and Desouki, I.A.M. (1979) Success of some intergeneric crosses in the tribe Phaseoleae. *Research Bulletin, Faculty of Agriculture, Ain Shams University no. 1056.* Ain Shams University, Cairo, Egypt, 18 pp. (*Plant Breeding Abstracts* 51(5) Entry 4677, 1981).

Moss, J.P., Singh, A.K., Sastri, D.C. and Dundas, I.S. (1988) Wide hybridization in legumes at ICRISAT. In: *Biotechnology in Tropical Crop Improvement: Proceedings of the International Biotechnology Workshop, 12-15 January 1987, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 87-95.

Mukhopadhyay, S. (1986) Intergeneric relationship between three genera of Leguminosae. *Journal of the Indian Botanical Society* 65, 124-129.

Naithani, S.P. (1941) Cytological studies on Indian pulses. Part I—the somatic chromosomes and the prochromosomes of *Cajanus*. *Proceedings of the National Academy of Science, India* 11, 67-73.

Pathak, G.N. (1948) Cytological studies of a spontaneously-originated tetraploid *Cajanus cajan* Millsp. *Indian Journal of Genetics and Plant Breeding* 8, 68-71.

Pathak, G.N. and Yadava, R.S. (1951) Spontaneously-originated hexaploid and tetraploid plants in *Cajanus cajan* Millsp. *Current Science* 20, 304.

Pundir, R.P.S. and Singh, R.B. (1978) Leguminosae. In: Askell Love (ed), *IOPB Chromosome Number Reports LXII. Taxon* 27(5/6), 533-534.

Pundir, R.P.S. and Singh, R.B. (1983a) Analysis of root tip chromosomes of UPAS 120 pigeonpea. *International Pigeonpea Newsletter* 2, 11-12.

Pundir, R.P.S. and Singh, R.B. (1983b) Cross-compatibility among *Cajanus*, *Atylosia*, and *Rhynchosia* species. *International Pigeonpea Newsletter* 2, 12-14.

Pundir, R.P.S. and Singh R.B. (1983c) Inheritance of some qualitative traits in *Cajanus* and *Atylosia* crosses. *International Pigeonpea Newsletter* 2, 11.

Pundir, R.P.S. and Singh, R.B. (1985a) Crossability relationships among *Cajanus*, *Atylosia* and *Rhynchosia* species and detection of crossing barriers. *Euphytica* 34, 303-308.

Pundir, R.P.S. and Singh, R.B. (1985b) Cytogenetics of F_1 hybrids between *Cajanus* and *Atylosia* species and its phylogenetic implications. *Theoretical and Applied Genetics* 71, 216-220.

Pundir, R.P.S. and Singh, R.B. (1985c) Biosystematic relationships among *Cajanus*, *Atylosia*, and *Rhynchosia* species and evolution of pigeonpea (*Cajanus cajan* (L.) Millsp.). *Theoretical and Applied Genetics* 69, 531-534.

Pundir, R.P.S. and Singh, R.B. (1986) Karyotypic analysis of *Cajanus*, *Atylosia* and *Rhynchosia* species. *Theoretical and Applied Genetics* 72, 307-313.

Pundir, R.P.S. and Singh, R.B. (1987) Possibility of genetic improvement of pigeonpea (*Cajanus cajan* (L.) Millsp.) utilizing wild gene sources. *Euphytica* 36, 33-37.

Rao, N.K. (1978) Leguminosae. In: Askell Love (ed), *IOPB Chromosome Number Reports LXII. Taxon* 27(5/6), 534.

Reddy, B.V.S., Green, J.M. and Bisen, S.S. (1978) Genetic male sterility in pigeonpea. *Crop Science* 18, 362-364.

Reddy, L.J. (1981a) Pachytene analyses in *Cajanus cajan, Atylosia lineata* and their hybrid. *Cytologia* 46, 397-412.

Reddy, L.J. (1981b) Pachytene analysis in *Atylosia sericea* and *Cajanus cajan* x *A. sericea* hybrid. *Cytologia* 46, 567-577.

Reddy, L.J. (1981c) Pachytene analyses in *Atylosia scarabaeoides* and *Cajanus cajan* x *A. scarabaeoides* hybrid. *Cytologia* 46, 579-589.

Reddy, L.J. (1984) Fusion of centromeres and star formations at pachytene of *Cajanus* x *Atylosia* hybrids. *Heredity* 53, 435-439.

Reddy, L.J. and De, D.N. (1983) Cytomorphological studies in *Cajanus cajan* x *Atylosia lineata*. *Indian Journal of Genetics and Plant Breeding* 43, 96-103.

Reddy, L.J., Green, J.M. and Sharma, D. (1981) Genetics of *Cajanus cajan* (L.) Millsp. × *Atylosia* spp. In:*Proceedings of the International Workshop on Pigeonpeas, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 39-50.

Rieger, R. Michaelis, A. and Green, M.M. (1976) *Glossary of Genetics and Cytogenetics–Classical and Molecular*. Fourth edition. Springer-Verlag, Berlin, 647 pp.

Roy, A. and De, D.N. (1965) Integeneric hybridization of *Cajanus* and *Atylosia*. *Science and Culture* 31, 93-95.

Roy, B. (1933) Studies in the development of the female gametophyte in some leguminous crop plants of India. *Indian Journal of Agricultural Sciences* 3, 1098-1107.

Sanjappa, M. and Sathyananda, N. (1979) Fabaceae. In: Askell Love (ed), *IOPB Chromosome Number Reports LXIV. Taxon* 28(4), 393-394.

Saxena, K.B., Dundas, I.S., Byth, D.E. and Wallis, E.S. (1982) Effect of spontaneous chromosome doubling on some vegetative and reproductive characteristics of pigeonpea [*Cajanus cajan* (L.) Millsp.]. *Legume Research* 5, 83-86.

Schulz-Schaeffer, J. (1980) *Cytogenetics, Plants, Animals, Humans*. Springer-Verlag, New York, 446 pp.

Sen, N.K. and Mukhopadhyay, I. (1961) Studies in embryo culture of some pulses. *Indian Agriculturalist* 5, 48-56.

Sharma, A.K. and Sharma, A. (1980) *Chromosome Techniques: Theory and Practice*. Third edition. Butterworths, London, Sydney.

Sharma, P.C. and Gupta, P.K. (1982) Karyotypes in some pulse crops. *Nucleus* 25(3), 181-185.

Shohet, S. and Strange, R.N. (1987) Isolation of single cells and protoplasts from pigeonpea leaves. *International Pigeonpea Newsletter* 6, 17-19.

Shrivastava, M.P. and Joshi, R.K. (1972) A smear technique for root tip chromosome preparation of *Cajanus cajan* (L.) Millsp. *JNKVV Research Journal* 6(1), 59-60.

Shrivastava, M.P., Laxman Singh and Joshi, R.K. (1972) Induction and cytomorphological study of autotetraploidy in *Cajanus cajan* (L.) Millsp. *JNKVV Research Journal* 6(1), 47-50.

Shrivastava, M.P., Sharma, D. and Laxman Singh (1973) Karyotype analysis in 15 varieties of *Cajanus cajan* (L.) Millsp. and *Atylosia lineata* (W.&A.). *Cytologia* 38, 219-227.

Singh, D.N., Bansal, R.K. and Mital, S.P. (1942) *Cajanus obcordifolia* Singh–A new species of *Cajanus*. *Indian Journal of Agricultural Sciences* 12, 779-784.

Sinha, R.R., Das, K. and Sen, S.K. (1983) Nutritional requirement of tissue cultures of some tropical legume crops. *Indian Journal of Experimental Biology* 21, 113-119.

Sinha, S.S.N. and Kumar, P. (1979) Mitotic analysis in thirteen varieties of *Cajanus cajan* (L.) Millsp. *Cytologia* 44, 571-580.

Srivastava, V. (1978) Pollen morphology of *Cajanus cajan* (L.) Willd. (Leguminosae) cultivars and their hybrids. *Grana* 17, 107-109.

Tewari, V. and Singh, B.D. (1986) Cytological behaviour of autotetraploids in pigeonpea *Cajanus* *cajan* (L.) Millsp. *Narendra Deva Journal of Agricultural Research* 1(2), 163-166 (*Plant Breeding Abstracts* 58(10) Entry 9139, 1988).

Tewari, V., Singh, R.B. and Singh, B.D. (1981) Colchicine induced tetraploids in pigeonpea (*Cajanus cajan* (L.) Millsp.). *Legume Research* 4, 83-89.

Tripathi, S.N. Patil, B.D. and Shukla, G.P. (1984) Phylogenic and hybridization potentials in *Atylosia* and *Cajanus* species. *Forage Research* 10, 5-9.

van der Maesen, L.J.G. (1986) *Cajanus DC. and Atylosia W.&A. (Leguminosae). Agricultural University Wageningen Papers 85-4 (1985).* Agricultural University, Wageningen, the Netherlands, 225 pp.

Xu, Z., Davey, M.R. and Cocking, E.C. (1985) Root protoplast isolation and culture in higher plants. *Scientia Sinica* 28(4), 386-392.

Young, Nevin D., Zamir, Daniel, Ganal, Martin W. and Tanksley, Steven D. (1988) Use of isogenic lines and simultaneous probing to identify DNA markers tightly linked to the *Tm-2a* gene in tomato. *Genetics* 120, 579-585.

Chapter 6

PIGEONPEA: GENETICS

K.B. SAXENA and D. SHARMA

Senior Plant Breeder, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Andhra Pradesh 502 324, India and Grain Legume Breeder, Malang Research Institute for Food Crops (MARIF), P.O. 66, Malang 65101, East Java, Indonesia.

INTRODUCTION

Until recently *Cajanus* was considered a monotypic genus belonging to the tribe Phaseoleae, sub-tribe Cajaninae, family Leguminosae, and sub-family Papilionacae. The earlier sub-divisions *Cajanus bicolor* DC. and *Cajanus flavus* DC. based on flower colour, seeds per pod, length of stripes, and flowering duration etc. represent simple genetic variation and are now considered different forms or varieties (Pathak, 1970). However, van der Maesen (1986) has recently revised the taxonomy of the genera *Cajanus* and *Atylosia* and the two are merged into one genus *Cajanus* as proposed earlier by Roy and De (1965). Hybrids between pigeonpea and some *Cajanus* species have been successfully attempted by several workers, since the studies by Deodikar and Thakar in 1956. *Cajanus* species inter-fertile with pigeonpea belong to the secondary gene pool of pigeonpea, and the species that do not cross with pigeonpea belong to the tertiary gene pool. Scientists at ICRISAT Center have successfully incorporated genes for high protein from *Cajanus scarabaeoides* var. *scarabaeoides* and *Cajanus sericeus* into pigeonpea cultivars (Saxena *et al.*, 1984).

Among the cultivated crops pigeonpea has the maximum range for maturity duration extending from 90 to 300 days. In the past, identification of an appropriate maturity duration type for a given environment and cropping system was the dominant feature of adaptation and evolution for this crop. This resulted in the isolation of maturity types, and restricted gene flow from one maturity group to other. However, the cross-pollinating nature of the crop has resulted in the maintenance of a reservoir of wide genetic variability in a given maturity gene pool of landraces.

Mahta and Dave (1931) studied the landraces in Madhya Pradesh (then Central Provinces), India and reported the morphological features of 36 different types in cultivation.

In recent years extensive inter-maturity group hybridizations initiated at ICRISAT Center have resulted in broadening the genetic variability within a particular maturity duration and the production of new character combinations, such as; large seed size and an increased number of seeds per pod in short-duration types, and resistance to sterility mosaic disease in short- and medium-duration types.

The large genetic variation available in over 11,000 pigeonpea accessions held in the ICRISAT gene bank, the hybridization of diverse maturity types, and the introgression of genes from the secondary gene pool of *Cajanus* species, offer tremendous scope and opportunity to develop improved pigeonpea types for different agro-ecological situations, farming systems, and crop use, e.g., varieties for sole, inter-, and alley cropping, dry seed or green seeds for vegetable purposes, fuel wood, and forage production, etc.

Recently, the development of relatively photoperiod-insensitive, short-duration (Maturity group 0) genotypes at ICRISAT Center has opened up new vistas for extending the adaptation of the crop to sub-tropical high elevations and temperate regions, where pigeonpea can be successfully grown under irrigation during the short summer season despite long days. Extension of pigeonpea cultivation to nontraditional areas and well-managed sole cropping systems with high plant populations and irrigation is likely to require different plant types, growth habits, and combinations of seed and pod characteristics, besides resistance to diseases and pests that are less economically important when pigeonpea is cultivated under subsistence farming conditions.

There has been no systematic sustained effort to study various aspects of pigeonpea genetic systems. Sporadic efforts have been confined to the inheritance of some qualitative and quantitative characters, and combining ability studies involving limited germplasm. The lack of cultivar genetic purity due to frequent cross-pollination, and inadequate research support have limited wellplanned detailed genetic studies on this crop. Sharma and Green (1975) discussed genetic limitations and the scope for pigeonpea improvement. This chapter presents available information on various aspects of pigeonpea genetics, and its implications.

QUALITATIVE GENETICS

Leaflets

Shape

In general the trifolate leaflets of pigeonpea are lanceolate, but some morphological variations in leaflet shape have been reported. According to D'Cruz *et al.* (1971), the first report of inheritance of leaflet shape in pigeonpea was published by Pandya *et al.* (1954). They referred to both obovate and round-shaped leaflets and reported an F_2 ratio of 3 lanceolate:1 round leaflets. The monogenic inheritance of lanceolate leaflet shape was also confirmed by Patil and D'Cruz (1965), Deokar *et al.* (1971), D'Cruz and Deokar (1970), and D'Cruz *et al.* (1971). Deshpande and Jeswani (1956) observed segregation ratios of 3:1 for lanceolate and 15:1 for obcordate leaflets in the F_2 generation of two different crosses. D'Cruz *et al.* (1971) reported a ratio of 117 oblong or oval (round) leaflets with obtuse apecies:75 lanceolate leaflets with acute apecies:64 obçordate leaflets with retuse apecies in the F_2 population of a cross involving obcordate and round(oval) leaflet types. D'Cruz *et al.* (1973) reported monogenic inheritance in round × obcordate leaflet types, and assigned the gene symbols llt_r, and *llt*. They concluded that three allelic genes *Llt*, llt_r, and *llt* are involved in the inheritence of lanceolate, round, and obcordate leaflet shapes.

Stem

Colour

The predominant stem colour in pigeonpea germplasm of Indian origin is green, while in African germplasm the predominant colour is purple. In certain cases, unstable purple stem pigmentation due to the exposure of stems to direct sunlight is observed. Purple stem colour was found dominant to green and to be controlled by a single factor *Pst* (D'Cruz and Deokar, 1970; D'Cruz *et al.*, 1971; D'Cruz *et al.*, 1974). However, in a cross between cultivars N. Black × Purple Grained, Deokar and D'Cruz (1972) reported an F_2 ratio of 45 purple:19 green, and suggested that three genes Pst_a, Pst_b, and Pst_c governed stem colour in this cross. These simply inherited contrasting stem colours i.e., purple vs green have been used as markers to detect the extent of natural out-crossing in pigeonpea (Bhatia *et al.*, 1983).

Secondary Growth

Saxena *et al.* (1988a) reported a corky-stem in pigeonpea caused by the development of an additional periderm layer in the stem. This character is governed by two genes one recessive *(sm)*, and the other dominant *(Ck)*. For the corky stem character to develop, the presence of the *Ck* allele in either the homozygous or heterozygous condition is essential. The dominant *sm* allele completely masked the expression of the *Ck* allele and resulted in a normal, smooth stem surface.

Flower

Colour

The inheritance of creamy white flowers was reported by Patil and D'Cruz (1962). They observed an F_2 ratio of 49 yellow:15 creamy white. Patil *et al.* (1972) confirmed the dominance of yellow over white flowers and assigned the gene symbol *Yfl* to yellow flower colour.

The genetics of the colour of the ventral surface of standard petals was first reported by Dave (1934), who found an F_2 ratio of 3 orange:1 yellow. Shaw (1936), D'Cruz and Deokar (1970), and D'Cruz *et al.* (1971) confirmed single gene inheritance for this character and assigned the gene symbol *Yvs*. However, Deokar and D'Cruz (1972) reported dihybrid complementary gene action and they assigned the gene symbols $Oyvs_a$ and $Oyvs_b$. Deokar *et al.* (1972b) found that this trait was controlled by four factors, and symbolized the genes as Yvs_a, Yvs_{b2}, Yvs_{c2}, and Yvs_{d2}.

Deokar and D'Cruz (1972) observed that the colour of the dorsal surface of the standard petal was governed by a single dominant gene, $Oyvs_a$. In another cross, Deokar and D'Cruz (1971) reported that this trait was governed by two genes, *Llt* and *I-Llt*. Of these, one was basic, and the other inhibitory in action. D'Cruz *et al.* (1973) found that the colour of the dorsal surface of the standard petal was due to the presence of two complementary genes, $Oyds_a$ and $Oyds_b$. Marekar and Chopde (1985) reported that the colour of the dorsal surface of pigeonpea flowers was controlled by four genes. These include one basic *(Rvds)*, one inhibitory *(I-Rvds)*, and two anti-inhibitoty ($A\text{-}I\text{-}Rvds_1$ and $A\text{-}I\text{-}Rvds_2$). Jain and Joshi (1964) found that colour of the veins and dorsal surface was due to the presence of two factors. According to them gene *V* was responsible for deep purple veins, and gene *P* diluted the effect of gene *V* resulting in light purple veins but with *v* it gave yellow veins. Deokar and D'Cruz (1971) reported that the colour of veins on the dorsal surface of standard petals was governed by three factors *Llt*, *I-Llt*, and *A-I-Llt*, one of which *(I-Llt)* was inhibitory to the main factor for purple veins *(Llt)*, and the other *(A-I-Llt)* was anti-inhibitory in action. Deokar *et al.* (1971) observed that a purple-veined dorsal surface on standard petals was dominant to yellow veins, and due to two duplicate factors $Pvds_1$, $Pvds_2$. D'Cruz *et al.* (1974) and Patil (1970) reported the dominance of red vein colour over yellow. A gene symbol *Rdvds* for red vein was assigned. Kolhe *et al.* (1972) found a dihybrid complementary ratio involving genes $Rdvds_a$ and $Rdvds_b$.

Male Sterility

In pigeonpea male sterility coupled with natural out-crossing can be utilized to improve populations and develop high-yielding hybrids. Several forms of genetic male sterility in pigeonpea were identified by Reddy *et al.* (1977). The most useful of these forms was characterized by translucent anthers caused by the non-separation of tetrads, associated with a persistent tapetum, and controlled by single recessive gene ms_1. Another source of genetic male sterility, characterized by brown arrow-head shaped anthers, and controlled by a single recessive gene (ms_2) was reported by Saxena *et al.* (1983a). These two genetic male-sterile systems are conditioned by different and independent genetic systems (Saxena *et al.*, 1983b). Saxena *et al.* (1981a) reported partial male sterility in pigeonpea and based on the F_1 and F_2 data of a cross between fertile and partially sterile lines, they reported that this character was controlled by a single recessive gene.

Floral Modifications

Two floral modifications, wrapped flower and cleistogamous "free-stamen" flower, which ensure self-pollination in pigeonpea, have been identified. On the basis of F_1 and limited F_2 data, Byth *et al.* (1982) observed that the genes for wrapped flowers were dominant in action. Unpublished work at ICRISAT Center has shown that the "free-stamen" trait, derived from an intergeneric cross, is governed by a single recessive gene.

Pod

Colour

Krauss (1927) was the first to study variation for pod colour in the F_2 generation, and reported a ratio of 3 maroon blotched:1 light tinted. Later on Shaw (1931), Wilsie and Takahashi (1934), and D'Cruz *et al.* (1970) reported that streaked pod colour was dominant over green pod colour, and that a single gene was responsible for streaked pods. A dihybrid F_2 segregation (9 dark:3 maroon blotched:4 green) was reported by Dave (1934) and de Menezes (1956). A single gene dominance of greenish-black pod colour over maroon blotched was reported by Patil and D'Cruz (1965). An F_2 ratio of 15 blotched:1 green was observed by D'Cruz and Deokar (1970) and they assigned the gene symbols $Gppd_1$ and $Gppd_2$. Deokar and D'Cruz (1971) on the contrary, assigned gene symbols *Blp* and *I-Llt*. Deokar *et al.* (1971) reported a dihybrid supplementary gene action (9 purple:3 green with purple streaks:4 green with purple shade). Deokar *et al.* (1972a) found that the colour development in unripe pigeonpea pods was due to the interaction of four factors, two of which (Blp_1 and Blp_2) were basic, one was inhibitory *(I-Blp)*, and one anti-inhibitory *(A-I-Blp)*. Deokar *et al.* (1971) assigned *Gpstpd* and *Gpshpd* as symbols for the genes determining purple pod colour.

Saxena *et al.* (1984) observed intra-plant pod colour variation in a pure-breeding pigeonpea line ICP 3773, where the pods within a plant and within a branch on a plant were either completely green and/or green with purple streaks of variable intensities. They postulated that this pod colour variation and its unpredictable expressivity was perhaps governed by the presence, absence, or interaction of one or more unstable genes. They further hypothesized that these genes would be able to suppress the expression of the stable pod colour genes. The suppression was complete in green pods and incomplete in streaked pods.

Open Carpel

Saxena *et al.* (1988b) identified an open carpel mutant in pigeonpea in which the development of the placenta and ovule were restricted, and the carpel was open because a ventral suture did not develop. This condition was found to be under the control of single recessive gene *cd*$_1$.

Seed

Colour

A dihybrid F$_2$ ratio for seed colour 9 purple black:3 white with purple spots:3 brown:1 white was reported by Dave (1934) and de Menezes (1956). In crosses between reddish-brown and white-seeded genotypes, Dave (1934) and Deokar *et al.* (1971) reported that brown seed colour was dominant over white and was controlled by a single gene *Brsd*. But, D'Cruz and Deokar (1970) and Deokar and D'Cruz (1971) found a dihybrid ratio (9 reddish brown:7 white) in the F$_2$ generation, and assigned gene symbols *Llt* and *Brsd*. D'Cruz *et al.* (1973), in a cross involving cultivars round leaf × purple grain, reported a dihybrid (9:3:3:1) F$_2$ ratio and assigned gene symbols *Brsd* to round leaf and *Wpsd* to purple grained. In another cross, involving cultivars obcordifolia × purple grained, they reported an F$_2$ ratio of 9 brown:7 white and the two genes involved were assigned *Brsd*$_a$ and *Brsd*$_b$. Deokar and D'Cruz (1972) classified the F$_2$ population of a cross involving cultivars N. Black × purple grained into six phenotypic classes and two genes *Oyvs*$_a$ and *Brsd* were suggested as responsible for seed coat colour. Deokar *et al.* (1972a) demonstrated that in a cross involving Red Grained × round leaf mutant, the red seed was dominant to white and was controlled by one gene, designated as *Rsd*. Similar results were also reported by Marekar and Chopde (1985). Patil *et al.* (1972) observed that reddish brown seed colour was governed by three genes symbolized as *Brsd*$_1$, *Brsd*$_2$, and *Brsd*$_3$. The genetics of seed colour in pigeonpea seem to be quite complicated and influenced by basic genes, inhibitory gene action, modifiers, and probably unstable gene systems as has also observed in several other crops. To reach a proper understanding, detailed and well planned studies are required to determine the genetic systems involved.

Disease Resistance

The resistance or susceptibility of a crop plant to a particular disease pathogen is the manifestation of the host and parasite interaction controlled by the co-evolving genetic systems of both the host and the parasite. In centres of origin and crop diversity, the host population contains a wide spectrum of protective mechanisms, that ensure survival against a high diversity of pathogenicity in the parasite. This results in a host/parasite equilibrium, and most of the host genotypes have some degree of resistance against the parasite. However, on the contrary, in new areas of crop adaptation and intensive cultivation of a particular genotype, genes for virulence to overcome the narrow genetic base of the host are favoured, causing susceptibility in the new cultivar.

Simmonds (1981) discussed the importance of horizontal resistance (HR) present in landraces and vertical resistance (VR), present in highly selected new varieties, in relation to crop breeding strategies. He emphasized that although VR genes are easy to handle and useful in certain situations, the loss of HR during the process of selecting for high VR is hazardous and responsible for disease epidemics.

In the past pigeonpea cultivation in India, and areas of Africa and Latin America, has been confined to subsistence agriculture based on adapted landraces. The development of improved varieties by hybridization and selection under experimental conditions, and cultivation in intensive production systems under irrigated conditions is a relatively recent phenomenon. Therefore, for planned disease management, it is essential that the genetic systems operating in a given host/pathogen environment are well understood. At present studies on the genetics of disease resistance are limited and preliminary.

More than 50 pigeonpea diseases caused by a number of causal agents have been documented. However, only some diseases cause serious economic losses to this crop. Nene *et al.* (1981) reviewed the disease situation in different pigeonpea growing regions and concluded that on the Indian subcontinent and in eastern Africa fusarium wilt *(Fusarium udum)* is the most important disease. Sterility mosaic and phytophthora blight *(Phytophthora drechsleri* f. sp *cajani)* are two other important diseases on the Indian sub-continent. Alternaria blight *(Alternaria tenuissima)* is an important disease affecting the late-sown pigeonpea crop in eastern and northeastern India. Plant breeders and pathologists have been successful in identifying sources of resistance and have bred cultivars resistant to one or more diseases. However, the effects of resistant varieties on crop production and the dynamics of host/parasite interactions are not known, since production in the farmers fields is still dominated by landraces or direct selections from them.

Wilt

Pal (1934) reported that the resistance to wilt in pigeonpea was controlled by multiple factors, while Shaw (1936) observed that two complementary genes conferred resistance to wilt. Pathak (1970) confirmed the presence of two complementary genes that determine resistance to wilt. Joshi (1957) reported that a single dominant gene controlled wilt resistance in the cross he studied. Pawar and Mayee (1986) also observed that resistance to wilt in 10 crosses studied under wilt-sick conditions was determined by a single dominant gene. Sharma (1986) discussed the probable causes of variability in a proportion of resistant and susceptible plants in different generations of different crosses. He confirmed the dominance of resistance over susceptibility, and suggested that the resistant parents (ICP 8860 and ICP 8869) had major genes for wilt resistance, while the susceptible parent (ICP 6997) had minor or polygenes for field resistance, and that it's degree of susceptibility varied from place to place within the wilt-sick nursery. This type of genetic system is likely to influence the proportion of resistant and susceptible plants in segregating populations in a random fashion, and consequently complicate the genetic ratios and their interpretations. He studied F_1, F_2, BC_1, and BC_2 populations along with the parents. It would be helpful to study F_3 and F_4 lines and families to obtain a better understanding of the genetics of wilt resistance based on progeny and family reactions rather than on a single plant's reaction. Selection procedures need to be adopted so that selection for both major and minor genes is possible. The combination of the two genetic systems is likely to confer more stable resistance to wilt.

Sterility Mosaic

The causal agent of this disease has yet to be clearly established, but it is believed to be a virus. Seth (1962) and Nene (1972) reported that the causal organism is transmitted by eriophyid mite *Aceria cajani*.

Singh, B.V. *et al.* (1983) studied the inheritance of resistance to sterility mosaic disease in 15 crosses involving 5 resistant and 3 susceptible genotypes in F_1, F_2, BC_1, and BC_2 generations. They postulated that resistance to this disease was under the control of four independent loci, consisting of two duplicate dominant genes (Sv_1 and Sv_2) and two duplicate recessive genes (sv_3 and sv_4). For the expression of resistance at least one dominant allele at locus 1 or 2 and homozygous recessive genes at locus 3 or 4 are essential. However, observations from the set of crosses studied by the authors are not adequate to establish clear allelic relationships among the resistant genes, and one fails to understand the interpretations of the data by the authors. To establish allelic relationships among the resistant genes it is essential that crosses among all resistant parents for disease reaction are studied.

Sharma *et al.* (1984) reported observations on the inheritance of resistance involving susceptible, tolerant (ring spot), and resistant genotypes in the F_1 and F_2 generations. They found that in all crosses susceptibility was dominant over tolerance and resistance, but that resistant lines differed in the expression of their resistance in the crosses with tolerant genotypes. In certain crosses the tolerance was dominant over resistance of certain lines, while it was recessive to the resistance in other lines. In crosses between resistant and susceptible lines they observed 9:7 and 3:1 segregation for resistant and susceptible reactions in different crosses. They explained the disease reaction in F_1 and segregation in F_2 on the basis of two genes and more than two alleles per locus. It appears that inheritance of resistance to sterility mosaic is complicated, and determined by multiple allelic series. In order to determine the numbers of, and hierarchical relationships between the alleles it would be desirable to study a large number of crosses with varying disease-resistant reactions, and inter- and intra-group crosses between different resistant and susceptible types.

Phytophthora and Alternaria Blights

Sharma *et al.* (1982) studied inheritance of resistance to the P2 isolate of *Phytophthora drechsleri* f.sp *cajani* fungus in pot culture and under field conditions. They reported that the resistance to this pathogen is controlled by a single dominant gene Pd_1.

Sharma *et al.* (1987) reported that resistance to alternaria blight (*Alternaria tenuissima*) is widely distributed in pigeonpea and its wild relative *Cajanus* spp. Observations of F_1 and F_2 generations from three crosses involving resistant and susceptible cultivars indicated that resistance to alternaria blight was controlled by a single recessive gene, abr_1. Singh *et al.* (1988) confirmed its monogenic recessive nature, but gave it the gene symbol al_1.

Growth Habit and Plant Type

Most pigeonpeas can be conveniently grouped on the basis of growth habit into indeterminate and determinate types. However, sometimes the segregants from crosses involving indeterminate and determinate types express an intermediate condition resulting in a semi-determinate growth habit. In indeterminate types the racemes form a long terminal panicle, while in determinate types a somewhat corymb-shaped inflorescence terminates the growth. The semi-determinate types have a condensed short-panicled inflorescence with flowers bunched together at the top.

Besides the basic growth habit, plant types in pigeonpea are determined by erect and decumbent stem characteristics, branching habit (primary, secondary, and tertiary) and branch angle. Plant height, though important, varies a good deal with latitude and time of sowing mainly because of its sensitivity to daylength. However, there is a considerable genetic variation for plant height, and types can be conveniently referred to according to their plant height at a given location. Height can vary from less than 1 m to 3-4 m.

The determinate types are relatively earlier in maturity duration and are shorter in height than the commonly cultivated indeterminate types, that are adapted to a wide range of moisture regimes, soil types, and subsistence farming systems. Determinate types have received plant breeders' attention in recent years and are adapted to well managed sole-cropping systems in irrigated areas.

Besides the normal traditionally cultivated types a number of mutant plant types have been isolated and are being maintained as genetic stocks. These include decumbent, dwarf, and non-branching single culm types.

In traditional subsistance farming, involving mixed and inter-cropping of all kinds, tall types have advantages. In recent years farmers have shown preference for; short-duration determinate types for intensive sole cropping in non-traditional pigeonpea-growing areas, and dwarf types for ease of insecticide application. However, little attention has been given to the study of the genetics of different component characteristics of plant type, particularly character correlation (associated characters, and correlated responses or linkage relationships), and interactions in crosses involving different plant types, that are useful when breeding crop varieties for different conditions.

Shaw (1936) reported the dominance of "crowded" over "open" inflorescences. According to Waldia and Singh (1987a), Shaw perhaps identified the "crowded" and "open" inflorescences as determinate and indeterminate growth habits. However, experience at ICRISAT Center with hundreds of crosses involving indeterminate and determinate types has shown that indeterminate growth habit is dominant. In certain crosses particularly those involving such large-seeded types as ICP 7035 and Hy 3C that have short, condensed, indeterminate, or semi-determinate inflorescences, the hybrids also have rather short, condensed inflorescences. Shaw (1936) perhaps studied such crosses and reported the determinate growth habit as being dominant. True determinate types such as Prabhat and Pusa Ageti were established only in the early 1960s. Reddy and Rao (1974) also reported the dominance of the monogenically indeterminate growth habit. In crosses T 21 × AL 15 and ICPL 94 × H 76-20, Waldia and Singh (1987a) reported that two dominant genes, *Id* and *D* with epistatic (inhibitory) interaction, control the indeterminate growth habit in pigeonpea.

The inheritance of determinate, indeterminate, and semi-determinate characters have been studied at ICRISAT Center. Results indicate that these traits are governed by two independent genes. Indeterminate was dominant to determinate and controlled by a single gene, *Nd* (S.C. Gupta, ICRISAT, personal communication). Similarly, semideterminate was dominant over determinate and was governed by one gene, *Sd*. The crosses between semi-determinate and indeterminate types segregated into 12 indeterminates:3 semi-determinates:1 determinate in the F_2 generation, suggesting that the gene for indeterminate habit suppressed the expression of the semideterminate gene when it was present in a homozygous or heterozygous condition, and that the determinates were double recessive (S.C. Gupta, ICRISAT, personal communication).

Most pigeonpeas are erect and bushy in growth habit except the prostrate or decumbent types that trail on the ground. Deshpande and Jeswani (1952) and Deokar and D'Cruz (1971) reported that prostrate growth habit was recessive to the normal erect type, and controlled by a single gene. However, Patil and D'Cruz (1965) and Shinde *et al.* (1971) observed an F_2 ratio of 13 normal:3 creeping types. Deokar *et al.* (1971) observed that growth habit was controlled by three genes Cgr_a, Cgr_b, and Cgr_{b2}, giving a ratio of 45 erect:9 creeping:10 prostrate in the F_2 generation. D'Cruz *et al.* (1974) reported that prostrate character was controlled by three factors, symbolized as Egr_{a2}, Egr_{b2}, and Egr_{c2}.

Plant Stature

A number of genetic studies have been reported on plant height and branching habit (erect, compact, spreading), the main components of plant type. However, the results vary considerably. This is probably because the two characters in conventional cultivated types have a considerable range, and a strong environmental effect on the two characters results in quantitative variation. Accurate qualitative analysis is difficult, unless the parental types are extreme well defined forms.

The use of dwarfing genes in pigeonpea is likely to be very useful when breeding for high yields since the traditional pigeonpea cultivars are not amenable to efficient crop management. Sen *et al.* (1966) identified bushy dwarf pigeonpea phenotypes where the dwarfness was controlled by a recessive gene, *d*. Based on F_1 and F_2 data Waldia and Singh (1987b) reported that dwarf phenotype in the D_0 dwarf line was governed by two non-allelic recessive genes t_1 and t_2. Saxena *et al.* (1989a) studied inheritance of three dwarfs D_6, PD_1, and PBNA and reported that the dwarfing trait in each line was controlled by a single recessive gene. The D_6 and PD_1 lines had a similar allele t_3 where as PBNA had a different allele t_3^h for dwarfness, which was recessive to the D_6/PD_1 allele, thus indicating the existence of a multiple allelic series.

Cultivated pigeonpea types are mainly recognized as erect or compact, and spreading. However, a range of intermediate types with a varying range of spread are common. Dominance of the erect growth habit over the spreading type was observed by Shaw (1931). D'Cruz and Deokar (1970), reported that a single dominant gene, *Sbr* controlled spreading habit, and that the erect types were homozygous recessive. According to de Menezes (1956) branching angle is quantitatively inherited. D'Cruz *et al.* (1971) observed that branching habit was governed by three duplicate-complementary factors Sbr_{a2}, Sbr_{b2}, and Sbr_{c2}, giving an F_2 ratio of 54 spreading:10 erect types. Deokar *et al.* (1972b) observed that spreading was dominant over erect, and that two complementary genes SBR_a and SBR_b were responsible for this expression. Marekar (1982) reported that the close branching habit was controlled by one basic (*Clbr*), and two inhibitory complementary genes ($I\text{-}Clbr_a$ and $I\text{-}Clbr_b$). The F_2 ratio of 111 erect: 145 spreading, observed by Marekar and Chopde (1985), indicated the presence of one basic, and three anti-inhibitory complementary genes. Since plant spread is a function of; branch angle, number and length of primary branches, and the extent of secondary and tertiary branching, it appears to be a quantitatively varying character and hybrids are often between the two extreme parental types. It is likely that detailed quantitative genetic analysis of the components of plant spread may give a better understanding of inheritance of its genetic system.

Positive association of yield with plant height, plant spread, and number of branches suggests that spreading, tall, indeterminate types have an advantage (see Chapter 3). Nevertheless, tall compact and spreading types are widely grown in northern India, perhaps because they are ideal for basket making and for use as thatch. Rao *et al.* (1981) reported that genotypes that produce more and longer branches, and spread well are better suited to intercropping.

To date limited work has been done to develop genotypes with different plant types that are desirable for new production systems. A good understanding of the genetics of various plant type components, their correlations, and correlated selected responses amongst themselves, and with yield and yield components in different maturity groups is essential for a well planned pigeonpea improvement programme. Information on the inheritance of dwarfing in different stocks, and their influence on productivity remains to be determined. Nevertheless, ICRISAT scientists have incorporated the dwarfing gene into several different maturity types.

Recently a non-branching uniculm type has been isolated and is being maintained in genetic stocks at several institutions. The genetics of non-branching uniculm plants have not been studied. Some plant breeders believe that this mutant plant type may be useful in very high plant populations under irrigation (Laxman Singh, EARCAL, personal communication).

Response to Photoperiod

Pigeonpea cultivars of different maturity durations are differentiated by a wide range of photoperiod and temperature sensitivities, resulting in the specific adaptation of types to different latitudes, seasons, and cropping systems. Pigeonpea is a quantitatively short-day plant and most cultivars flower in daylengths of 11 to 11.5 h (Gooding, 1962; Spence and Williams, 1972). No pigeonpea cultivar is truly photoperiod-insensitive and the degree of sensitivity varies quantitatively; the earliest-maturing types being the least sensitive.

On the basis of monthly sowings of diverse maturity pigeonpea cultivars (ICRISAT, 1977) four major photoperiod response groups (Sharma *et al.*, 1981) were developed at ICRISAT Center (Table 3.3). It was also observed that insensitivity to photoperiod was partially dominant in July, November, and December sowings at 17° N. However, under the longer days of February sowing, reversal of dominance was observed; i.e., long-day photoperiod-insensitivity was found to be dominant and controlled by a single gene difference. Saxena (1981) studied flowering behaviour under natural (14.8-h maximum) and artificially extended (16-h) photoperiods in four crosses involving photoperiod-insensitive and photoperiod-sensitive genotypes. He reported that under extended photoperiod three major genes; *Ps*$_3$ (conditioning >106 days), *Ps*$_2$ (>82 days), and *Ps*$_1$ (>70 days) control flowering in the sensitive parent MS 4A, and hierarchically, *Ps*$_3$ over-rides the expression of *Ps*$_2$, and *Ps*$_2$ over-rides *Ps*$_1$. Therefore the photoperiod-insensitive genotypes were triple recessive homozygotes and expressed in the extended photoperiod environments.

Since there is a wide range of daylength sensitivity among the cultivars of different maturity groups, genetic determination will vary from one cross to another depending on the parents involved. With parents representing extreme maturities (highly sensitive and least sensitive) the genetic segregation may present simple one or two gene differences between the two parental types, as in February sowings of the cross Pusa Ageti (88 days to flower) × EC-107638 (277 days to flower) (ICRISAT, 1977), and as observed by the authors in July sowings of the cross QPL 1 (59 days to flower) × T 7 (160 days to flower).

To gain a clear understanding of the genetics of long-day photoperiod sensitivity, it would be desirable to study all the possible cross-combinations between parents representing various sensitivity groups, and one or two genotypes of different maturity durations within a particular sensitivity group, under controlled photoperiod and temperature environments. However, breeders at ICRISAT Center and at the University of Queensland, Australia, have identified a number of extra-short-duration lines, such as QPL 1 and QPL 2 which are least long-day photoperiod-sensitive.

Inheritance in Interspecific Crosses

Some *Cajanus* species possess economically desirable characters that are not available in the pigeonpea gene pool. To transfer such traits from these species to cultivated pigeonpea, breeders need to understand the inheritance pattern of the traits in such interspecific crosses.

Reddy (1973), Reddy *et al.* (1981a), Kumar *et al.* (1985), and Pundir and Singh (1985) have studied the inheritance of some morphological traits in crosses involving pigeonpea and its wild relatives.

Seed Strophiole

Some *Cajanus* species are characterized by the presence of a prominent strophiole on the seed surface. In *C. scarabaeoides* var. *scarabaeoides*, *C. sericeus*, and *C. albicans* the presence of the strophiole was controlled by two genes (*NS* and *SDI*) with inhibitory action (Reddy *et al.*, 1981a; Kumar *et al.*, 1985). But Pundir and Singh (1985) reported that seeds with strophioles in *Cajanus* spp are due to the presence of two genes (s_1 and s_2) with duplicate gene action.

Seed Colour

Pundir and Singh (1985) studied inheritance of seed colour in *C. scarabaeoides* var. *scarabaeoides* and *C. cajanifolius* in crosses with orange-seeded pigeonpea lines. They reported that the dark seed colour of *Cajanus* spp. was governed by a single partially dominant gene, *Osc*.

Reddy *et al.* (1981a) and Kumar *et al.* (1985) found that seed mottling, a prominent trait in *Cajanus* spp., was controlled by two complementary genes, *Msd*$_a$ and *Msd*$_b$.

Pod Hairiness

Pods of *C. scarabaeoides* var. *scarabaeoides* have dense hairs on their surface. Reddy (1973) and Pundir and Singh (1985) reported that this trait was governed by a single dominant gene, designated as *Hp*.

Leaflet Shape

The obovate leaflet shape of *C. scarabaeoides* var. *scarabaeoides* and *C. albicans* was found to be controlled by a single partially dominant gene (Kumar *et al.*, 1985; Pundir and Singh, 1985; Reddy, 1973). Pundir and Singh (1985) designed the gene symbols L_1 and L_2. However, in a cross between *Cajanus cajan* and *C. lineatus*, Reddy (1973) reported dominance of lanceolate over ovate leaflet shape.

Growth Habit

Kumar *et al.* (1985) and Pundir and Singh (1985) reported the twining growth habit of *C. scarabaeoides* var. *scarabaeoides* and *C. albicans* as controlled by two genes with epistatic gene action resulting in a 13 non-twining:3 twining ratio. Pundir and Singh (1985) assigned gene symbols *I* and *T*. The erect growth habit of pigeonpea was dominant to the spreading growth habit of *C. scarabaeoides* var. *scarabaeoides*, and was controlled by two inhibitory genes (Reddy, 1973). Pundir and Singh (1985), however, reported that in the F_1 of a cross between pigeonpea and *C. scarabaeoides* var. *scarabaeoides* the plants were intermediate between erect and spreading habits, and in the F_2 generation they observed a ratio of 1 erect:1 spreading:14 intermediate, suggesting that two genes (Eg_1, Eg_2) with partial dominance were responsible for the growth habit.

Pod Characters

Pundir and Singh (1986) studied inheritance for pod length and ovule number in six interspecific F_2 populations. The interspecific crosses of *C. lineatus* and *C. scarabaeoides* var. *scarabaeoides* showed transgressive segregation for pod length, however, in the interspecific crosses involving pigeonpea a restricted segregation was observed that was attributed to a negative gene interaction in the two species.

QUANTITATIVE GENETICS

Quantitative genetic studies provide the necessary rationale for adopting a particular breeding procedure, and also help to improve its efficiency. Information on most of these aspects is limited for pigeonpea. Moreover, the available information is specific to the material, and the study and generalized inferences are not possible because of the:

- Heterogeneity of parental populations due to the frequently cross-pollinated nature (20-50%) of the crop.
- Use of a narrow range (maturity, plant type, etc.) of parental populations that do not represent distinct identities of gene pools with diverse gene frequencies.
- single season, single location studies based on individual plant observations. These lead to high genotype × environment interactions.
- Inappropriate statistical analyses (Arunachalam, 1976).

In general, the importance of additive genetic variance in controlling the inheritance of the characters of agronomic and economic importance appears to be well established. This is true for most of the grain legumes and other crops. However, pigeonpea workers have reported both additive and nonadditive gene action for grain yield and other quantitative characters, but critical information on the extent of nonadditive effects, particularly dominance and epistasis components is not very decisive. Most of the diallel studies have involved a non-random set of open-pollinated varieties with lesser linkage disequilibrium than the inbred lines; therefore, proper estimates of dominance and epistasis are difficult to obtain. Linkages are an important consideration with epistasis because epistatic components of variance are increased by gene linkage (Cockerham, 1963), and are therefore, likely to be expressed properly in studies involving inbred lines.

Table 6.1. Summary of **gene action and heritability estimates** for some economic traits in pigeonpea.

		Gene action			Heritability (%)	
Trait	Additive	Non-additive	Additive + non-additive	Low (<50%)	Medium (50-75%)	High (>75%)
Grain yield	3[1],6,20,21	11,15,22,23,14	24,25	1,2,6,7,9,14,15,16	1,3,12,19	2,10
Pods plant^{-1}	21	15	26	9,11,15	18,19	6,10
Seeds pod^{-1}	3,21,27		25,26	6,15	18	
Seed size	3,4,7,15,24,21,27	23	11,17,25	11,15,17,19	18	4,5,10
Clusters plant^{-1}					18	
Primary branches	20			18		
Secondary branches	20			18		
Pod-bearing length					18	
Protein (%)	3	7,8	8	7,8,9,13	3,13	
Plant height	6,16	3,23	26,15,21,24	1,2,15,16	3,18,19	1,2,6,9,10
Plant width	6		26	1,3		
Days to maturity	3,4		26,15	15	14	18,19
Days to flowering	6,11,17,14,24	24	15,21,20		1,2,9,11,15,17,19	1,2,3,7,18

[1] Numbers refer to the following references:
1. Munoz and Abrams, 1971
2. Khan and Rachie, 1972
3. Pandey, 1972
4. Sharma *et al.*, 1972
5. Joshi, 1973
6. Sharma *et al.*, 1973a
7. Sharma *et al.*, 1973b
8. Sharma *et al.*, 1974
9. Rubaihayo and Onim, 1975
10. Sheriff and Veeraswamy, 1977
11. Dahiya and Brar, 1977
12. Malhotra and Sodhi, 1977
13. Dahiya *et al.*, 1977
14. Dahiya and Satija, 1978
15. Sidhu and Sandhu, 1981
16. Sharma, 1981
17. Gupta *et al.*, 1981
18. Kumar and Reddy, 1982
19. Sidhu *et al.*, 1985
20. Chaudhari *et al.*, 1980
21. Saxena *et al.*, 1981b
22. Laxman Singh and Pandey, 1974
23. Reddy *et al.*, 1979
24. Reddy *et al.*, 1981b
25. Venkateswarlu and Singh, 1982
26. Kapur, 1977
27. Mohamed *et al.*, 1985

The high estimates of general combining ability (GCA) variances mostly obtained from varietal diallel crosses are biased upwards, because of the failure of the assumptions, lack of epistasis, gene frequencies of one-half, and the independent distribution of genes among the parents. The GCA will include dominance, and epistatic and additive effects (Baker, 1978). The results of reported studies on various quantitative characters in pigeonpeas are summarized in Table 6.1.

Gene Action

Saxena *et al.* (1981b) observed the predominance of additive gene action for yield and yield components. They demonstrated that in pigeonpea agronomic considerations in field evaluation trials and the inclusion of a parent with only moderately different phenology have significant influence on estimates of genetic variances. They suggested that studies on the estimation of genetic variances should be conducted using the same cultural practices as commercial cultivation. Reddy *et al.* (1981b) and Sidhu and Sandhu (1981) reported the importance of both additive and non-additive gene action, while the predominance of non-additive gene action was observed by Dahiya and Brar (1977). Besides estimates of the genetic parameters, a consideration of the fact that there is little inbreeding depression in pigeonpea beyond the F_2 generation indicates that dominance is not an important genetic variance component for yield in this crop.

Sharma *et al.* (1972) reported predominance of additive gene action for seed size from a 10-parent diallel study. However, the genes controlling smaller seed size were found to be dominant over the genes controlling larger seeds. Gupta *et al.* (1981) using generation mean analysis confirmed additive gene action, and reported that seed size difference between ICP 8504 (100-seed mass = 11.54g) and Prabhat (100-seed mass = 6.46g) was determined by only two or three genes.

For days to flower Gupta *et al.* (1981) reported predominance of additive gene effects, while Pandey (1972), Sharma *et al.* (1973b), and Dahiya and Satija (1978) observed additive genetic variance with partial dominance for earliness.

Plant height was studied in a nine-parent diallel by Sharma (1981). He reported the importance of both additive and dominance gene effects. Genes controlling tall stature were dominant over genes controlling short stature. The degree of dominance was in over dominance range, i.e., better than the better parent.

Saxena and Sharma (1981) observed high GCA variance indicating additive gene action for leaf fresh mass, leaf area, specific leaf mass, petiole length, and petiole mass. For specific leaf mass and petiole mass dominance was also important, and large and heavy petioles were found to be controlled by recessive genes (Sharma and Saxena, 1983).

Heritability

Heritability estimates provide good guidelines on the efficiency of selection as they refer to the proportion of the phenotypic variance that is due to genetic variation. A high heritability estimate suggests that the concerned character can be easily selected in the test environment. The estimate can also be used to calculate genetic advance under a given selection intensity, and hence helps in determining the population size necessary to exercise selection. However, the heritability estimate is valid for a given population, and the environment in which it was obtained. Therefore, it is difficult to generalize heritability estimates from one population to another (Dudley and Moll, 1969).

In pigeonpea, a number of reports on heritability estimates for various quantitative traits have been published. Together these estimates provide some general ideas about the ease of selection for a particular character. For the sake of convenience, the estimates have been grouped as high (>75%), medium (50-75%), and low (<50%).

Table 6.1 shows a large variation in estimates for all the important agronomic traits. However, most of the studies suggest that characters such as seed yield, pods per plant, protein content, etc. generally have low heritability. On the contrary, days to flower, plant height, and seed size have high heritability estimates.

Heterosis

Although critical information on the occurrence and magnitude of the nonadditive variance (dominance and epistasis) responsible for the manifestation of heterosis is lacking in pigeonpea, considerable hybrid vigour over the mid-parent and better parent values have been reported by several workers for grain yield and other characters.

Solomon *et al.* (1957) were the first to report hybrid vigour in pigeonpea in 10 inter-varietal crosses. In some crosses they observed hybrid vigour over the better parent up to a maximum of 24.5% for grain yield together with; plant height, plant spread, stem girth, number of fruiting branches, and leaf length and width. Subsequently, a number of reports have been published on hybrid vigour for yield and yield components (Table 6.2). Recently, Singh, S.P. *et al.* (1983) reported up to 22.1% mid-parent heterosis in the cross Mukta (medium-duration) × UPAS-120 (short-duration). Evaluation of medium- and short-duration pigeonpea hybrids in multilocational trials has shown 20 to 49% heterosis over the well-adapted, recommended control cultivar (Saxena *et al.*, 1986b). Some new experimental hybrids have outyielded the best control cultivar by over 100% (Saxena *et al.*, 1989b).

Generally a high level of hybrid vigour is observed among crosses involving parents with diverse phenologies. Hybrids involving pigeonpea and other *Cajanus* species manifest very high vigour for vegetative growth (L.J. Reddy, ICRISAT, personal communication).

Most of the reported studies on hybrid vigour are from experiments conducted in one environment, and such estimates, suffer from considerable bias due to genotype × environment interaction (Jinks, 1983). This bias is considerably accentuated if a particular phenological group is better adapted to the test environment. ICRISAT observations have shown that the hybrids between medium-duration (150 to 200 days) and longduration (200 days and above) types express considerable heterosis for yield at Patancheru, India (17° N), where medium-duration genotypes are well adapted. Here too the hybrids being closer to medium types (intermediate between the two parents, and with partial dominance for earliness) have the advantage of better adaptation, while the late parents suffer from drought stress. At Gwalior, India (22° N) the late types are well adapted and, therefore, the late parents give higher yields than the hybrids between medium- and long-duration types, because they are not well adapted at that location. Hence, studies conducted at a single location may suffer from the bias caused by genotype × environment interaction, and may give an impression of "pseudo-heterosis".

Component analyses of hybrids have shown high yield in the heterotic crosses to be closely associated with heterosis for pods per plant, number of primary branches, and plant height, that all contribute to increased total biomass (Reddy *et al.*, 1979; Marekar, 1981; Venkateswarlu *et al.*, 1981, Saxena *et al.*, 1986a; Cheralu *et al.*, 1989). To realize a high level of hybrid vigour for yield

Table 6.2. Summary of hybrid vigour recorded for yield and yield components in pigeonpea.

Character	Reference[1]
Seed yield	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17
Pods plant^{-1}	3,4,5,7,9,10,11,12,14
Plant height	1,2,3,4,5,6,9,11,14,15
Branches plant^{-1}	1,3,4,6,10,11,14
Seed size	4,5,6,11,12
Plant spread	1,3,4
Days to flowering	3,5,7
Days to maturity	5
Clusters plant^{-1}	3
Stem girth	1
Seeds pod^{-1}	11

[1] Numbers refer to the following references:
1. Solomon *et al.*, 1957
2. Sharma *et al.*, 1973a
3. Veeraswamy *et al.*, 1973
4. Shrivastava *et al.*, 1976
5. Reddy *et al.*, 1979
6. Marekar, 1981
7. Venkateswarlu *et al.*, 1981
8. Singh, S.P. *et al.*, 1983
9. Omanga, 1984
10. Sinha *et al.*, 1986
11. Saxena *et al.*, 1986a
12. Patel *et al.*, 1987
13. Saxena *et al.*, 1986b
14. Cheralu *et al.*, 1989
15. Saxena *et al.*, 1989b
16. Saxena *et al.*, 1989c
17. Jadhav and Nerkar, 1983

Shrivastava *et al.* (1976), Reddy *et al.* (1979), and Venkateswarlu *et al.* (1981) suggested selection of parental lines belonging to diverse maturity groups. However, it is not the extent of hybrid vigour that needs to be considered when breeding a hybrid variety, or using a particular cross, or selecting lines, but the performance levels of the parents and the F_1 compared to those of the adapted best available variety.

With the discovery of genetic male sterility in pigeonpea (Reddy *et al.*, 1978; Saxena *et al.*, 1983b) and the presence of natural out-crossing, it has been possible to breed hybrid pigeonpea varieties. However, theoretical genetic considerations are not sufficiently clear enough to be decisive in favour of hybrid varieties, or pure line varieties as breeding strategies for the future. In order to justify a major thrust in a breeding programme on F_1 hybrid development, a large dominance variance is essential. Heterosis, which can result from all types of nonadditive gene action, such as additive × additive, need not necessarily indicate a high level of dominance. Compton (1977) suggested that inbreeding depression is better evidence of dominance than heterosis. In pigeonpea inbreeding depression does not seem to be significant. Therefore, in all theoretical probabilities it is possible to select pure lines equal in performance to F_1 hybrid, i.e., it may be possible to fix a considerable part of the observed heterosis. This has been reported by Williams (1959) for tomato, Brim (1973) for soybean, and Singh (1974) for mung bean. However, pigeonpea breeding programmes need to consider the two alternatives as complementary, since development of superior hybrids is totally dependent on the development of superior parental lines. Further studies on varietal and hybrid performance, and on the economics of seed and crop production will provide the necessary basis for future developments.

FUTURE

Adaptation of pigeonpea to vastly diverse agro-ecological conditions has resulted in the establishment of a wide range of variation in qualitative and quantitative characters. However, the development of improved types through hybridization and recombination of the available variability in pigeonpea and other species of *Cajanus* has been limited. This is now receiving attention in attempts to improve production in both traditional and intensive production systems, and to extend the crop's adaptation beyond tropical and sub-tropical regions.

During the past 25 years breeders have successfully developed a large number of short-duration, large seeded, high-yielding types suitable for sole cropping under high levels of management, and disease resistant types in different maturity groups. However, the initial success of an intensive effort does not indicate the ultimate efficiency of the breeding procedures, or full utilization of the genetic potential of the crop. Future research needs to concentrate on improving the efficiency of approaches and procedures to increase the rate of directed improvement, and develop new types of different phenologies with increased productivity.

A good understanding of genetics and the genetic systems determining qualitative and quantitative characters is essential. The genetic research on pigeonpea reviewed in this chapter is limited and fragmentary. For most qualitative characters, there are large differences in the reported genetic interpretations, and sometimes segregation ratios can not be clearly explained. Also, only a limited number of crosses has been studied, therefore, it is not possible to determine allelic relationship. Such character descriptions as thick and thin, broad and narrow, or spreading and compact are subjective, and difficult to define. Thus, genetic interpretation of such situations is greatly influenced by the parental material used in the study. Most of the characters have been studied individually, and linkage relationships and groups are not sufficiently well defined for their effective use as markers in breeding programmes. Gene symbols assigned by different workers do not follow the standard internationally accepted procedure. This causes considerable confusion with regard to the character being referred to or studied, particularly in cases where the character can not be specifically defined.

In addition to information on linkage of various qualitative characters and the important linkage groups, the influence of qualitative characters on quantitative traits, and correlations between different qualitative characters are important. These indicate recombination of the different characters, and the possibility of indirect selection for correlated qualitative and quantitative characters. Information on these aspects is either completely lacking, or limited to a single phenological group or plant type. Genetic studies in future should not only consider the character variation in pigeonpea, but should also involve other *Cajanus* species with emphasis on inheritance of the trait, it's expression, and correlated responses in pigeonpea backgrounds.

As discussed earlier, quantitative genetic studies in pigeonpea suffer from several limitations, the main ones being; the choice of a genetically narrow range of parents, single test locations (high g × e interaction), and procedural errors.

The presence of both additive and nonadditive gene action of various degrees for yield and other characters has been reported by several pigeonpea workers—this is confusing. It is essential to critically investigate the relative importance of dominance and epistasis, and their role in the expression of observed heterosis in the crop. Future studies should emphasize the involvement of a broad genetic base (parental types), well planned and conducted experiments, and properly defined crop culture (cultivation practices and environment). Critical information on gene action is basic if proper breeding strategies and procedures are to be determined.

REFERENCES

Arunachalam V. (1976) Evaluation of diallel crosses by graphical and combining ability methods. *Indian Journal of Genetics and Plant Breeding* 36, 358-366.

Baker, R.J. (1978) Issues in diallel analysis. *Crop Science* 18, 533-536.

Bhatia, G.K., Sharma, D. and Faris, D.G. (1983) Maintenance of genetic purity in pigeonpea seed. *International Pigeonpea Newsletter* 2, 27-28.

Brim, C.A. (1973) Quantitative genetics and breeding. In: Cadwell, B.E. (ed), *Soybeans: Improvement, Production, and Uses. Agronomy Series number 16.* American Society of Agronomy, Inc., Madison, Wisconsin, USA, pp. 155-186.

Byth, D.E., Saxena, K.B. and Wallis, E.S. (1982) A mechanism for inhibiting cross-fertilization in pigeonpea (*Cajanus cajan* (L.) Millsp.). *Euphytica* 31, 405-408.

Chaudhari, V.P., Manke, V.G. and Chopde, P.R. (1980) Diallel analysis in pigeonpea. *Indian Journal of Agricultural Sciences* 50, 388-390.

Cheralu, C., Muralidhar, V., Satyanarayana, A. and Venkateswarlu, S. (1989) Heterosis in relation to combining ability in pigeonpea (*Cajanus cajan*). *Indian Journal of Agricultural Sciences* 59, 68-70.

Cockerham, C.C. (1963) Evaluation of genetic variances. In: Hanson, W.D. and Robinson, H.F. (eds), *Statistical Genetics and Plant Breeding. Publication no. 982.* National Academy of Sciences in National Researchers Council, Washington, D.C., pp. 53-94.

Compton, W.A. (1977) Heterosis and additive × additive epistasis. *Soybean Genetics Newsletter* 4, 60-62.

Dahiya, B.S. and Brar, J.S. (1977) Diallel analysis of genetic variation in pigeonpea (*Cajanus cajan*). *Experimental Agriculture* 13, 193-200.

Dahiya, B.S., Brar, J.S. and Bhullar, B.S. (1977) Inheritance of protein content and its correlation with grain yield in pigeonpea (*Cajanus cajan* (L.) Millsp.). *Qualitas Plantarum/Plant Foods for Human Nutrition* 27, 327-334.

Dahiya, B.S. and Satija, D.R. (1978) Inheritance of maturity and grain yield in pigeonpea. *Indian Journal of Genetics and Plant Breeding* 38, 42-44.

Dave, B.B. (1934) Inheritance of characters in *Cajanus indicus*. *Indian Journal of Agricultural Sciences* 4, 674-691.

D'Cruz, R., Bhole, G.R. and Deokar, A.B. (1971) Genetic studies in pigeonpea VIII. N. Green × Round leaf. *Indian Journal of Heredity* 3, 67-72.

D'Cruz, R. and Deokar, A.B. (1970) Genetic studies in pigeonpea I. N. Green × Red grained. *Research Journal of Mahatma Phule Agricultural University* 1, 44-53.

D'Cruz, R., Manke, B.S. and Deokar, A.B. (1970) Genetic studies in pigeonpea. IV. Rahar × Red grained. *Poona Agricultural College Magazine* 60, 23-26.

D'Cruz, R., Pachpol, L.S. and Deokar, A.B. (1974) Genetic studies in pigeonpea. IX. N.P.51 × Prostrate. *Punjabrao Krishi Vidyapeeth Research Journal* 2, 77-81.

D'Cruz, R., Patil, P.S. and Deokar,A.B. (1973) Genetic studies in pigeonpea. XIII. Leaflet shape, flower and seed colour. *Botanique (Nagpur)* 4, 117-124.

de Menezes, O.B. (1956) Genetics and improvement of the pigeonpea (*Cajanus indicus* Spreng). *Ceres Minas Gerais* 10(55), 20-44.

Deodikar, G.B. and Thakar, C.V. (1956) Cyto-taxonomic evidence for the affinity between *Cajanus indicus* Spreng. and certain erect species of *Atylosia* W.&A. *Proceedings of the Indian Academy of Sciences, Section B* 43, 37-45.

Deokar, A.B., Bhole, G.R. and D'Cruz, R. (1971) Genetic studies in pigeonpea. VII. Creeping 3-2-8 × Prostrate. *Research Journal of Mahatma Phule Agricultural University* 2, 26-37.

Deokar, A.B. and D'Cruz, R. (1971) Genetic studies in pigeonpea III. Round leaf × Creeping 3-2-3. *Journal of the University of Poona* 40, 23-30.

Deokar, A.B. and D'Cruz, R. (1972) Genetic studies in pigeonpea II. N. Black × Purple grained. *Research Journal of Mahatma Phule Agricultural University* 3, 12-20.

Deokar, A.B., Manke, S.B. and D'Cruz, R. (1972a) Genetic studies in pigeonpea. VI. Leaflet shape, pod and seed coat colour. *Indian Agriculturist* 16, 193-197.

Deokar, A.B., Pachpol, L.S. and D'Cruz, R. (1972b) Genetic studies in pigeonpea. X. NP64 ×NP82. *Botanique, (Nagpur)* 3, 35-40.

Deshpande, R.B. and Jeswani, L.M. (1952) A prostrate mutant in pigeonpea (*Cajanus cajan* (L.) Millsp.) – a possible soil conservation plant. *Indian Journal of Genetics and Plant Breeding* 12, 50-51.

Deshpande, R.B. and Jeswani, L.M. (1956) A case of pleiotropy in pigeonpea. *Current Science* 25, 201-202.

Dudley, J.W. and Moll, R.H. (1969) Interpretation and use of estimates of heritability and genetic variances in plant breeding. *Crop Science* 9, 257-262.

Gooding, H.J. (1962) The agronomic aspects of pigeonpea. *Field Crop Abstracts* 15, 1-5.

Gupta, S.C., Saxena, K.B. and Sharma, D. (1981) Inheritance of days to flower and of seed size in pigeonpea. In: *Proceedings of the International Workshop on Pigeonpeas, volume 2, 15-19 December 1980, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 61-66.

ICRISAT (1977) *Pigeonpea Breeding Annual Report 1976-77.* Patancheru, A.P., India: Legumes Program, ICRISAT (Limited distribution).

Jadhav, B.D. and Nerkar, Y.S. (1983) Heterosis for grain yield in pigeonpea grown under different cropping seasons. *Indian Journal of Agricultural Sciences* 53, 528-531.

Jain, S.K. and Joshi, B.C. (1964) Estimation of linkage and penetrance parameters in a study of petal color in the pigeonpea. *Genetics* 49, 611-615.

Jinks, J.L. (1983) *Biometrical Genetics of Heterosis, Reappraisal of Theory and Practice.* Springer-Verlag, Berlin.

Joshi, A.B. (1957) Genetics of resistance to diseases and pests. *Indian Journal of Genetics and Plant Breeding* 17, 305-317.

Joshi, S.N. (1973) Variability and correlation studies in pigeonpea (*Cajanus cajan* L.). *Madras Agricultural Journal* 60, 412-414.

Kapur, R. (1977) Genetic analysis of some quantitative characters at different population levels in pigeonpea (*Cajanus cajan* (L.) Millsp.). MSc thesis, Punjab Agricultural University, Ludhiana, India.

Khan, T.N. and Rachie, K.O. (1972) Preliminary evaluation and utilization of pigeonpea germplasm in Uganda. *East African Agricultural and Forestry Journal* 38, 78-82.

Kolhe, A.K., Ghatge, R.D., Deokar, A.B. and D'Cruz, R. (1972) Genetic studies in pigeonpea. XIV. Round leaf × *Obcordifolia* (N-black). *Research Journal of Mahatma Phule Agricultural University* 3, 21-26.

Krauss, F.G. (1927) Improvement of the pigeonpea genetic analysis of *Cajanus indicus* and creation of new varieties through hybridization and selection. *Journal of Heredity* 18, 227-232.

Kumar, A.S. and Reddy, T.P. (1982) Path coefficient analysis of yield attributes in pigeonpea (*Cajanus cajan* (L). Millsp.). *Genetica Agraria* 36, 63-72.

Kumar, P.S., Subrahmanyam, N.C. and Faris, D.G. (1985) Morphological variation and inheritance in a pigeonpea intergeneric hybrid. *Current Science* 54, 346-348.

Laxman Singh and Pandey, R.L. (1974) Genetic analysis of some quantitative characters in pigeonpea (*Cajanus cajan* (L.) Millsp.). *Himachal Journal of Agricultural Research* 2, 1-3.

Mahta, D.N. and Dave, B.B. (1931) Studies in *Cajanus indicus*. *Memoirs of the Department of Agriculture in India, Botanical Series* 19, 1-25.

Malhotra, R.S. and Sodhi, J.S. (1977) Genetic variability and discriminant function studies in pigeonpea (*Cajanus cajan* L.). *Madras Agricultural Journal* 64, 677-678.

Marekar, R.V. (1981) Heterosis in pigeonpea. *Research Bulletin of the Marathwada Agricultural University* 5, 33-38.

Marekar, R.V. (1982) Inheritance study in pigeonpea (*Cajanus cajan* (L.) Millsp.)–1, Wavy shoot × Multifoliate. *Punjabrao Krishi Vidyapeeth Research Journal* 6, 1-5.

Marekar, R.V. and Chopde, P.R. (1985) Inheritance studies in pigeonpea. III. E.B.3 × Multifoliate. *Punjabrao Krishi Vidyapeeth Research Journal* 9, 5-12.

Mohamed, M.El S., Ariyanayagam, R.P. and Bekele, I. (1985) Inheritance of essential pod characters and maturity in pigeonpea (*Cajanuus cajan*. [L.] Millsp.). *Zeitschrift füer Pflanzenzuchtung/Journal of Plant Breeding* 94, 128-134.

Munoz, A.M. and Abrams, R. (1971) Inheritance of some quantitative characters in pigeonpeas (*Cajanus cajan* (L.) Millsp.) *Journal of Agriculture of the University of Puerto Rico* 55, 22-43.

Nene, Y.L. (1972) *A Survey of Viral Diseases of Pulse Crops in Uttar Pradesh*. *Research Bulletin no. 4*. Govind Ballabh Pant University of Agriculture and Technology, Pantnagar, U.P., India, 191 pp.

Nene, Y.L., Kannaiyan, J. and Reddy, M.V. (1981) Resistance to major pigeonpea diseases. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 121-128.

Omanga, P.A. (1984) The use of male-sterile lines to measure the nature and magnitude of hybrid vigour in pigeonpea. *East African Agricultural and Forestry Journal (Special Issue)* 44, 327 (abstract).

Pal, B.P. (1934) Recent progress in plant breeding at Pusa. *Agriculture and Livestock in India* 4, 505-515.

Pandey, R.L. (1972) Inheritance of some quantitative characters in pigeonpea (*Cajanus cajan* (L). Millsp.). MSc thesis, Jawaharlal Nehru Krishi Vishwa Vidyalaya, Jabalpur, India.

Pandya, P.S., Patil, J.A. and Chaudhary, B.B. (1954) "Round and Tiny" leaf mutants in *Cajanus cajan* Millsp. *Poona Agricultural College Magazine* 45, 18.

Patel, J.A., Pathak, A.R., Zaveri, P.P. and Shah, R.M. (1987) Combining ability analysis in pigeonpea (*Cajanus cajan* (L.) Millsp.). *Indian Journal of Genetics and Plant Breeding* 47, 183-187.

Pathak, G.N. (1970) Red gram. In: *Pulse crops of India*. Indian Council of Agricultural Research, New Delhi, India, pp. 14-53.

Patil, J.A. (1970) Extension of the linkage group I-Blpd-Llt in pigeonpea (*Cajanus cajan* Millsp.). *Research Journal of Mahatma Phule Agricultural University* 1, 37-43.

Patil, J.A. and D'Cruz, R. (1962) Inheritance of white flower color in pigeonpea. *Current Science* 31, 119-120.

Patil, J.A. and D'Cruz, R. (1965) Linkage studies in pigeonpea. *Indian Journal of Genetics and Plant Breeding* 25, 234-238.

Patil, J.A., Deokar, A.B. and Maslekar, S.R. (1972) Inheritance of leaflet number, flower and seed coat colour in redgram (*Cajanus cajan* Millsp.). *Research Journal of Mahatma Phule Agricultural University* 3, 6-11.

Pawar, N.B. and Mayee, C.D. (1986) Reaction of pigeonpea genotypes and their crosses to Fusarium wilt. *Indian Phytopathology* 39, 70-74.

Pundir, R.P.S. and Singh, R.B. (1985) Inheritance of inter-generic crosses between *Cajanus* and *Atylosia* spp. *Indian Journal of Genetics and Plant Breeding* 45, 194-198.

Pundir, R.P.S. and Singh, R.B. (1986) Inheritance pattern for pod length and ovule number in wide crosses among *Cajanus* and *Atylosia* species. *Euphytica* 35, 649-652.

Rao, M.R., Willey, R.W., Sharma, D. and Green, J.M. (1981) Pigeonpea genotype evaluation for intercropping. In: *Proceedings of the International Workshop on Pigeonpeas, volume 2, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 263-270.

Reddy, B.V.S., Green, J.M. and Bisen, S.S. (1978) Genetic male sterility in pigeonpea. *Crop Science* 18, 362-364.

Reddy, B.V.S., Reddy, L.J. and Murthi, A.N. (1977) Reproductive variants in *Cajanus cajan* (L.) Millsp. *Tropical Grain Legume Bulletin* 7, 11.

Reddy, L.J. (1973) Interrelationship of *Cajanus* and *Atylosia* species as revealed by hybridization and pachytene analysis. PhD thesis, Indian Institute of Technology, Kharagpur, India.

Reddy, L.J., Green J.M. and Sharma, D. (1981a) Genetics of *Cajanus cajan* (L) Millsp. × *Atylosia* spp. In: *Proceedings of the International Workshop on Pigeonpeas, volume 2, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 39-50.

Reddy, L.J., Saxena, K.B., Sharma, D. and Green, J.M. (1981b) Some combining ability analyses in pigeonpea. In: *Proceedings of the International Workshop on Pigeonpeas, volume 2, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 93-104.

Reddy, R.P., Rao, K.V. and Rao, N.G.P. (1979) Heterosis and combining ability in pigeonpea. *Indian Journal of Genetics and Plant Breeding* 39, 240-246.

Reddy, R.P. and Rao, N.G.P. (1974) Inheritance and relation with some yield components of plants and flowering habit in *Cajanus*. *Indian Journal of Genetics and Plant Breeding* 34, 94-99.

Roy, A. and De, D.N. (1965) Intergeneric hybridization of *Cajanus* and *Atylosia*. *Science and Culture* 31, 93-95.

Rubaihayo, P.R. and Onim, J.F.M. (1975) A study of some characters in pigeonpea. *SABRAO Journal* 7, 183-187.

Saxena, K.B. (1981) Report of research work carried out from March 1979 to September 1981, Department of Agriculture, University of Queensland, St. Lucia, Brisbane, Australia. Patancheru, A.P., India: Legumes Program, ICRISAT, 40 pp. (Limited distribution).

Saxena, K.B., Byth, D.E., Dundas, I.S. and Wallis, E.S. (1981a) Genetic control of sparse pollen production in pigeonpea. *International Pigeonpea Newsletter* 1, 17-18.

Saxena, K.B., Byth, D.E., Wallis, E.S. and De Lacy, I.H. (1981b) Genetic analysis of a diallel cross of early-flowering pigeonpea lines. In: *Proceedings of the International Workshop on Pigeonpeas, volume 2, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 81-92.

Saxena, K.B., Byth, D.E., Wallis, E.S. and Dundas, I.S. (1983a) Genetic basis of male sterility in pigeonpea. *International Pigeonpea Newsletter* 2, 20-21.

Saxena, K.B., Dundas, I.S., Faris, D.G. and Gupta, S.C. (1988a) Genetics and histology of a corky-stem mutant in pigeonpea. *Journal of Heredity* 79, 221-222.

Saxena, K.B., Dwivedi, S., Kumar, R.V. and Faris, D.G. (1986a) Performance of hybrid pigeonpea using wilt resistant male sterile C 11 and BDN 1 lines. *International Pigeonpea Newsletter* 5, 21-23.

Saxena, K.B., Faris, D.G. and Kumar, R.V. 1984. *Pigeonpea Breeding, Report of Work, June 1983-May 1984. Pigeonpea Breeding Progress Report-7.* Patancheru, A.P., India: Legumes Program, ICRISAT, 99 pp. (Limited distribution).

Saxena, K.B., Faris, D.G., Reddy, L.J., Sharma, D., Reddy, B.V.S., Gupta, S.C. and Green, J.M. (1986b) Prospects for hybrid pigeonpeas. In: Napompeth, B. and Subhadrabandhu, S. (eds), *New Frontiers in Breeding Researches. Proceedings of the Fifth International Congress Society for the Advancement of Breeding Researches in Asia and Oceania (SABRAO)*. Kasetsart University, Bangkok, Thailand, pp. 379-388.

Saxena, K.B., Githiri, S.M., Laxman Singh and Kimani, P.M. (1989a) Characterization and inheritance of dwarfing genes of pigeonpea. *Crop Science* 29, 1199-1202.

Saxena, K.B., Laxman Singh, Gupta, S.C., Chauhan, Y.S. and Reddy, M.V. (1989b) Hybrid pigeonpea development and prospects. Paper presented at the seminar on Strategies for Increasing Pulses Production, 3-4 January 1989, Agricultural Research Station Badnapur, Maharashtra, India.

Saxena, K.B., Laxman Singh and Rao, A.N. (1989c) Results of cooperative hybrid pigeonpea trials conducted during 1988. Paper presented at the Second Cooperative Hybrid Pigeonpea Planting Plan Meeting, 3-4 April 1989, Tamil Nadu Agricultural University, Coimbatore, India.

Saxena, K.B. and Sharma, D. (1981) Variation for leaf characters and relationship with grain yield and seed size in pigeonpea. *Indian Journal of Genetics and Plant Breeding* 41, 340-345.

Saxena, K.B., Singh, A.K. and Faris, D.G. (1988b) The morphogenesis and inheritance of an open carpel mutant *cd1* in pigeonpea. *Journal of Heredity* 79, 75-76.

Saxena, K.B., Wallis, E.S. and Byth, D.E. (1983b) A new gene for male sterility in pigeonpea (*Cajanus cajan* (L.) Millsp.). *Heredity* 51, 419-421.

Sen, S., Sur, S.C. and Sen Gupta, K. (1966) Inheritance of dwarfness in pigeonpea (*Cajanus cajan* (L.) Millsp.). *Zuchter* 36, 379-380.

Seth, M.L. (1962) Transmission of pigeonpea sterility by an eriophyid mite. *Indian Phytopathology* 15, 225-227.

Sharma, D. (1986) Breeding disease resistant varieties of pigeonpea (*Cajanus cajan* (L.) Millsp.) In: Tikka, S.B.S. (ed), *Pigeonpea Genetics and Improvement*. Sharda Publishing Academy, Gujarat, India, pp. 103-139.

Sharma, D., Bhadouria, S.S., Laxman Singh and Sharma, H.K. (1974) Genetic analysis of protein content in pigeonpea. *Indian Journal of Genetics and Plant Breeding* 34, 230-235.

Sharma, D. and Green, J.M. (1975) Perspective of pigeonpea and ICRISAT's breeding program. In: *International Workshop on Grain Legumes, 13-16 January 1975, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 19-29.

Sharma, D., Gupta, S.C., Rai, G.S. and Reddy, M.V. (1984) Inheritance of resistance to sterility mosaic disease in pigeonpea–I. *Indian Journal of Genetics and Plant Breeding* 44, 84-90.

Sharma, D., Kannaiyan, J. and Reddy, L.J. (1982) Inheritance of resistance to blight in pigeonpeas. *Plant Disease* 66, 22-25.

Sharma, D., Kannaiyan, J. and Saxena, K.B. (1987) Sources and inheritance of resistance to Alternaria blight in pigeonpea. *SABRAO Journal* 19, 109-114.

Sharma D., Laxman Singh, Baghel, S.S. and Sharma, H.K. (1972) Genetic analysis of seed size in pigeonpea *(Cajanus cajan)*. *Canadian Journal of Genetics and Cytology* 14, 545-548.

Sharma, D., Reddy, L.J., Green, J.M. and Jain, K.C. (1981) International adaptation of pigeonpeas. *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 71-81.

Sharma, D. and Saxena, K.B. (1983) Genetic analysis of some leaf characteristics in pigeonpea [*Cajanus cajan* (L.) Millsp.]. *Field Crops Research* 7, 257-263.

Sharma, H.K. (1981) Genetic analysis of plant height in pigeonpea. In: *Proceedings of the International Workshop on Pigeonpeas, volume 2, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 55-59.

Sharma, H.K., Laxman Singh and Sharma, D. (1973a) Combining ability in diallel crosses of pigeonpea. *Indian Journal of Agricultural Sciences* 43, 25-29.

Sharma, H.K., Laxman Singh and Sharma, D. (1973b) Genetic analysis of flower initiation in pigeonpea. *Indian Journal of Genetics and Plant Breeding* 33, 393-397.

Shaw, F.J.F. (1931) Report of the Imperial Economic Botanist. *Scientific Reports of the Imperial Institute of Agricultural Research, Pusa 1929-30*. Pusa, India, pp. 10-32.

Shaw, F.J.F. (1936) Studies in Indian pulses: the inheritance of morphological characters and wilt resistance in rahar (*Cajanus indicus* Spreng.). *Indian Journal of Agricultural Sciences* 6, 139-187.

Sheriff, N.M. and Veeraswamy, R. (1977) Genotypic and phenotypic variability of mutants in redgram (*Cajanus cajan* (L.) Millsp.). *Madras Agricultural Journal* 64, 45-47.

Shinde, V.K., D'Cruz, R. and Deokar, A.B. (1971) Genetic studies in pigeonpea–XI. Creeping 3-2-8 × Red grained. *Poona Agricultural College Magazine* 61, 53-55.

Shrivastava, M.P., Laxman Singh and Singh, R.P. (1976) Heterosis in pigeonpea. *Indian Journal of Genetics and Plant Breeding* 36, 197-200.

Sidhu, P.S. and Sandhu, T.S. (1981) The role of genetical studies in developing new cultivars of pigeonpea for nontraditional areas of north India. In: *Proceedings of the International Workshop on Pigeonpeas, volume 2, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 117-128.

Sidhu, P.S., Verma, M.M., Cheema, H.S. and Sra, S.S. (1985) Genetic relationships among yield components in pigeonpea. *Indian Journal of Agricultural Sciences* 55, 232-235.

Simmonds, N.W. (1981) *Principles of Crop Improvement*. Essex ELBS and Longman, New York, 408 pp.

Singh, B.V., Pandya, B.P., Gautam, P.L., Beniwal, S.P.S. and Pandey, M.P. (1983) Inheritance of resistance to sterility mosaic virus in pigeonpea. *Indian Journal of Genetics and Plant Breeding* 43, 487-493.

Singh, K.B. (1974) Exploitation of heterosis in pulse crops. *Indian Journal of Genetics and Plant Breeding* 34A, 752-756.

Singh, S.P., Govil, J.N. and Ram, H. (1983) Combining ability and heterosis in early pigeonpea hybrids. *Indian Journal of Genetics and Plant Breeding* 43, 481-486.

Singh, U.P., Singh, P. and Singh, R.M. (1988) Inheritance of field resistance to alternaria blight in pigeonpea. *International Pigeonpea Newsletter* 7, 4-5.

Sinha, S.C., Srivastava, A.N. and Singh, K.N. (1986) Heterosis in relation to genetic divergence in pigeonpea. *International Pigeonpea Newsletter* 5, 20-21.

Solomon, S., Argikar, G.P., Solanki, M.S. and Morbad, I.R. (1957) A study of heterosis in *Cajanus cajan* (L.) Millsp. *Indian Journal of Genetics and Plant Breeding* 17, 90-95.

Spence, J.A. and Williams, S.J.A. (1972) Use of photoperiod response to change plant design. *Crop Science* 12, 121-122.

van der Maesen, L.J. (1986) *Cajanus DC. and Atylosia W.&A. (Leguminosae). Agricultural University Wageningen Papers 85-4 (1985).* Agricultural University, Wageningen, the Netherlands, 225 pp.

Veeraswamy, R., Rathnaswamy, R., Ragupathy, A. and Palaniswamy, G.A. (1973) Genotypic and phenotypic correlations in *Cajanus cajan* (L.) Millsp. *Madras Agricultural Journal* 60, 1823-1825.

Venkateswarlu, S., Reddy, A.R. and Singh, R.M. (1981) Heterosis in pigeonpea and the implications in producing hybrids on commercial basis. *Madras Agricultural Journal* 68, 496-501.

Venkateswarlu, S. and Singh, R.B. (1982) Combining ability in pigeonpea *Indian Journal of Genetics and Plant Breeding* 42, 11-14.

Waldia, R.S. and Singh, V.P. (1987a) Inheritance of stem termination in pigeonpea (*Cajanus cajan* (L.) Millsp.). *Euphytica* 36, 525-527.

Waldia, R.S. and Singh, V.P. (1987b) Inheritance of dwarfing genes in pigeonpea. *Indian Journal of Agricultural Sciences* 57, 219-220.

Williams, W. (1959) The isolation of "pure line" from F_1 hybrids of tomato and the problems of heterosis in inbreeding crop species. *Journal of Agricultural Science, Cambridge* 53, 347-353.

Wilsie, C.P. and Takahashi, M. (1934) Natural crossing in the pigeonpea. *Journal of Agricultural Research* 49, 923-927.

Chapter 7

PIGEONPEA: ADAPTATION

R.J. TROEDSON, E.S. WALLIS, and LAXMAN SINGH

Senior Research Officer, Department of Agriculture, University of Queensland, St. Lucia, Queensland 4067, Australia, Group Manager, Bureau of Sugar Experiment Stations, P.O. Box 86, Indooroopilly, Queensland, Australia, and Principal Agronomist, Eastern African Regional Cereals and Legumes (EARCAL) Network, ICRISAT, C/o OAU/STRC, J.P. 31 SAFGRAD, P.O. Box 30786, Nairobi, Kenya.

INTRODUCTION

The term adaptation refers to the relationship between a plant or crop and its environment, and can be used in two ways (Byth, 1981), i.e., to describe both a process and a condition: the process is one of modification to suit new environmental circumstances, and the condition is the result of that process. In the latter case, the process may be unknown or ignored, and adaptation describes the present performance of a population in one or more environments. This, the condition, is the emphasis of this chapter. The effects of specific environmental factors on the growth and development of pigeonpea are first discussed, after which the net result of their interaction is described in terms of the cropping systems in which pigeonpea is currently produced. This is, in practice, an extremely broad topic because of the multitude of environments, farming, and cropping systems in which pigeonpea is grown, and the wide diversity among genotypes in the expression of an array of agriculturally significant characteristics.

However, the dynamic nature of adaptation is not ignored. Pigeonpea has been grown in some "traditional" cropping systems for centuries but has been incorporated into several others only in the last two decades. Particularly in the latter case, the process of adaptation is occurring through the identification, evaluation, and exploitation of agronomic and genetic variability. Even traditional systems should be subject to review to ensure that historical definitions of adaptation continue to represent efficient and effective means of meeting the requirements of both the farming and the wider communities.

Pigeonpea is often reported to be a crop well-adapted to marginal conditions and non-responsive to inputs (Edwards, 1981; Whiteman *et al.*, 1985). As a generalization this reflects a confusion between the responses of the crop (or particular genotypes) to current production conditions, and the potential of the crop when known limits are alleviated, by either genetic or agronomic means. Certainly, such attributes of pigeonpea as long crop duration, perenniality, indeterminateness, photothermal sensitivity of flowering, low harvest index, and the state of semi-equilibrium with diseases and pests all indicate that genetic improvement of pigeonpea has been limited in comparison with more developed crop plants such as wheat, rice, and soybean, that have received the sustained input of agricultural scientists and producers over a long period of time. However, pigeonpea (and other legume crops) have traditionally been considered secondary to the staple cereals, and so given the poorest land, little or no inputs, and often grown in adverse climatic conditions. The deep-rooting character of pigeonpea provided access to limited but otherwise unavailable reserves of soil nutrients and water, and the low harvest index ensured some yield but generally constrained responsiveness to improved conditions.

In this context, "well adapted" often refers more to survival than to productiveness in harsh conditions, and to limited growth during the vegetative period. While this ability may be of limited value in seed crops, it was significant for traditional crops that were also valued as sources of forage, firewood, and craft materials. As the use of pigeonpea as a sole crop is expanding, and as escalating demand and prices are emphasizing the importance of productivity in all cropping systems, the traditional view of adaptation is being overtaken by a need to understand the limitations to productivity, particularly of seed.

FACTORS INFLUENCING ADAPTATION

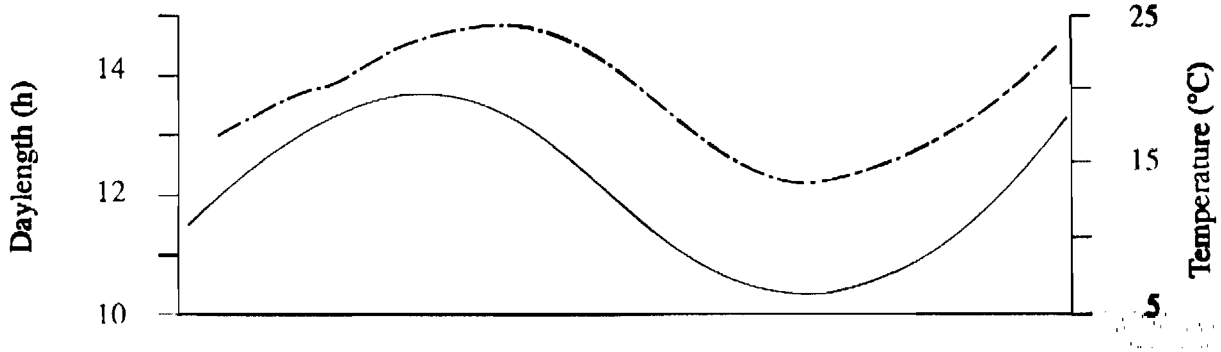
Climate

Photothermal Effects on Flowering

Pigeonpea, along with the majority of crop legume species of tropical origin, is described in general terms as having a quantitative short-day flowering response (Summerfield and Roberts, 1985b). That is, the onset of flowering is hastened as daylength shortens. However, both variation in sensitivity to photoperiod, including apparent day-neutrality (Ariyanayagam and Spence, 1978; Turnbull *et al.*, 1981) and major effects of temperature on the timing of flowering (McPherson *et al.*, 1985), are evident, although thorough investigations of these effects are few.

Some typical response types are illustrated in Figure 7.1, using data from Akinola and Whiteman (1975) and Turnbull (1986). The line UQ 1 demonstrates a quantitative, possibly even an obligate, short-day response. This genotype may have a long juvenile period and/or a short critical photoperiod (see Table 8.3). Sequential sowings which began around 110 days prior to the summer solstice did not flower until the short days of the following autumn, and time to flowering was progressively reduced. Flowering time was again increased in sowings made late in the summer, possibly because of lower temperatures in the period preceding flowering. Regression analyses indicated that the rate of progress to flowering was strongly associated with photoperiod, and with temperature at photoperiods below the critical photoperiod (Table 8.3).

Both UQ 39 and Prabhat appear to be unresponsive to photoperiod but sensitive to mean temperature. However, the range of temperatures experienced by these sowings was small, and the relationships between flowering and temperature were different for the two genotypes. In UQ 39, flowering occurred more rapidly in sowings made in cool conditions (around the spring equinox), while in Prabhat, cool temperature sowings (around the autumn equinox) delayed flowering.



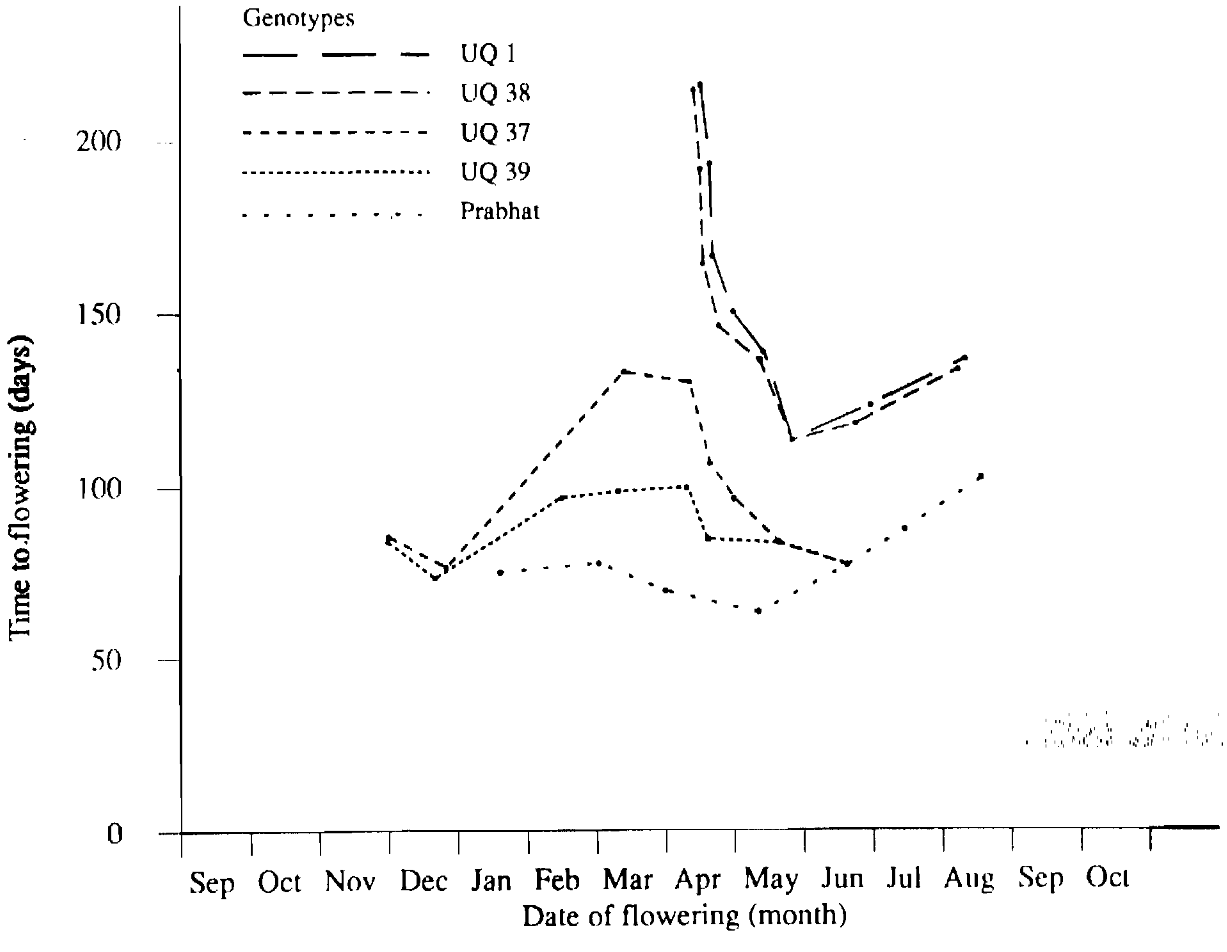


Figure 7.1. Variation in time to flowering (days) plotted against date of flowering for a range of sowings at Redland Bay, Australia (28°S), of pigeonpea genotypes of differing maturity.

Source: Data from Akinola and Whiteman, 1975; Turnbull, 1986.

ICRISAT scientists have developed a classification of maturity types based on time to flowering in sowings around the longest day at Hyderabad (17°N) (Sharma *et al.*, 1981). Ten maturity groups are recognized, from Group O (flowering in less than 60 days) to Group IX (flowering in more than 160 days). These groups are presented in Table 3.3. While this classification is useful as a general description, caution is needed for specific applications such as the prediction of phenology in a new environment. Genotypic variation in responses to photoperiod and temperature are such that not only time to flowering, but relative rankings also vary across locations. In addition, some genotypes are phenologically adapted over wide geographical areas while others perform well in a more limited range of environments (Sharma *et al.*, 1981). Seasonal ranges of day length, and variations caused by changes of sowing date, become progressively greater as latitude increases, so that the responses of photoperiod-sensitive genotypes become more acute (Lawn and Williams, 1987). Data from Khon Kaen, Thailand (Figure 7.2) illustrate that changes can occur in relative rankings across sowing dates, although there is considerable consistency because of the similar latitude (16°N) to that at which the original classification was determined. Even larger variations occur when differences in latitude are more pronounced (Sheldrake, 1984).

Controlled-environment studies have confirmed substantial effects of both photoperiod and temperature on the timing of flowering. Using genotypes from a wide range of maturity groups, McPherson *et al.* (1985) concluded that the effects of temperature were at least as important as those of day length. In all genotypes tested, the rate of progress of flowering demonstrated a broad optimum-type response to temperature, with most rapid flowering in the range 20-28°C (Figure 7.3). Turnbull (1986) reported similar findings for several early genotypes, and demonstrated that the optimum temperature for floral initiation (determined by dissection of apices) was lower than that for the rate of floral development between initiation and anthesis. Floral initiation was also more sensitive to temperature extremes: it was inhibited at either 16° or 32°C, whereas once initiation had occurred, exposure to a 16/32°C, diurnal regime did not inhibit further floral development. Considerable genotypic variation was demonstrated in the apparent requirement for, and length of, a juvenile phase (0-18 days), and the number of inductive cycles required to induce floral initiation (7-14), (Turnbull, 1986).

It is clear that much remains to be learnt about photothermal effects on flowering in pigeonpea. Summerfield and Roberts (1985a), referring to legumes in general, suggested that the influence of temperature on flowering is likely to be substantial in many species previously considered to be primarily responsive to photoperiod. Pigeonpea can be included in this category. While studies such as those described above have pointed to the importance of the effects of temperature on flowering, even in genotypes with clear photoperiod sensitivity, the confounding of temperature and photoperiod effects in field studies means that causal relationships, and the nature of any interactions, cannot be detected with confidence from much of the present field data.

Further experimentation in controlled-environment conditions is required, but the objectives, treatments, and experimental conditions require precise definition to ensure that the range of treatments is appropriate, and that errors associated with confounding of effects and artefactual responses are avoided (Lawn, 1981; Summerfield and Roberts, 1985a; Turnbull and Ellis, 1987).

In practice, phenological responses have a major influence on the role of pigeonpea in cropping systems and the selection of genotypes for particular niches. A detailed description is given later in this chapter.

Other Effects of Temperature

Angus *et al.* (1981) estimated the threshold daily mean temperature for emergence of pigeonpea under field conditions as 12.8°C. This was one of the highest values of the 30 species tested in their study, but was intermediate among the nine tropical crop legumes, whose range was 9.6-14.7°C. Emergence (50%) required 58.2 day-degrees above the threshold temperature, which would accumulate in 26 days at 15°C, 8 days at 20°C, and 5 days at 25°C. It is reported (de Jabrun *et al.*,

1981) that at least 85% germination occurred at a range of temperatures between 19 and 43°C inclusive, but that no germination occurred at either 7.1 or 46.5°C.

Controlled-environment studies (McPherson *et al.*, 1985; Turnbull, 1986) have demonstrated

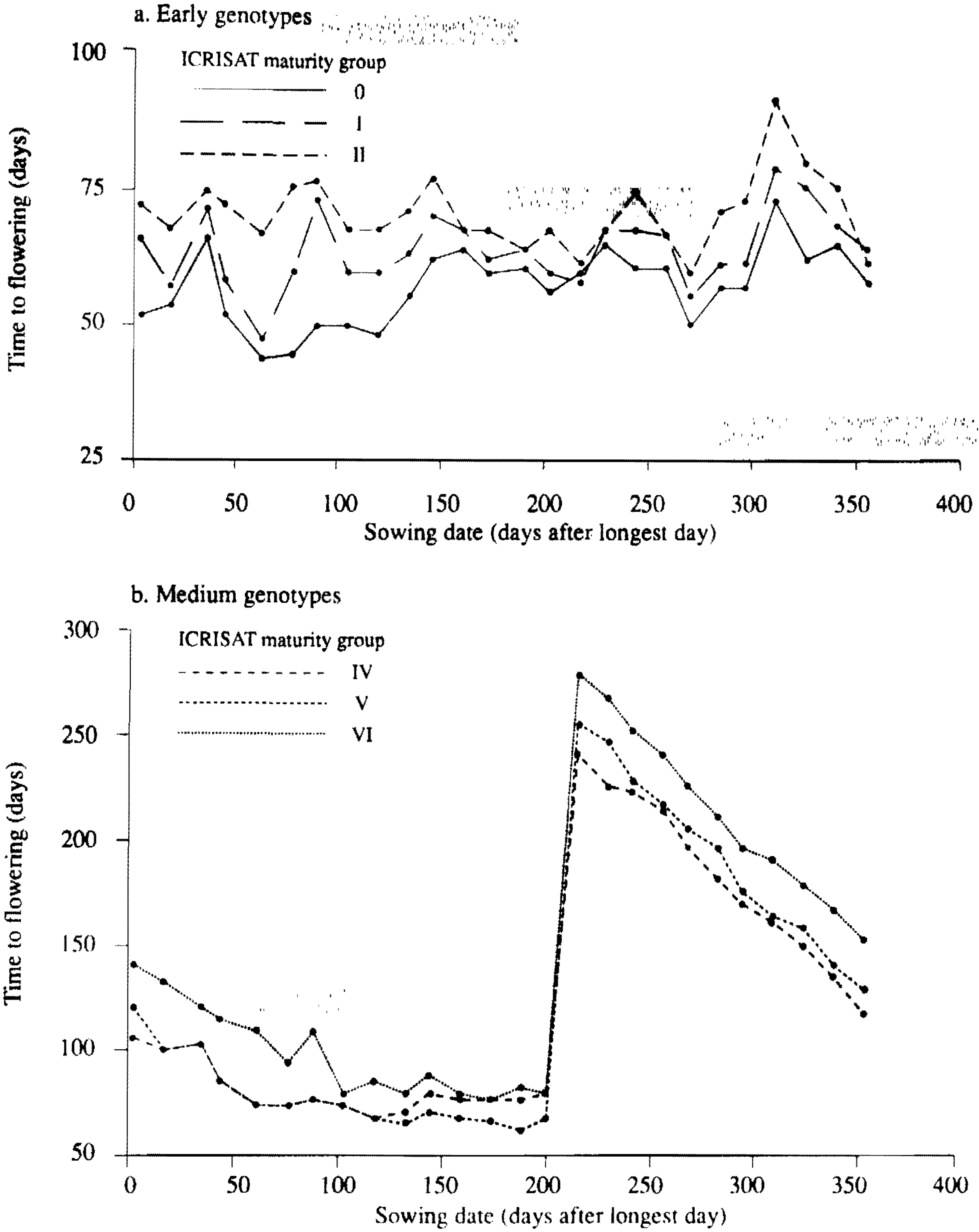


Figure 7.2. Variation in time to flowering (days) plotted against sowing date (days after longest day) for a range of sowings at Khon Kaen, Thailand (16°N) of pigeonpea genotypes of differing maturities, a. Early, b. Medium.

Source: Sukarin *et al.*, unpublished.

that growth-related attributes such as plant height, numbers of nodes, shoot dry mass, and leaf area increase with increasing temperature in the ranges commonly tested (16-32°C). Field observation in northern India, where the daily maximum temperature is consistently between 35 and 45°C for two months either side of the summer solstice, suggests that such high maximum temperatures do not present a serious limitation to the vegetative growth of pigeonpea if water

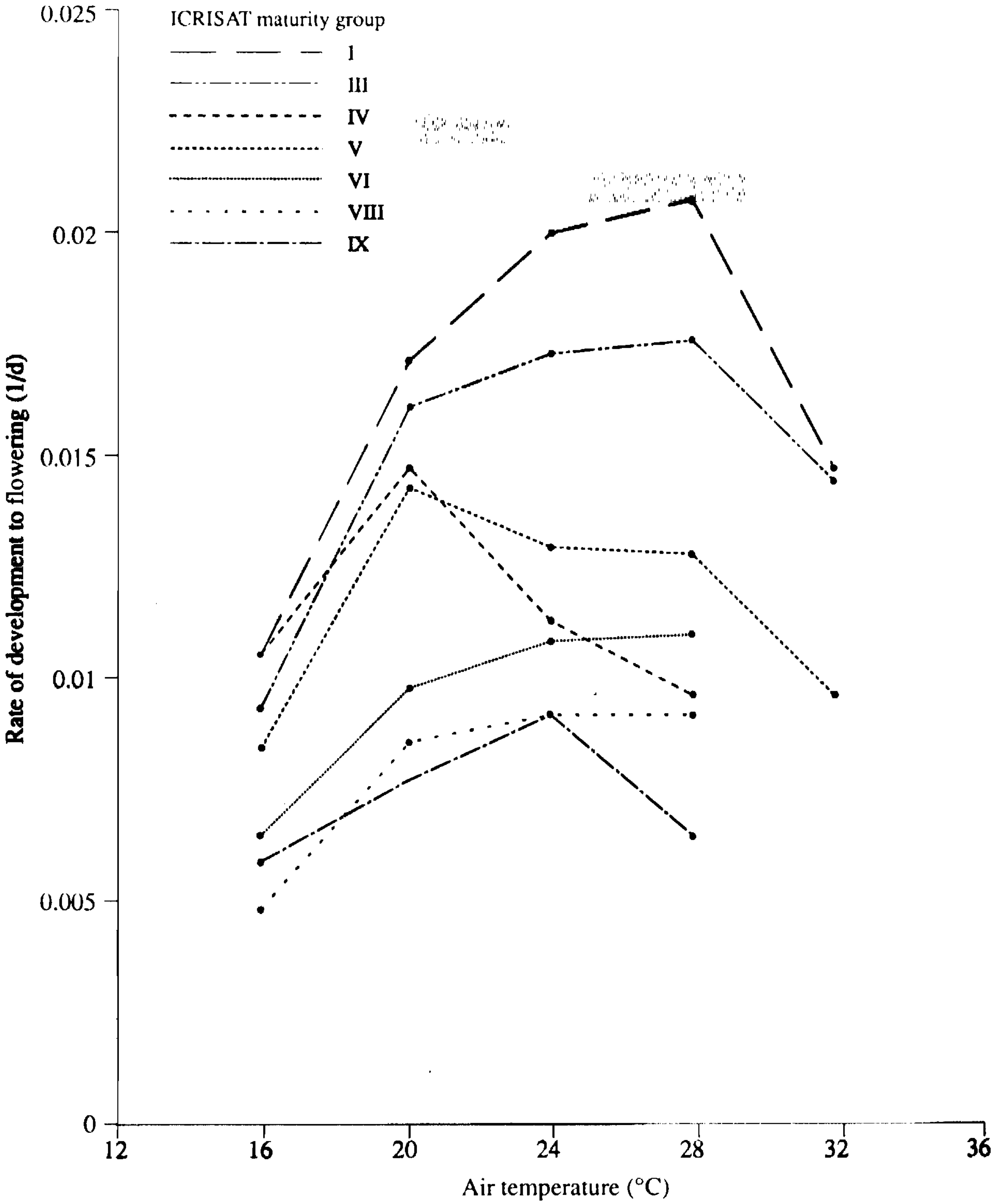


Figure 7.3. The effect of air temperature (°C) on the rate of development from sowing to flowering (1/d) of pigeonpea genotypes of differing maturity.

Source: McPherson *et al.*, 1985.

supply is adequate. However, Turnbull (1986) reported that high constant day temperature (35°C) in a controlled environment increased floral abortion and decreased pod set.

Conversely, vegetative growth in controlled environments is slow at temperatures below 20°C, and exposure to relatively mild frost is lethal for leaves and meristems. Brief periods of temperatures between -2 and -3°C caused varying degrees of defoliation, but exposure for 10 hours to temperatures between -1 and -3°C was lethal (Morton *et al.*, 1982). Akinola and Whiteman (1975) suggested that pod set was lower in sowings that flowered in periods of low temperature.

Clearly, pigeonpea production systems reflect these responses to temperature. Pigeonpea is grown during the warm season in the tropics and subtropics, and off-season production is confined to frost-free areas. The growth of long-season crops which remain in the field during winter is extremely limited during that period.

Radiation

Radiation provides the source of energy for dry matter (DM) accumulation and plant growth, and thus establishes an upper limit of productivity that is subject to restriction by other environmental constraints (Lawn and Williams, 1987). In general, pigeonpea crops are more likely to be limited by water than by irradiance, although two important exceptions are; extended periods of cloud cover during monsoon seasons (Versteeg and van Keulen, 1986), and intercrops that are shaded by their companion crop (Natarajan and Willey, 1980). In addition, interception of radiation is limited by the slow leaf-area development in pigeonpea observed both in seedlings and in intercrops after the harvest of the companion crop (Sheldrake and Narayanan, 1979).

Pigeonpea is most sensitive to low irradiance during the period of pod formation (the 4 weeks after flowering), when pod retention is strongly related to current assimilation (Table 7.1, Thirathon *et al.*, 1987). In practice, however, most pigeonpea is sown during the early part of the wet season and does not flower until the monsoon period is over. Observation of experimental sowings which commenced flowering during the monsoon indicated that pod set was very poor while the cloud cover persisted, but recovered once it dissipated (R.J. Troedson, personal observation). Apparent genotypic differences in pod retention in shaded conditions have been observed at the University of Queensland.

The low initial crop growth rate (CGR) of pigeonpea relative to many other crops is well recognized (Rachie and Roberts, 1974; Sheldrake and Narayanan, 1979; Willey *et al.*, 1981; Muchow, 1985b; Whiteman *et al.*, 1985). Rather than a consequence of greater partitioning of DM to roots, the low CGR is primarily the result of the substantially lower assimilatory surface (and thus, the

Table 7.1. Effects of shading during various growth stages on subsequent pod and seed development of pigeonpea.

Growth stage	Effect
Vegetative	None
Weeks 1 and 2 after flowering	Reduction of maximum pod number (MP) MP (% of control) = $-86.28 + 20.85S - 1.03S^2$, $R^2=0.86^{**}$, where S = assimilate supply (g)
Weeks 3 and 4 after flowering	Increased pod loss (PL) PL(%) = $60.43 - 360.22S + 1101.91S^2$, $R^2= 0.42^{*}$
Weeks 5-8 after flowering	Reduced seed size

Source: Thirathon *et al.*, 1987.

lower interception of radiation) of pigeonpea seedlings, and the magnification of that effect by the exponential nature of early crop growth (Brakke and Gardner, 1987). The critical leaf area index (LAI) (that is required for 95% interception of radiation) is also high (5-7) (Rachie and Roberts, 1974; Rowden *et al.*, 1981).

The low early CGR has several implications for sole crops. The period of growth prior to full canopy cover is relatively long, as therefore is the optimum time of flowering. In environments characterized by terminal drought stress, faster-growing legume crops may be able to outyield pigeonpea because of their shorter duration (Lawn and Williams, 1987). Weed competition can cause substantial reductions in growth and yield if weeds are not controlled during early growth (Shetty, 1981). Weed problems and lack of economical control measures can be a significant factor influencing the suitability of particular environments or fields for pigeonpea production.

By contrast, the low early CGR of pigeonpea and its apparent tolerance of low irradiance enhance its suitability as an intercrop, because it has little effect on the development of the companion crop but can respond immediately the companion crop is harvested (Sheldrake and Narayanan, 1979; Trenbath, 1981). Genotypic differences in growth during these two phases of an intercrop have been identified (Rao *et al.*, 1981), and are also discussed in Chapter 8.

Water

Over 90% of the pigeonpea cropping area is rainfed (Singh and Das, 1987), principally in sub-humid areas where the growing-season rainfall is between 500 and 1000 mm (Reddy and Virmani, 1981). Several attributes of pigeonpea are reflected in its adaptation to these areas.

Firstly, pigeonpea has a deep and extensive root system (Rachie and Roberts, 1974; Sheldrake and Narayanan, 1979), which provides access to water stored deep in the soil profile when that in the surface layers is depleted. This source of water is particularly important for long-duration crops. Water extraction has been reported from 180 cm in a Vertisol (Sardar Singh and Russell, 1981) and from 220 cm in an Oxisol (B. Singh *et al.*, unpublished).

Secondly, pigeonpea can endure periods of water deficit as a result of relatively high levels of dessication tolerance and osmotic adjustment (Flower and Ludlow, 1987). Osmotic adjustment enables continued growth and survival as plant water deficits increase, which may permit continued root growth and water extraction. However, Flower and Ludlow (1987) observed relatively little variation in either character in a wide range of pigeonpea accessions.

Compared to other crop legumes, stomatal conductance in pigeonpea is relatively insensitive to saturation deficit, so that stomata of well-watered plants remained open when evaporative demand was high (Muchow, 1985c; De Vries, 1986). As water deficits developed, both leaf water potential and stomatal conductance declined only gradually, permitting continued photosynthesis, while the ability of pigeonpea to reduce radiation load by shedding leaves or altering leaf orientation was relatively limited in one study (Muchow 1985a,b) but strongly expressed in another with a different genotype (De Vries, 1986).

The combination of drought tolerance and polycarpic flowering habit may enable pigeonpea to survive a period of water deficit during which all reproductive structures are shed, and then to reflower and set a new crop once the stress is relieved. However, pigeonpea like all crops, will yield poorly or not at all if drought stress during reproductive growth is severe and persistent (Sinha, 1981; Troedson, 1987).

Selection of the most appropriate phenology depends on the nature of the water limitation. Later-maturing genotypes are most suited to situations of intermittent water deficits on soils of good water-holding capacity. Where water deficits are more severe (e.g., through low rainfall or shallow soil) and/or terminal, early genotypes are likely to be more productive (Sharma *et al.*, 1981; Muchow, 1985a).

Certainly, both biomass and seed yields may be enhanced in pigeonpeas of all maturity groups by the application of irrigation (Sinha, 1981; Venkataranam and Sheldrake, 1985). Optimum water management of pigeonpea is discussed in Chapter 11.

Thirdly, pigeonpea is susceptible to waterlogging, so that many areas of high rainfall and/or impermeable soils are unsuitable for pigeonpea production. Mortality may result from physiological damage and/or the effects of diseases such as phytophthora blight caused by *Phytophthora drechsleri* f. sp *cajani* (Chauhan, 1987). One apparent cause of physiological damage is ethylene produced by soil microflora, so that damage is greatest in soils of high organic matter content. Short-term or intermittent waterlogging impairs or eliminates nitrogen fixation and can lead to serious nitrogen deficiency in the shoots. Genotypic variability in physiological tolerance of waterlogging has been observed (Chauhan, 1987), and tolerance to phytophthora blight is essential in waterlogging-prone environments.

Edaphic Factors

Chemical Limitations

Pigeonpea is grown on a wide range of soil types of varying physical and chemical characteristics. The major soils in India are alluvials, Vertisols and Alfisols, which range in reaction from pH 6.5 to 8.5 (Reddy and Virmani, 1981). Pigeonpea soils in Central America and Southeast Asia are more acidic (Ariyanayagam and Griffith, 1987; Craswell *et al.*, 1987).

Mineral nutrition does not appear to have been a serious limitation to the adaptation of pigeonpea. Pigeonpea is widely reported to be unresponsive to fertilizers (Morton, 1976; Edwards, 1981), but it is likely that deficiencies of non-target elements have masked responses to those applied (Edwards, 1981). A review of studies in India indicated consistent responses to N, P, and K, depending on soil test (Kulkarni and Panwar, 1981), although very few studies have related responsiveness of pigeonpea to soil test results. Aspects of mineral nutrition are discussed in detail in Chapter 9, while other specific chemical limitations are briefly discussed here.

Pigeonpea is able to tolerate a broad range of soil pH, with reasonable growth reported on soils in the pH range 5.0 to 8.5 (Edwards, 1981). The major problem on alkaline soils is likely to be specific nutrient deficiencies, that can also be induced by excessive liming of acid soils. Poor nodulation has been observed in the first year of pigeonpea on some high (8.0) pH soils in New South Wales, Australia (J. Holland, personal communication). Acid soils are not a feature of traditional pigeonpea-growing areas in India, but are important in Central America, Fiji, and areas of potential pigeonpea production in Southeast Asia. Pigeonpea is more sensitive to strongly acid conditions than groundnut or cowpea (Chong *et al.*, 1987).

Responses to lime in both shoot growth and nodulation have been reported in soils below pH 5.0 (Edwards, 1981). Genotypic differences in response to low pH have also been observed. Cowie *et al.* (1987) reported that root growth of one cultivar (Royes) was restricted on soil of pH 5.1 and 50% aluminium saturation of the cation exchange complex, while another cultivar (Hunt) was unaffected. A study of 18 genotypes in soil of pH 4.3 indicated that some were limited by calcium deficiency alone, while others required pH amendment for adequate growth (R.J. Troedson, unpublished). Under field conditions, genotypes that suffer root damage are susceptible to drought stress because of their limited root development.

Pigeonpea is relatively sensitive to salinity and has not been produced in saline areas. Among several crop legumes, pigeonpea was rated as more sensitive than guar, cowpea, soybean, and black gram, and less sensitive than green gram, although only one or two genotypes of each species were tested (Keating and Fisher, 1985). However, salinity is developing in many pigeonpea-producing areas of India (Chauhan, 1987). Genotypic differences have been identified and screening is being conducted by ICRISAT.

Physical Limitations

Soil texture influences the adaptation of pigeonpea principally through effects on aeration, water-holding capacity, and soil strength. Aeration can become limiting in wet soils, and waterlogging is more likely to be a problem in clay than in sandy soils, so that nodulation is often poor on clays (Sheldrake and Narayanan, 1979). However, high clay soils are widely used for pigeonpea production because of the need for adequate water storage for dryland crops. In monsoon environments, waterlogging can cause extensive plant mortality in seedlings, but its impact can be substantially reduced through the use of ridges or beds (Kampen, 1982).

Pigeonpea is intermediate among crop legumes in susceptibility to mechanical impedance caused by high soil strength (So and Woodhead, 1987). Compaction of both a Vertisol and an Oxisol by agricultural traffic restricted root growth, and, as a consequence, shoot growth and seed yield, when soil conditions were dry (Table 7.2, Kirkegaard *et al.*, in press). However, when irrigation was applied, soil strength in the compaction layer was reduced sufficiently to enable root penetration.

Table 7.2. Effects of soil compaction on soil bulk density (g cm^{-3}) and shoot dry matter (DM) (g m^{-2}) at 40 DAS of pigeonpea in two clay soils.

	Vertisol			Oxisol			
		Shoot DM (g m^{-2})			Shoot DM (g m^{-2})		
Compaction treatment	Bulk density (g cm^{-3})	1984 (dry)	1988 (wet)	Bulk density (g cm^{-3})	1987 (wet)	1988 (wet)	1987 (rain excl.)
Deep ripped	1.01	90	142	1.01	275	286	110
Moderate compaction	1.17	73	169	1.37	295	313	119
Severe compaction	1.28	44	147	1.45	304	268	69
LSD (0.05)	0.04	14	ns	0.06	ns	ns	44

1. ns = not significant

Source: Kirkegaard *et al.*, in press.

PIGEONPEA PRODUCTION SYSTEMS

Crop production systems have various objectives (e.g., stability of subsistence production, sustainability of resources, maximization of returns) and may be classified in several ways. The cropping systems of resource-poor farmers in dryland environments are greatly influenced by the need to meet human and animal food requirements and other domestic needs, and then to have a marketable surplus if possible. In contrast, in irrigated or assured-rainfall environments production for the market assumes greater importance. In the former situation, that is often characterized by high variability in the incidence of rainfall, stability of production over seasons is a more important consideration than the pursuit of high yield. The choice of crops in both systems (rainfed and irrigated) depends on the inherent efficiency of the individual crops that make up the system, and also on complementary effects between the crops (intercropping systems) and their duration (multiple cropping systems).

Specific crop attributes can also provide a convenient conceptual framework for the classification of crop production systems. The diverse array of production systems for pigeonpea is most strongly influenced by the wide range of phenological responses exhibited by pigeonpea genotypes. We have followed Byth *et al.*, (1981) who defined three general classes of production systems for pigeonpea, based on phenological development. These are long-season, full-season, and short-season crops (Figure 7.4).

Long-season Crops

Long-season or long-duration crops are those which are sown near the longest day of the year, and which do not flower until after the shortest day of the year (Figure 7.4). These are photoperiod-sensitive genotypes in which the delay in flowering is most probably due to a combination of a

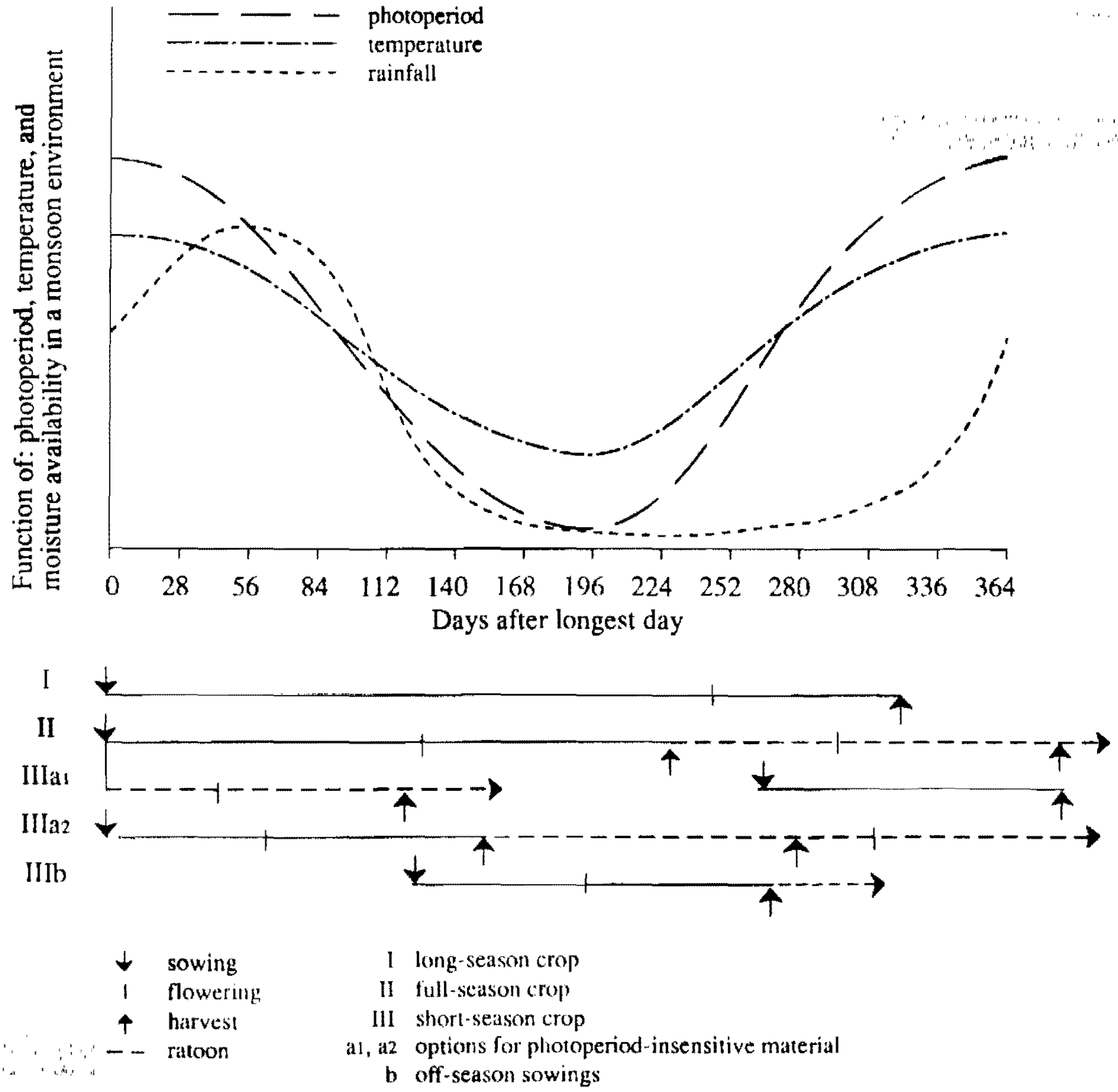


Figure 7.4. A generalized classification of production systems in pigeonpea.
Source: Byth *et al.*, 1981.

short critical photoperiod for floral induction, and inhibition or delay of floral development by low temperatures over the winter period (Byth *et al.*, 1981; Saxena *et al.*, 1985).

This is the traditional cropping system in large areas of northern and central India. Because the long growing season results in extensive vegetative development, these genotypes are usually sown at low density and intercropped. The companion crop is generally a fast-maturing cereal or legume (or both) and the pigeonpea canopy does not develop extensively until after the harvest of the companion crop (Natarajan and Willey, 1980). A deep and extensive root system develops and the pigeonpea crop relies on exploitation of stored soil water for most of the cropping period, although seed yield is boosted by any rainfall during the dry period. Seed yield of pigeonpea can be high (2-4 t ha^{-1}) in this system when growing conditions are favourable and the population of pigeonpea is at normal levels (4-5 plants m^{-2}, equivalent to 40-50,000 plants ha^{-1}).

Long-season pigeonpea is also grown in Myanmar, Africa, and the Americas. In Africa it is commonly intercropped with maize, sorghum, cowpea, and cassava (Acland, 1971). In Central and South America and the Caribbean, the usual intercrop is maize. In India, intercropping with sorghum is the predominant practice. Panwar (1980) reported that grain yield of the long-duration pigeonpea cultivar T 7 in an intercrop with sorghum was only 40% of its sole crop yield of 2.6 t ha^{-1}, while the intercropped sorghum yielded 2.4 t ha^{-1}. By contrast, with a less competitive intercrop component such as black gram, which yielded 1.5 t ha^{-1}, the yield of T 7 was not reduced compared to the sole crop yield.

Pigeonpea/legume combinations are common in Africa with cowpea, and with groundnut in India although mung bean, black gram and soybean also occur. Studies at ICRISAT on Alfisols have shown that when plant populations of each crop (pigeonpea and groundnut) were at the level of their sole-crop optimum, yields averaged 82% of the sole groundnut crop plus 85% of the medium-duration pigeonpea crop; i.e., there was a yield advantage of 67% over sole cropping (Willey *et al.*, 1981).

The adaptation of medium- and long-duration genotypes to several intercropping systems in rainfed agriculture, is also influenced by semi-equilibrium with major diseases (fusarium wilt (*Fusarium udum*), and sterility mosaic disease) and insect pests (pod borer, *Helicoverpa armigera*, and pod fly, *Melanagromyza obtusa*). Some losses caused by these pests are usually observed and tolerated. Recent research has sought to reduce these losses by resistances and manipulation of phenology. For example, in areas of adaptation of long-duration pigeonpea in northern India where the winters are cooler, pod fly is a major pest. By reducing the duration of flowering and increasing the synchrony of maturity, resulting in an overall reduction of maturity duration by 20-30 days, the pod fly and borer losses are considerably reduced (S.S. Lal, personal communication). A cultivar (Bahar) which possesses these attributes has recently been widely adopted.

A variation on the use of long-season crops is their utilization as perennials. Pigeonpea is intrinsically perennial and is often grown in backyards, around annual crops, on field bunds, or as boundary plants (Buranasilpin, 1983; Sharma and Sowley, 1984; Kannaiyan *et al.*, 1988). Systems such as the alley cropping developed at the International Institute for Tropical Agriculture (IITA) as an alternative to shifting cultivation may also incorporate perennial pigeonpeas as single or double rows in alleys spaced at 2-4m (R.C. Gutteridge, personal communication). Modifications in alley arrangement, such as increases in the alley width, may reduce the area of the annual crop area affected by competition, and increase benefits from the system.

A system using perennial pigeonpea strips 4.0-m wide alternating with 8.0-m wide strips of annual crops is presently being investigated at ICRISAT Center (C.K. Ong, ICRISAT, personal communication). Studies have indicated that perennial pigeonpea behaves like medium-duration types in the first year and is less competitive than *Leucaena* to the annual crops in the system Multiple prunings for fodder harvests are possible, with some sacrifice in grain yield. Different cutting intervals and pruning height have been investigated (Salih, 1981; Bahar, 1982; Tayo, 1985; Venkataratnam and Sheldrake, 1985). Perennial pigeonpea can be used as a green manure crop to improve site characteristics through accumulation of organic matter, penetration of layers of gravel or dense clay, and improvement of soil structure, with the added benefit that it can be easily cleared from the land afterwards.

Full-season Crops

Full-season crops, often called medium-duration crops, are defined as those which occupy the full length of the warm season (Figure 7.4). They are sown before or around the longest day of the year, but with genotypes that flower after 3-4 months, so that crop maturity occurs during the cool season. Such crops are grown in central India, Fiji, Central America, and some tropical and subtropical areas of Australia. They are more suited to monsoon environments where the onset of the wet season, and thus sowing time, is reasonably consistent. In sub-tropical Australia, their use is complicated by the considerable year-to-year variability in the timing of sowing rains. Because these genotypes are photoperiod-sensitive, phenology and therefore agronomic management (sowing density, etc.), varies considerably with sowing time (Wallis *et al.*, 1981). As a result, the use of this system in Australia has diminished in favour of short-season crops.

The medium-duration (160-200 days maturity) cultivars are adapted to the central and peninsular plateau in India between latitudes 10° to 20°N where soils are relatively shallow and winters are milder than in the north. The onset of terminal drought stress is more rapid than on the heavy soils. These cultivars may be ratooned, especially if irrigation is available (Venkataratnam and Sheldrake, 1985). The medium-duration cultivars may be intercropped with cotton, sorghum, maize, groundnut, soybean, pearl millet and several other short-statured minor millets, upland rice, and other grain legumes.

Intercropping with medium-duration pigeonpea is well adapted to dryland agriculture where the growing period is constrained by soil moisture availability. These are proven systems of maximizing stability to agricultural production in central and peninsular India (Rao and Willey, 1980). The characteristics, advantages, and disadvantages of this system are discussed by Willey (1985). Many of these systems (based on medium- and long-duration pigeonpea) have been described in detail elsewhere (Aiyer, 1949; Laxman Singh and Shrivastava, 1976; Jodha, 1981; Panwar, 1980; Laxman Singh, 1980; Tarhalkar and Rao, 1980; Chapter 12).

In summarizing the results of 51 experiments in India on sorghum pigeonpea intercrops grown at either 1:1 or 2:1 sorghum:pigeonpea ratio, Rao and Willey (1980) found that in the intercrop sorghum grain yield was reduced to 90% of the average sole crop yield of 3.2 t ha^{-1} and pigeonpea grain yield was reduced to 55% of the average sole crop yield of 1.4 t ha^{-1}. With a 2:1 maize-pigeonpea intercrop at Msekera Research Station in Zambia, Kannaiyan *et al.* (1988) found that maize yielded 96% of its sole crop yield of 4 t ha^{-1} and pigeonpea ICP 7035 yielded 1.2 t ha^{-1}.

Short-season Crops

Short-season crops fall into two categories: early-maturing and off-season crops. Early-maturing crops (Figure 7.4) are those which utilize photoperiod-insensitive genotypes, that flower between 60 and 80 days after sowing. Flowering time of individual genotypes may differ by 5-10 days between environments, due to the effects of temperature and, possibly, slight photoperiod sensitivity. Early-maturing crops were described over 150 years ago (Roxburgh, 1832) but intensive research efforts during the last two decades have led to the development and release of short-duration, photoperiod-insensitive cultivars (Lal and Sinha, 1972; Gupta *et al.*, 1987; Meekin *et al.*, 1987). These cultivars permit the use of pigeonpea in double or multiple cropping systems as distinct from the traditional use of pigeonpea as a long-season crop.

Early-maturing crops are grown in northwest India, Australia, and Fiji. In India and Australia, sowings around the longest day permit rotations with winter or spring crops. In Fiji, sowings are made in the later part of the wet season, either 1 or 2 months (light soils) or 3 or 4 months (heavy soils) after the longest day. Pigeonpea is grown in rotation with sugarcane on light soils, or rice on heavy soils. Recent studies have demonstrated that pigeonpea can be grown as an intercrop with newly planted cane, and produce seed yields of 1-2 t ha^{-1} without reducing the subsequent yield of the cane (V. Chand, unpublished).

Double cropping of short-duration pigeonpea with wheat is increasingly being adopted in northern India; pigeonpea is grown during the monsoon period and is harvested by November, in time for sowing of the wheat crop. More details are given in Chapter 12.

In Australia, early-maturing genotypes are grown in the summer rainfed cropping areas of the tropics and subtropics (Wallis *et al.*, 1981; Meekin *et al.*, 1987). Only sole crops are grown, at densities of 20-30 plants m^{-2}. Lower density is used in marginal dryland areas. Pigeonpea is grown in rotation with winter or summer cereals and oilseeds including wheat, barley, sorghum, and sunflower. Other legume crops in these rotations are chickpea and mung bean. Pigeonpea production in Australia is fully mechanized, and top-podding genotypes are preferred for ease of pesticide spraying and harvesting.

There is scope for extending this system to drier environments, by using even shorter-duration pigeonpea genotypes (<110 days) that can escape drought stress. In the Rift Valley of Kenya where a single wheat crop is grown, the potential of fitting short-duration pigeonpea into rotations with wheat is currently being explored. These extra-short-duration genotypes (maturing in 90-100 days at latitude 17°N at ICRISAT Center) also have the potential of extending the adaptation of pigeonpea to temperate regions up to latitude 45° and higher altitudes of 2000m. They have been successfully grown in Washington State, USA, where the frost-free growing season is limited to the period between May and October (W.J. Kaiser, personal communication).

In environments with warm winters (minimum temperatures >15°C) it is possible to exploit the perennial characteristics of short-duration pigeonpea by obtaining ratoon harvests. Chauhan *et al.* (1984) reported a total yield of 5.2 t ha^{-1} of dry seed from June-sown ICPL 87 in three harvests, the first in September, the second in November, and the third in March. This variety was released in India as "Pragati" in 1986 (Gupta *et al.*, 1987). This system gives much higher yields than the traditional medium-duration genotypes in this environment over a similar time period (Chauhan *et al.*, 1987).

In Sri Lanka 4-5 t ha^{-1} from short-duration genotypes like ICPL 87, ICPL 312, and ICPL 151 were obtained at Maha-Illuppallama in two ratoon harvests when sown in May 1987 with the final harvest at 9 months (S.J.B.A. Jayasekara, personal communication). In Australia, because of the occurrence of frost during the winter period, ratooning is generally only feasible in spring-sown crops (Figure 7.4) or in frost-free areas of the tropics, and where water is not a major limitation (Meekin *et al.*, 1987). Spring sowing is constrained by the relatively high temperature requirement for germination (Angus *et al.*, 1981).

A ratoon system would also be suitable for the production of vegetable pigeonpea, which as an alternative to serial or sequential sowings, could provide green pods over a period of several ratoon harvests. In Gujarat, India, 11 t ha^{-1} of green pods have been obtained from five harvests of ICPL 124 within a season (D.G. Faris *et al.*, ICRISAT, unpublished).

A major limitation of this system is a requirement of continued moisture supply for the production of economical ratoon harvests. For example, in monsoon environments, irrigation during the dry season is required, even for soils with high moisture-holding capacities. However, this system may be well suited to rainfed agriculture in environments where rainfall is higher and distributed over longer periods as in Sri Lanka.

Another limitation to this system is the ability for growth recovery after harvest of the first flush of pods. Genotypic differences in ratoonability have been found, but identification of genotypes with greater drought and low temperature tolerance would improve this character.

Short-duration pigeonpea can also be intercropped with other short-statured food legumes such as mung bean, urd bean, cowpea, soybean, and groundnut. Saraf and Amar Chand (1980) reported no reduction in seed yield of short-duration (ICRISAT group III) pigeonpea cultivar T 21 when intercropped with mung bean or urd bean. The pigeonpea yielded 2 t ha^{-1} and the intercrops 0.8 - 1.0 t ha^{-1}, which was equivalent to their yield as sole crops.

Off-season Crops

Off-season crops are those sown at least 2 months after the longest day (Figure 7.4). Either photoperiod-sensitive or insensitive genotypes may be sown; flowering is relatively early, even in sensitive types, because of the short daylengths, unless growth is restricted by low temperatures. These crops are grown in areas of favourable winter temperatures, such as in eastern India, Fiji, and tropical or sub-tropical coastal parts of Australia (Wallis *et al.*, 1981). In India these crops are often referred to as postrainy-season crops. More details are given in Chapter 12.

FUTURE

It is clear that a wide diversity in phenology and habit exists in pigeonpea, and that it is grown in a wide range of contrasting production systems. In fact greater differences exist in growth and development among genotypes adapted to the various production systems, than between many other crop species (D.E. Byth, unpublished). As a result, it is likely that pigeonpea could be grown in inventive ways in many more cropping systems than the traditional, and even the more recently established ones described in this chapter. Early pigeonpea is a good example – crops of these genotypes were described over 150 years ago (Roxburgh, 1832), but all factors supporting their widespread adoption (including attitudes towards innovation) have only recently become operative. We expect that the frontiers of adaptation of pigeonpea will continue to expand and that early genotypes will play a, if not the, major role in that expansion.

Acknowledgements

Financial support from the Australian Centre for International Agricultural Research for the pigeonpea project at the University of Queensland is acknowledged. The assistance of Mr A. Watkinson in preparation of the figures is greatly appreciated.

REFERENCES

Acland, J.D. (1971) *East African Crops: An Introduction to the Production of Field and Plantation crops in Kenya, Tanzania, and Uganda*. Longmans, London, pp. 140-141 (reprinted).

Aiyer, A.K.Y.N. (1949) Mixed cropping in India. *The Indian Journal of Agricultural Sciences* 19, 439-543.

Akinola, J.O. and Whiteman, P.C. (1975) Agronomic studies on pigeonpea (*Cajanus cajan* (L.) Millsp.). 1 Field responses to sowing time. *Australian Journal of Agricultural Research* 26, 43-56.

Angus, J.F., Cunningham, R.B., Moncur, M.W. and MacKenzie, D.H. (1981) Phasic development in field crops 1. Thermal response in the seedling phase. *Field Crops Research* 3, 365-378.

Ariyanayagam, R.P. and Griffith, S.M. (1987) Soil and climatic environment in the Caribbean region: yield reductions in pigeonpea due to drought, salinity, acidity, and alkalinity. In: *Adaptation of Chickpea and Pigeonpea to Abiotic Stresses. Proceedings of the Consultants' Workshop, 19-21 December 1984, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 149-158.

Ariyanayagam, R.P. and Spence, J.A. (1978) A possible gene source for early, day-length neutral pigeonpeas, *Cajanus cajan* (L.) Millsp. *Euphytica* 27, 505-509.

Bahar, F.A. (1982) Cultural practices for pigeonpea (*Cajanus cajan* (L.) Millsp.) as forage, green manure and grain crop. *Dissertation Abstracts International, Section B* 43, 10.

Brakke, M.P. and Gardner, F.P. (1987) Juvenile growth in pigeonpea, soybean, and cowpea in relation to seed and seedling characteristics. *Crop Science* 27, 311-316.

Buranasilpin, P. (1983) Pigeonpea research in Thailand. *International Pigeonpea Newsletter* 2, 9-10.

Byth, D.E. (1981) Genotype × environment interaction and environmental adaptation in plant improvement - an overview. In: Byth, D.E. and Mungomery, V.E. (eds), *Interpretation of Plant Response and Adaptation to Agricultural Environments.* Australian Institute of Agricultural Science, Brisbane, pp. 2-10.

Byth, D.E., Wallis, E.S. and Saxena, K.B. (1981) Adaptation and breeding strategies for pigeonpea. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 450-465.

Chauhan, Y.S. (1987) Screening for tolerance to salinity and waterlogging: case studies with pigeonpea and chickpea. In: *Adaptation of Chickpea and Pigeonpea to Abiotic Stresses. Proceedings of the Consultants' Workshop, 19-21 December 1984, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 93-103.

Chauhan, Y.S., Venkataratnam, N. and Johansen, C. (1987) The agronomy of multiple harvest pigeonpea. In: Wallis, E.S. and Byth, D.E. (eds), *Food Legume Improvement for Asian Farming Systems: Proceedings of an International Workshop held in Khon Kaen, Thailand, 1-5 September 1986. ACIAR Proceedings no. 18.* ACIAR, Canberra, p. 234.

Chauhan, Y.S., Venkataratnam, N. and Sheldrake, A.R. (1984) The high-yield potential of extra-early pigeonpeas in peninsular India. *International Pigeonpea Newsletter* 3, 28-31.

Chong, K., Wynne, J.C., Elkan, G.H. and Schneeweis, T.J. (1987). Effects of soil acidity and aluminium content on *Rhizobium* inoculation, growth and nitrogen fixation of peanuts and other grain legumes. *Tropical Agriculture (Trinidad)* 64, 97-104.

Cowie, A.L., Rayment, G.E. and Chand, V. (1987) Responses of pigeonpea to lime on an Oxisol in Fiji. In: Wallis, E.S. and Byth, D.E. (eds), *Food Legume Improvement for Asian Farming Systems: Proceedings of an International Workshop held in Khon Kaen, Thailand, 1-5 September 1986. ACIAR Proceedings no. 18.* ACIAR, Canberra, pp. 258-259.

Craswell, E.T., Loneragan, J.F. and Keerati-Kasikorn, P. (1987) Mineral constraints to food legume production in Asia. In: Wallis, E.S. and Byth, D.E. (eds), *Food Legume Improvement for Asian Farming Systems: Proceedings of an International Workshop held in Khon Kaen, Thailand, 1-5 September 1986. ACIAR Proceedings no. 18.* ACIAR, Canberra, pp. 99-111.

de Jabrun, P.L.M., Byth, D.E. and Wallis, E.S. (1981) Imbibition by and effects of temperature on germination of mature seed of pigeonpea. In: *Proceedings of the International Workshop on Pigeonpeas, volume 2, 15-19 December 1980, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 181-187.

De Vries, J.D. (1986) Water relations and nitrogen fixation of three grain legumes during water stress. MSc thesis, University of Florida, USA, 107 pp.

Edwards, D.G. (1981) Development of research on pigeonpea nutrition. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 205-211.

Flower, D.J. and Ludlow, M.M. (1987) Variation among accessions of pigeonpea (*Cajanus cajan*) in osmotic adjustment and dehydration tolerance of leaves. *Field Crops Research* 17, 229-243.

Gupta, S.C., Saxena, K.B., Faris, D.G. and Sharma, D. (1987) Promising pigeonpea varieties from ICRISAT. In: Wallis, E.S. and Byth, D.E. (eds), *Food Legume Improvement for Asian Farming Systems: Proceedings of an International Workshop held in Khon Kaen, Thailand, 1-5 September 1986. ACIAR Proceedings no. 18.* ACIAR, Canberra, p.314.

Jodha, N.S. (1981) Intercropping in traditional farming systems. In: *Proceedings of the International*

Workshop on Intercropping, 10-13 January 1979, ICRISAT Center, India. Patancheru, A.P., India: ICRISAT, pp. 282-291.

Kampen, J. (1982) *An Approach to Improved Productivity on Deep Vertisols. Information Bulletin no. 11.* Patancheru, A.P., India: ICRISAT, 14pp.

Kannaiyan, J., Haciwa, H.C., Greenberg, D.C., Mbewe, M.N., Irwing, N.S. and Sohati, P.H. (1988) Pigeonpea research in Zambia. *International Pigeonpea Newsletter* 7, 12-13.

Keating, B.A. and Fisher, M.J. (1985). Comparative tolerance of tropical grain legumes to salinity. *Australian Journal of Agricultural Research* 36, 373-383.

Kirkegaard, J.A., So, H.B. and Troedson, R.J. (in press) Effect of environmental conditions on the response of pigeonpea to soil compaction on two contrasting clay soils - an Oxisol and a Vertisol. In: *Proceedings of the International Conference on Soil Compaction as a Factor Determining Plant Productivity, June 1989, Lublin, Poland.* International Society of Soil Science.

Kulkarni, K.R. and Panwar, K.S. (1981) Response of pigeonpea to fertilizers in India: a critical review. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 212-220.

Lal, S. and Sinha, S.C. (1972) 'Prabhat' - an extra early variety of red gram. *Farmer and Parliament* 7(7), 18-24.

Lawn, R.J. (1981) Potential contribution of physiological research to pigeonpea improvement. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 151-164.

Lawn, R.J. and Williams, J.H. (1987) Limits imposed by climatological factors. In: Wallis, E.S. and Byth, D.E. (eds), *Food Legume Improvement for Asian Farming Systems: Proceedings of an International Workshop held in Khon Kaen, Thailand, 1-5 September 1986. ACIAR Proceedings no. 18.* ACIAR, Canberra, pp. 83-98.

Laxman Singh (1980) Prevalent practices of mixed cropping and cropping systems of pulse crops in India. *Indian Journal of Genetics and Plant Breeding* 40A, 11-15.

Laxman Singh and Shrivastava, M.P. (1976) Cultivation systems and varietal adaptation of pigeonpea in Madhya Pradesh. *Indian Journal of Genetics and Plant Breeding* 36, 293-300.

McPherson, H.G., Warrington, I.J. and Turnbull, H.L. (1985) The effects of temperature and daylength on the rate of development of pigeonpea. *Annals of Botany* 56, 597-611.

Meekin, J.S., Troedson, R.J., Wallis, E.S. and Byth, D.E. (1987) Pigeonpea: a new summer legume crop. *Queensland Agricultural Journal* 113, 117-122.

Morton, J.F. (1976) The pigeonpea (*Cajanus cajan* Millsp.), a high protein, tropical bush legume. *HortScience* 11(1), 11-19.

Morton, J.F., Smith, R.E., Lugo-López, M.A. and Abrams, R. (1982) *Pigeonpeas (Cajanus cajan Millsp): A Valuable Crop of the Tropics.* Special Publication of the College of Agricultural Sciences, Department of Agronomy and Soils, University of Puereto Rico, Mayaguez, Pureto Rico, 123 pp.

Muchow, R.C. (1985a) Phenology, seed yield and water use of grain legumes grown under different soil water regimes in a semi-arid tropical environment. *Field Crops Research* 11, 81-97.

Muchow, R.C. (1985b) Canopy development in grain legumes grown under different soil water regimes in a semi-arid tropical environment. *Field Crops Research* 11, 99-109.

Muchow, R.C. (1985c) Stomatal behaviour in grain legumes grown under different soil water regimes in a semi-arid tropical enviroment. *Field Crops Research* 11, 291-307.

Natarajan, M. and Willey, R.W. (1980) Sorghum-pigeonpea intercropping and the effects of plant population density. 1. Growth and yield. *Journal of Agricultural Science, Cambridge* 95, 51-58.

Panwar, K.S. (1980) Intercropping with pigeonpea. *Indian Journal of Genetics and Plant Breeding* 40A, 64-69.

Rachie, K.O. and Roberts, L.M. (1974) Grain legumes of the lowland tropics. *Advances in Agronomy* 26, 1-132.

Rao, M.R. and Willey, R.W. (1980) Evaluation of yield stability in intercropping: studies on sorghum/pigeonpea. *Experimental Agriculture* 16, 105-116.

Rao, M.R., Willey, R.W., Sharma, D. and Green, J.M. (1981) Pigeonpea genotype evaluation for intercropping. In: *Proceedings of the International Workshop on Pigeonpeas, volume 2, 15-19 December 1980, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 263-270.

Reddy, S.J. and Virmani, S.M. (1981) Pigeonpea and its climatic environment. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 259-270.

Rowden, R., Gardiner, D., Whiteman, P.C. and Wallis, E.S. (1981) Effects of planting density on growth, light interception and yield of a photoperiod insensitive pigeonpea (*Cajanus cajan*). *Field Crops Research* 4, 201-213.

Roxburgh, W. (1832) *Flora Indica: Descriptions of Indian Plants.* W. Thacker and Co., Calcutta, and Parbury, Allen and Co., London.

Salih, A.F. (1981) Effect of number of cuts and time of cutting on pigeonpea forage yield. *Pulse Crops Newsletter* 1(4), 34.

Saraf, C.S. and Amar Chand (1980) Agronomic and economic aspects of intercropping systems with grain legumes in relation to phosphate levels. *Indian Journal of Genetics and Plant Breeding* 40A, 31-38.

Sardar Singh and Russell, M.B. (1981) Water use by a maize/pigeonpea intercrop on a deep Vertisol. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 271-282.

Saxena, K.B., Gupta, M.D., Chauhan, Y.S. and Faris, D.G. (1985) Low temperature-induced floral abscission in pigeonpea. *International Pigeonpea Newsletter* 4, 27-28.

Sharma, D., Reddy, L.J., Green, J.M. and Jain, K.C. (1981) International adaptation of pigeonpeas. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 71-81.

Sharma, D. and Sowley, G.K. (1984) Comparison of maize/pigeonpea intercropping patterns in Northern Ghana. *International Pigeonpea Newsletter* 3, 24-25.

Sheldrake, A.R. (1984) Pigeonpea. In: Goldsworthy, P.R. and Fisher, N.M. (eds), *The Physiology of Tropical Field Crops.* John Wiley and Sons Ltd., Chichester, pp.385-417.

Sheldrake, A.R. and Narayanan, A. (1979) Growth, development and nutrient uptake in pigeonpea (*Cajanus cajan*). *Journal of Agricultural Science, Cambridge* 92, 513-526.

Shetty, S.V.R. (1981) Some aspects of weed management in pigeonpeas. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 137-146.

Singh, R.P. and Das, S.K. (1987) Management of chickpea and pigeonpea under stress conditions, with particular reference to drought. In: *Adaptation of Chickpea and Pigeonpea to Abiotic Stresses. Proceedings of the Consultants' Workshop, 19-21 December 1984, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 51-61.

Sinha, S.K. (1981) Water availability and grain yield in pigeonpea. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 283-288.

So, H.B. and Woodhead, T. (1987) Alleviation of soil physical limits to productivity of legumes in Asia. In: Wallis, E.S. and Byth, D.E. (eds), *Food Legume Improvement for Asian Farming Systems: Proceedings of an International Workshop held in Khon Kaen, Thailand, 1-5 September 1986. ACIAR Proceedings no. 18.* ACIAR, Canberra, pp. 112-120.

Summerfield, R.J. and Roberts, E.H. (1985a) Grain legume species of significant importance in world agriculture. In: Halevy, A.H. (ed), *CRC Handbook of Flowering, volume 1.* CRC Press Inc., Boca Raton, Florida, pp. 61-73.

Summerfield R.J. and Roberts, E.H. (1985b) *Cajanus cajan.* In: Halevy, A.H. (ed), *CRC Handbook of Flowering, volume 1.* CRC Press Inc., Boca Raton, Florida, pp. 83-91.

Tarhalkar, P.P. and Rao, N.G.P. (1980) Genotype-density interactions and development of an optimum sorghum-pigeonpea intercropping system. *Indian Journal of Genetics and Plant Breeding* 40A, 39-43.

Tayo, T.O. (1985) Assessment of the effect of ratooning pigeonpea (*Cajanus cajan* (L.) Millsp.) in the lowland tropics. *Journal of Agricultural Science, Cambridge* 104, 589-593.

Thirathon, A., Byth, D.E., Fischer, K.S. and Whiteman, P.C. (1987) Effect on sink development of changes in assimilate supply during different growth stages of short-season pigeonpea. In: Wallis, E.S. and Byth, D.E. (eds), *Food Legume Improvement for Asian Farming Systems: Proceedings of an International Workshop held in Khon Kaen, Thailand, 1-5 September 1986. ACIAR Proceedings no. 18.* ACIAR, Canberra, p. 252.

Trenbath, B.R. (1981) Light-use efficiency of crops and the potential for improvement through intercropping. In: *Proceedings of the International Workshop on Intercropping, 10-13 January 1979, ICRISAT Center, India.*Patancheru, A.P., India: ICRISAT, pp. 141-154.

Troedson, R.J. (1987) Effect of plant density on pigeonpea (*Cajanus cajan* (L.) Millsp.) in sub-humid environments. In: *Proceedings of the Fourth Australian Agronomy Conference.* Australian Society of Agronomy, Melbourne, p. 222.

Turnbull, L.V. (1986) The role of photoperiod and temperature in early vegetative growth and floral development in selected lines of pigeonpea [*Cajanus cajan* (L.) Millsp.]. PhD thesis, University of Queensland, Australia, 309 pp.

Turnbull, L.V. and Ellis, M.L. (1987) Effect of incandescent and fluorescent lighting used in photoperiod extension on the vegetative growth and floral development of four lines of pigeonpea. *Field Crops Research* 17, 25-36.

Turnbull, L.V., Whiteman, P.C. and Byth, D.E. (1981) The influence of temperature and photoperiod on floral development of early flowering pigeonpea. In: *Proceedings of the International Workshop on Pigeonpeas, volume 2, 15-19 December 1980, ICRISAT Center, India.*Patancheru, A.P., India: ICRISAT, pp. 217-222.

Venkataratnam, N. and Sheldrake, A.R. (1985) Second harvest yields of medium-duration pigeonpea (*Cajanus cajan*) in peninsular India. *Field Crops Research* 10, 323-332.

Versteeg, M.N. and van Keulen, H. (1986) Potential crop production prediction by some simple calculation methods, as compared with computer simulations. *Agricultural Systems* 19, 249-272.

Wallis, E.S., Byth, D.E. and Whiteman, P.C. (1981) Mechanized dry seed production of pigeonpea. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15–19 December 1980, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 51–60.

Whiteman, P.C., Byth, D.E. and Wallis, E.S. (1985) Pigeonpea (*Cajanus cajan* (L.) Millsp.). In: Summerfield, R.J. and Roberts, E.H. (eds), *Grain Legume Crops.* Collins Professional and Technical Books, London, pp. 658-698.

Willey, R.W. (1985) Evaluation and presentation of intercropping advantages. *Experimental Agriculture* 21, 119-133.

Willey, R.W., Rao, M.R. and Natarajan, M. (1981) Traditional cropping systems with pigeonpea and their improvement. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 11-25.

Chapter 8

PIGEONPEA: PHYSIOLOGY OF YIELD FORMATION

R.J. LAWN and R.J. TROEDSON

Principal Research Scientist, Commonwealth Scientific and Industrial Research Organization (CSIRO), Division of Tropical Crops and Pastures, The Cunningham Laboratory, 306 Carmody Road, St. Lucia, Queensland 4067, Australia, and Senior Research Officer, Department of Agriculture, University of Queensland, St. Lucia, Queensland 4067, Australia.

INTRODUCTION

The pigeonpea (*Cajanus cajan* (L.) Millspaugh) is a morphologically variable species, cultivated in a multitude of production systems, and in a range of climatic conditions throughout the tropics and subtropics, for a diversity of uses. Any brief discussion of the physiology of yield formation in the crop must therefore necessarily begin with some qualifications as to the coverage to be undertaken. Thus, while pigeonpea is grown for its green pods and seeds as vegetables, its dried stems as fuel, and its foliage as forage or green manure, the present chapter explores the physiology of yield formation almost exclusively in the context of its main use: as a dried pulse or food legume. As is acknowledged later in the discussion of physiological constraints to yield improvement, some of the opportunities to improve the dry seed yield of pigeonpea may well compromise the alternative uses. Pigeonpea plants range from weakly perennial, herbaceous forms growing to around 1m tall, to short-lived perennials surviving for a up to decade, and forming woody shrubs to 4m tall. When grown as a pulse however, pigeonpea is cultivated as a field crop and plants rarely exceed 2m. Crops are usually harvested after maturation of the first crop of seeds, although occasionally, plants may be cut back, and regrowth ratooned to produce one or more successive flushes of seeds.

The formation of dry seed is the culmination of the plant's life cycle, and the yield of seed is the integrated outcome of the various physiological processes and subprocesses which constitute growth and development from germination to maturity. The outcome of each of these processes reflects an inherent genetic potential, the expression of which is modulated, to a greater or lesser degree, by various environmental factors, such as climate, soils, etc. The extent to which genetic potential is not realized in particular environments depends both on the plant genotype, and the intensity of the environmental constraints in that environment. As a field crop, pigeonpea is grown in a multitude of cropping systems, of varying durations, and both as a sole crop and an intercrop, and is therefore subject to many environmental constraints (see Chapter 7).

The rationale for discussing the physiology of yield formation in an important economic crop such as pigeonpea is simple: the key aim of physiological research is to help develop breeding strategies to overcome genetic constraints to yield potential, and agronomic approaches to relieve the diversity of environmental constraints to that potential (Lawn, 1981). Accordingly, the following discussion is organized to provide an overview of the physiological processes of growth and development which culminate in the formation of seed in pigeonpea, and of the constraints, both inherent and environmental, to increasing the efficiency of these processes and thus the yield of seed ultimately formed. In that way, opportunities to improve the performance of pigeonpea in the diversity of environments in which it is grown as a field crop might be more readily identified.

DEVELOPMENT AND GROWTH

Germination and Seedling Growth

Germination of pigeonpea is hypogeal, and emergence generally occurs more slowly than in epigeous species such as cowpea, mung bean, and soybean. Yet relatively few comparative studies detailing the nature and physiological basis of differences in germination behaviour between pigeonpea and other tropical grain legumes have been reported. Perhaps because of its hypogeal germination, pigeonpea emerges well from depth. Although emergence is progressively reduced when seed is sown below 5 cm, some seedlings can emerge from as deep as 30 cm (Figure 8.1). Larger-seeded genotypes appear better able to emerge from depth, perhaps because of larger energy reserves in the seed.

The growth rate of pigeonpea seedlings is relatively slow (Sheldrake and Narayanan, 1979), a factor of potential advantage where pigeonpea is intercropped with a rapidly growing cereal such as pearl millet or sorghum, but which may be disadvantageous in a monoculture and/or where weed competition is severe. The markedly slower growth rates appear to be due mainly to smaller seedling leaf areas, since net assimilation rates (NAR) of pigeonpea are comparable with those of other C_3 species (Rowden *et al* ., 1981). Comparative studies (Brakke and Gardner, 1987) showed that 10 days after sowing, the leaf area of pigeonpea seedlings was about one-third that of soybean and one fifth that of cowpea, but relative growth rates for both biomass and leaf area per plant were marginally but significantly greater in pigeonpea seedlings. The authors ascribed the differences in leaf area per seedling to differences in seed size, and to inherent differences in the leaflet areas between the species. It remains to be established to what extent the latter reflect differences

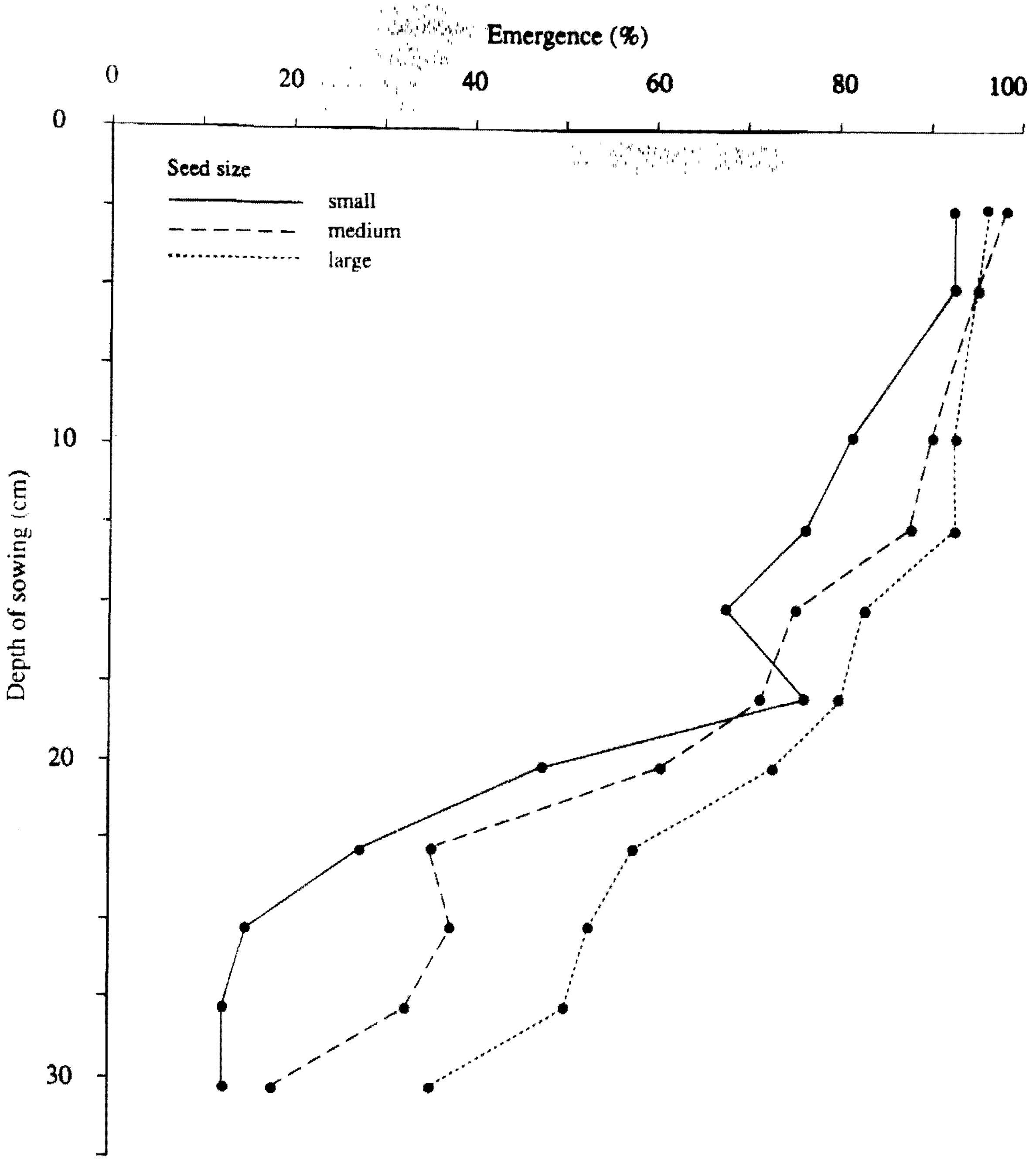


Figure 8.1. Effect of sowing depth (cm) and seed size on emergence of pigeonpea from a Vertisol at ICRISAT Center.
Source: ICRISAT, 1978.

in partitioning of seed reserves (e.g., into stem *vs* leaf) and leaf thickness (i.e., differences in specific leaf mass) and whether in pigeonpea, these are amenable to change through genetic selection. Not surprisingly, seedling growth rates are faster with larger-seeded genotypes of pigeonpea (Narayanan *et al.*, 1981).

Canopy Development, Light Interception, and Growth

Pigeonpea genotypes range in form from low, spreading bushes to tall, erect shrubs, with compact or open foliage. In the ICRISAT germplasm, the numbers per plant of primary branches range from 2.3 to 66.0 among genotypes, and of secondary branches, from 0.3 to 145.3, while height varies tenfold from 39 cm to 3.85 m (Remanandan *et al.*, 1988). Most genotypes, however, are freely branching when grown as spaced plants.

The seasonal profile of leaf area development in pigeonpea is typical of that found in most tropical grain legumes: under favourable growth conditions, leaf area index (LAI) increases exponentially until the canopy starts to close, at which time the older, by then shaded leaves begin to senesce and abscise. Thereafter, the rate of leaf area accumulation slows, and LAI ultimately reaches a maximum when the rate of new leaf development is approximately balanced by the loss of older leaves. LAI is sustained at near-maximum levels for a variable period depending on environmental conditions, and the phenological potential of the crop, but invariably declines during late reproductive ontogeny as assimilates are remobilized into pods and seeds.

Because of the small leaf area of its seedlings, the proportion of incident energy intercepted by the pigeonpea canopy (E_i) during much of the vegetative phase is very low compared with other tropical grain legumes. For example, in a comparative study with genotypes of soybean, mung bean, black gram *(Vigna mungo)*, cowpea, and lablab *(Dolichos lablab)* in which all species were sown in 25-cm rows at a population density of 350×10^3 plants ha^{-1}, full interception of photosynthetically active radiation (PAR) was not achieved by the pigeonpea genotypes until 9 weeks after sowing, whereas closed canopies of all other species were achieved by 6 weeks (Muchow, 1985a).

The time from sowing to flowering varies greatly among pigeonpea genotypes, locations, and sowing dates (see Chapter 7), so that the extent of vegetative development prior to flowering can vary immensely. Thus, a pigeonpea crop may reach maximum LAI prior to flowering, during flowering, or even partly into pod filling, depending on its phenology. Usually, maximum LAIs are of the order of 4.0-6.0, but can vary widely depending on; genotypic characteristics (particularly phenology), environmental factors (particularly water regime and soil type), and sowing density. Occasionally, extremely large LAIs (> 12.0) are reported (Sheldrake and Narayanan, 1979), but given that they are substantially in excess of that required for complete interception of PAR, and therefore that a large proportion of the lower leaves are shaded, they are usually transient. On the other hand, with very early flowering crops (e.g., photoinsensitive genotypes, or dry-season sowings), the duration of vegetative growth may be inadequate to ensure complete canopy closure (Rowden *et al.*, 1981).

As with other crops, biomass accumulation in pigeonpea is essentially a linear function of the amount of PAR intercepted by the crop canopy, which in turn is a function of crop LAI, at least during vegetative growth (Hughes *et al.*, 1981; Rowden *et al.*, 1981; Hughes and Keatinge, 1983). The proportion of incident energy intercepted by the pigeonpea canopy, E_i, increases with LAI, in accordance with the Beer-Lambert Law, such that $E_i = 1 - e^{-k.LAI}$, where *k* is the canopy extinction coefficient, and is characteristic of the canopy. The main crop influences on *k* are the orientation, angle, size, and spatial dispersion of leaves, which can be variously altered by genotypic effects, water status and, prior to canopy closure, spatial arrangement of plants. Canopy extinction coefficients for pigeonpea vary with genotype, but are generally lower than for larger-leaved species such as soybean and mung bean, because the smaller, lanceolate leaves of pigeonpea allow greater penetration of radiation into the canopy. Indeed, for small-leaved genotypes, *k* may be as low as 0.3 (Rowden *et al.*, 1981). The critical LAI, that is, the LAI necessary to ensure 95% interception of incident PAR ($E_i = 0.95$), is dependent on *k* , and for pigeonpea, varies from 3.9 (Muchow, 1985a) to > 6.0 (Rowden *et al.*, 1981).

During reproductive ontogeny, the inter-relationship between LAI and the proportion of PAR intercepted by the canopy becomes less apparent as an increasing proportion of the incident radiation is intercepted by floral structures and developing pods. For example, in canopies where an LAI > 6.0 was necessary for complete interception of PAR during the vegetative stage, complete interception of PAR was achieved with LAIs as low as 2.5 subsequent to flowering (Rowden *et al.*, 1981). The interception of PAR by reproductive structures is undoubtedly greatest in the more determinate genotypes, where the inflorescences are located in the uppermost several nodes of each branch, so that pods and flowers are clustered at the top of the canopy.

The slope of the linear relationship between increments in biomass production and cumulative PAR interception provides an estimate of the efficiency of conversion of intercepted PAR to biomass (E_c), usually expressed as g MJ^{-1}. Physiological factors which can contribute to differences in E_c include differences in the inherent photosynthetic capacity of leaves, the balance between photosynthesis and respiration, and *k*. For example, where *k* is small, as with pigeonpea, incident PAR is distributed over a larger leaf area, so that net efficiency of canopy photosynthesis might well be expected to be enhanced. Indeed, Thirathon *et al.* (1987b) reported *k* values of 0.35 in the upper, and 0.84, in the lower halves of the canopy, which suggests that dispersion of radiation through the pigeonpea canopy may be near optimal.

Experimental estimates of E_c for pigeonpea vary, from 0.9 (Natarajan and Willey, 1980a,b), 1.23 (Hughes and Keatinge, 1983), 1.30 (Muchow, 1985a), to a high of 1.62 (Thirathon *et al.*, 1987b). In all cases, however, these represent effiencies in net biomass accumulation, since senescent leaves and/or roots were not retrieved and included in the estimates of biomass gain. Nonetheless, E_c values for pigeonpea are comparable with those of other C_3 species. Indeed, one analysis (Charles-Edwards, 1982) suggests that were senescent leaves taken into consideration, E_c values for pigeonpea might be as large as 2.2 g MJ^{-1}, and thus be comparable with C_4 species.

While most pigeonpea genotypes are freely branching, the extent of branching is substantially influenced by inter-plant competition, and is reduced at denser plant populations, and when pigeonpea is grown as an intercrop. Thus even within genotypes, pigeonpea is morphologically plastic, and, at least above a minimum threshhold plant population, can accommodate wide variations in sowing density with only minimal effects on total biomass production. The threshhold plant population however is very much larger with earlier-flowering, photoperiod-insensitive genotypes than for laterflowering, photoperiod-sensitive types. For example, threshhold plant populations for the latter genotypes may be only 50×10^3 plants ha^{-1} (Akinola and Whiteman, 1975b), compared with $> 10 \times 10^5$ for short-duration, photoperiod-insensitive genotypes (Rowden *et al.*, 1981).

Most pigeonpea in India is grown as an intercrop with one or more other crop species, which can result in major changes to patterns of canopy development and radiation interception, especially where pigeonpea is the "minor" (i.e., the slower-growing, or the shorter-statured) component. In the common pigeonpea/cereal intercropping system (e.g., pigeonpea/sorghum - Natarajan and Willey, 1980a,b; and pigeonpea/maize - Sivakumar and Virmani, 1980), the canopy of the cereal develops more rapidly and is relatively unaffected by the intercrop, whereas the pigeonpea canopy is shaded and its growth is substantially reduced (Figure 8.2). Pigeonpea is evidently able to tolerate the sudden change from shade to full sunlight when the cereal is harvested, but the low LAI (0.3-0.6) and E_i (20-25%) at that time (Natarajan and Willey, 1980a,b; Sivakumar and Virmani, 1980) constrain subsequent biomass accumulation and canopy development. Selection of genotypes with specific traits appropriate to intercropping may be advantageous: such traits could include compact growth during the period of mixed cropping, combined with rapid branching and canopy development after the harvest of the cereal (Willey and Rao, 1981; Rao *et al.*, 1981).

In general, pigeonpea cultivars grown as intercrops with cereals are later-maturing than those used as sole crops (see Chapter 7). As such, the phenology of the pigeonpea complements that of the cereal in that most of the development of the pigeonpea (in terms of both ontogeny and biomass production) occurs after the harvest of the cereal. Effectively they are analogous to sequential crops, but the costs and difficulties associated with sowing and establishing the second crop in dry conditions are avoided (Rao and Willey, 1983). Shoot growth and radiation interception are much less affected when pigeonpea is intercropped with short-statured crops such as green and black gram, cowpea, groundnut and soybean, than with cereals (Hegde and Saraf, 1978; Giri *et al.*, 1981). In intercrops with various row combinations of these legumes, seed yield of pigeonpea was equivalent to that of a sole crop, or reduced at most by 18% (Giri *et al.*, 1981).

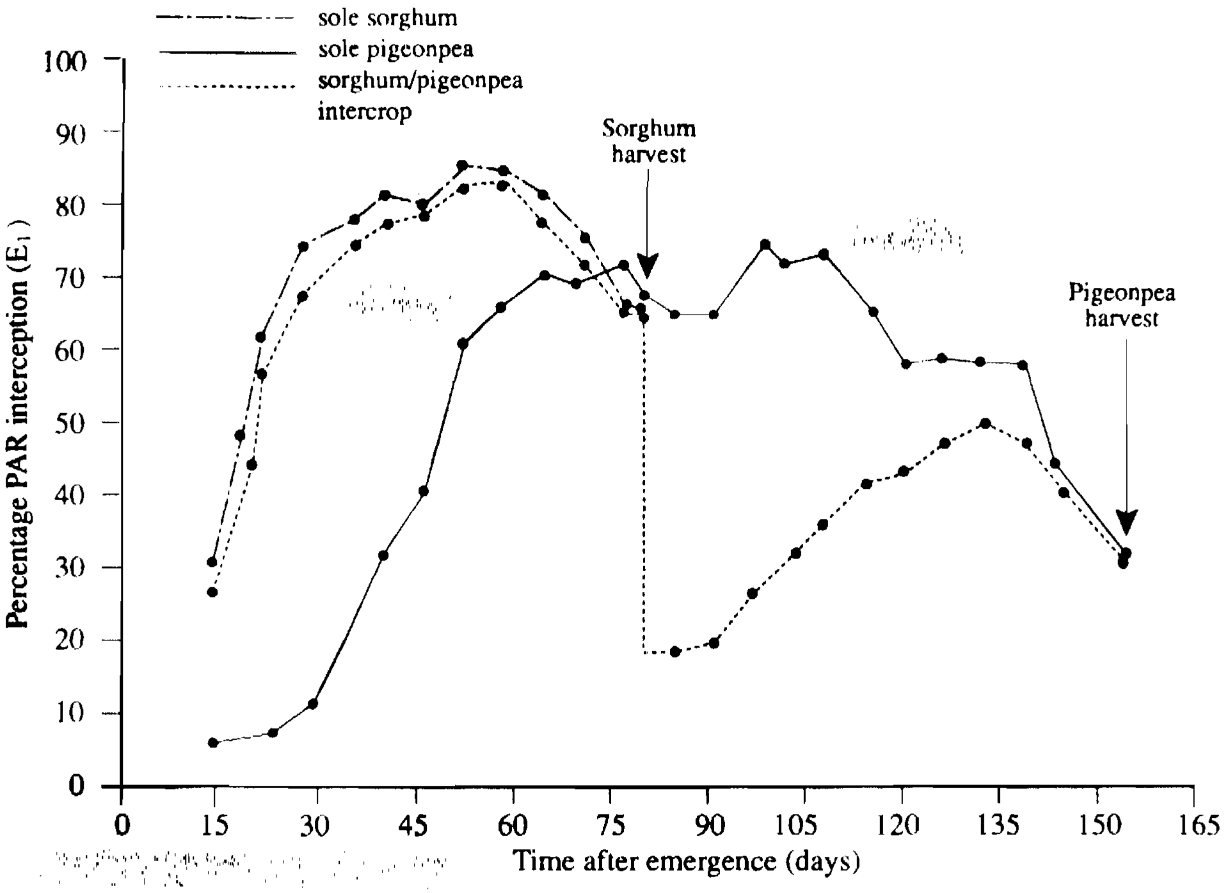


Figure 8.2. Seasonal profiles of PAR interception (% E_I) by sole crops of pigeonpea and sorghum, and of the intercrop, illustrating the complementary nature of the two components in the intercrop.

Source: Natarajan and Willey, 1980b.

Root Growth

Little information is available on the partitioning of biomass to roots and nodules in field-grown plants, undoubtedly because of the difficulty of sampling. Estimates from various sources including pot culture indicate that root:shoot ratios for biomass range between 0.1 and 0.3 (Table 8.1). However many of the lower values are from field studies in which root biomass is likely to be underestimated, perhaps by as much as 50% (Sheldrake and Narayanan, 1979), particularly at depth.

Pigeonpea is a deep-rooted crop (Whiteman *et al.*, 1985). Tall, upright genotypes are said to have a deeper root system than spreading, bushy genotypes (Kay, 1979). Certainly, root penetration and water extraction were deeper in later-maturing genotypes (B. Singh *et al.*, unpublished). Most experimental data show extensive root penetration, in that either the presence of roots or extraction of soil water is detected to the full depth sampled e.g., 120 cm (De Vries, 1986); 150 cm (Sheldrake and Narayanan, 1979); 180 cm (Sardar Singh and Russell, 1981); down to 220 cm (B. Singh *et al.*, unpublished). The depth of root penetration and the vertical distribution of roots appears to depend on the replenishment of soil water, because roots penetrate deeper when the upper soil layers remain dry (J. Kirkegaard *et al.*, unpublished). Regardless of soil moisture distribution, around 70% of root biomass and 50% of root length are commonly found in the top 30 cm of soil (Table 8.2).

Some evidence suggests that root development of pigeonpea is less, or at least slower, than that of other crops, presumably reflecting its initially slower crop growth rates. Pigeonpea roots

Table 8.1. Estimates of the pigeonpea root:shoot biomass ratio.

Sampling method	Days after sowing	Soil type	Root:shoot ratio	Reference
Excavation	140	Alfisol	0.10–0.13 (early) 0.12–0.13 (medium) 0.19–0.20 (late)	Kumar Rao and Dart, 1987
Pinboard	90	Oxisol	0.12	Kirkegaard *et al.*, unpublished
		Vertisol	0.19	
Cement boxes	Maturity	Alfisol	0.29	Sheldrake and Narayanan, 1979
		Vertisol	0.24	
Pots	90	Sand	0.29	Rao *et al.*, 1984
	120		0.15	

Table 8.2. Relative distributions (as percentages) of pigeonpea root biomass and root length with depth in the soil profile.

		Depth interval (cm)						
Days after sowing	Soil type	0-15	15-30	30-60	60-90	90-120	120-150	Reference
Root biomass								
90	Oxisol	57.0	16.8	16.2	10.4	-	-	Kirkegaard *et al.*, unpublished
	Vertisol	64.0	17.9	13.2	5.0	-	-	
Maturity	Alfisol	<——75——>		<——————25——————>				Sheldrake and Narayanan, 1979
	Vertisol	<——71——>		<——————29——————>				
Root length								
40	Oxisol	13.8	31.7	33.8	12.4	8.3	-	Kirkegaard *et al.*, unpublished
70	Vertisol	25.6	22.1	40.1	12.3	-	-	
60	Vertisol	25.4	42.4	22.9	5.9	3.4	-	Natarajan and Willey, 1980a
70[1]	Vertisol	27.5	20.4	24.4	17.4	6.9	3.4	Sheldrake and Narayanan, 1979
130[1]	Vertitol	26.9	23.0	16.8	15.0	10.9	7.4	
162[1]	Vertisol	29.4	22.3	18.8	14.0	10.5	5.0	

1. Means of two genotypes.

penetrated deeper than those of sorghum on the same site, but root length density was greater in the sorghum in all soil layers except the deepest sampled (Natarajan and Willey, 1980a). In another comparative study, root length density of pigeonpea was lower than that of soybean or groundnut, as was soil water extraction during a stress period of approximately 20 days (De Vries, 1986). However the pigeonpea may have extracted the additional water had the stress period extended.

Intercropping is likely to also cause changes in root development and uptake of water and nutrients (Snaydon and Harris, 1981), although in a pigeonpea/sorghum mixture these effects seemed to be small (Natarajan and Willey, 1980a, b). In the pigeonpea/sorghum system, the two crops overlap during the monsoon, when competition for light is more critical than competition for water.

REPRODUCTIVE PHYSIOLOGY

Environmental Modulation of Reproductive Ontogeny

The onset of flowering in pigeonpea is known to be acutely dependent on the sensitivity of genotypes to prevailing daylengths and temperatures (Lawn, 1981; Summerfield and Roberts, 1985). As such, differential genotypic sensitivity to photothermal regime has major implications for adaptation of genotypes with respect to latitude, altitude, and season (see Chapter 7). However, there is surprisingly little information available whereby the effects of photoperiod and temperature on flowering of pigeonpea might be quantified in any reliable and predictive manner. In controlled-environment (CE) studies, the effects of temperature and photoperiod can be of similar magnitude depending on the range of photothermal regimes sampled, and the relative photoperiodic sensitivity of the genotype (Turnbull *et al.*, 1981; McPherson *et al.*, 1985). Optimal temperatures for flowering appear to be around a mean daily temperature of 24°C (McPherson *et al.*, 1985). On the basis of present information however, little informed, generalized comment is possible on the nature of temperature effects, which vary before and after floral initiation; with the genotypes tested; and with the magnitude and diurnal range of the temperatures investigated (Ariyanayagam, 1981; Turnbull *et al.*, 1981; McPherson *et al.*, 1985). Of some interest is the apparent absence of complex photoperiod × temperature interactions when flowering behaviour is examined in terms of rate of development toward floral initiation or toward flowering (McPherson *et al.*, 1985), an observation consistent with experience with a wide range of Papilionaceous species (Summerfield and Roberts, 1987).

In serial sowing date studies in the field, most pigeonpea genotypes respond as quantitative, short-day plants, with the time from sowing to flowering longest for sowings made prior to the summer solstice, and shortening progressively as sowings are delayed into shortening days toward the winter solstice (Akinola and Whiteman, 1975a; Figure 7.1; Sharma *et al.*, 1981; Singh and Saxena, 1981). Very early flowering genotypes of pigeonpea appear to be relatively photoperiod-insensitive, even day-neutral in the field, a conclusion supported by limited CE data (Turnbull *et al.*, 1981; Turnbull and Ellis, 1987). In these genotypes, the predominant environmental factor influencing time to flowering is therefore temperature. This situation is analogous with that in other quantitative short-day pulses such as soybean and mung bean, where daylength-neutrality appears to be associated with earliness of flowering (Lawn and Williams, 1987). By further analogy with those species, it might be hypothesized that genotypic differences in photoperiodic response between pigeonpea genotypes are conditioned by genotypic differences in either or both their "critical" photoperiod (P_c), and their sensitivity to photoperiod over their range of quantitative response (i.e., where photoperiods exceed P_c), and that these effects are in turn modulated by temperature.

Thus for example, later-flowering genotypes would be so primarily because they possess relatively shorter P_cs, than earlier-flowering genotypes. As such, their flowering would be delayed at and above shorter daylengths than would be the case for the (earlier) genotypes with longer P_cs, that would accordingly need to experience longer days before flowering would be delayed. Differences in P_c would be augmented to a greater or lesser extent by differences between genotypes in their sensitivity to photoperiods longer than their respective P_cs, as well as in their sensitivity to temperature. There are very few data available from CE studies which might clarify this question, although the scarce available data are consistent with the above interpretation. For example, McPherson *et al.* (1985) reported that in CE studies, rate of development toward floral initiation was slower in 14-h than in 12-h days for all genotypes evaluated i.e., each genotype responded as a quantitative short-day plant with a $P_c < 14$ h. For several genotypes, rate of development was even more rapid at 10 h, which would suggest a $P_c < 12$ h for those genotypes. For others, rate of development at 10 h was similar or slightly slower than at 12 h, implying a P_c of between 12 to 14 h.

The strongest support for the above interpretation is provided by a re-analysis of the published field data, shown in Figure 7.1, from a serial sowing study of four pigeonpea genotypes, using

Table 8.3. Mean (and range) for days to flowering (f), and fitted equations and parameter estimates for relationships between rate of development toward flowering ($^1/_f$), and mean daily photoperiod (P) and mean daily temperature (T) between sowing and flowering, for four pigeonpea genotypes sown at eight 1-month intervals at latitude 27°S.

Genotype	f(days)	P_c at 20°C (h)	Fitted relationships[1]		R^2[2]
UQ 39	87.4 (72-100)	14.8	$^1/_f = 0.0119 + 0.00003T$ $^1/_f = 0.0419 - 0.00100T - 0.00064P$	$(P<P_c)$ $(P>P_c)$	0.55^{**}[3]
UQ 37	98.8 (75-131)	13.9	$^1/_f = 0.0120 + 0.0000001T$ $^1/_f = 0.0657 - 0.00154T - 0.00165P$	$(P<P_c)$ $(P>P_c)$	0.68^{**}
UQ 38	153.5 (115-217)	11.6	$^1/_f = 0.0050 + 0.00017T$ $^1/_f = 0.0331 - 0.00140T - 0.00541P$	$(P<P_c)$ $(P>P_c)$	0.80^{**}
UQ 1	158.1 (116-221)	11.7	$^1/_f = 0.0022 + 0.00029T$ $^1/_f = 0.0354 + 0.00146T - 0.00481P$	$(P<P_c)$ $(P>P_c)$	0.97^{**}

1. Derived from the data of Akinola and Whiteman, 1975a; see Figure 7.1, using the approach of Summerfield *et al.*, 1989).
2. Combined R^2 for $P<P_c$ and $P>P_c$, degrees of freedom corrected.
3. ** indicates significance at $P<0.01$.

the model and approach applied by Summerfield *et al.* (1989) to field data for soybean. The result is an acceptable fit to the pigeonpea data, with between 55-97% of the variation in rate of development at different sowing dates accounted for by variation in photothermal regime for the four genotypes (Table 8.3). The nature of the photothermal response surfaces is exemplified for one of the genotypes, UQ 1, in Figure 8.3.

Estimates of P_c (at 20°C, the mid-point of the range sampled in the original data) ranged from 14.8 h in the earliest genotype to about 11.6 h for the two late genotypes. For those sowings where the mean daily photoperiod prior to flowering (P) exceeded P_c, the rate of development in all four genotypes was negatively related to P, consistent with a quantitative short-day response, while the increasing magnitude of the partial regression coefficients would suggest that relative photoperiod-sensitivity was greater for the later genotypes. For those sowing dates where $P < P_c$, rate of development was positively related to mean daily temperature (T), suggesting that warmer temperatures promoted flowering, but where $P > P_c$, the relationship was negative for three of the four genotypes. One possible explanation is that because of the concommitant variation of T and P in the field environment (Figure 7.1), temperatures were warmest in midsummer when $P > P_c$, and may thus have exceeded the optima for development.

It remains to be established whether any of the late-flowering pigeonpea genotypes possess a true "juvenile" phase, during which the plant is insensitive to normally inductive conditions (Summerfield and Roberts, 1985) or whether their lateness to flower even under short-day conditions is merely a consequence of a relatively short P_c, combined with strong sensitivity to photoperiods above P_c. Neither is there any quantitative information available on the environmental control of flowering by ratoon growth in pigeonpea. Field experience suggests that where inductive photothermal conditions persist beyond maturity of the first flush of pods in photosensitive genotypes (e.g., as for summer-sown crops maturing into the autumn or winter (Wallis *et al.*, 1981; Venkataratnam and Sheldrake, 1985; Chauhan *et al.*, 1987)), flowering of the ratoon growth may be rapid. However, where the ratoon growth in photoperiod-sensitive genotypes occurs into lengthening days of early summer, flowering may be inhibited until the onset of shorter days in the autumn. In day-neutral genotypes, flowering of ratoon growth appears to occur freely, provided temperatures are favourable to growth (Wallis *et al.*, 1981).

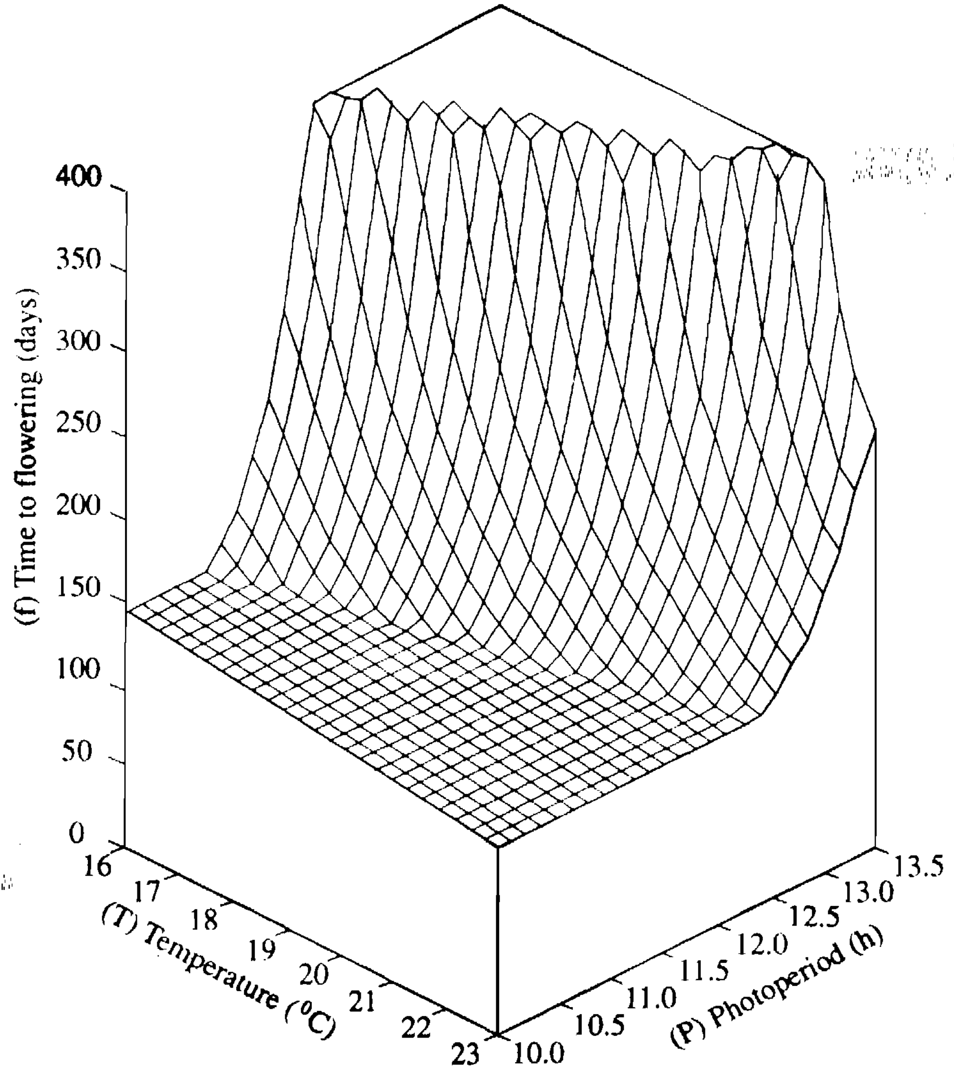


Figure 8.3. Response surface relating days to flowering (f), and rate of development toward flowering ($\frac{1}{f}$), to change in mean daily photoperiod (P) and mean daily temperature (T) between sowing and flowering, for pigeonpea genotype UQ 1, using the parameter estimates from Table 8.3.
The relationship was derived, using the approach of Summerfield *et al.*, 1989, from the data of Akinola and Whiteman, 1975a, wherein time to flowering was recorded from sowings at eight one-month intervals at latitude 27°S — see also Figure 7.1, and is truncated for f>400 days (long day-cool temperature conditions) for ease of presentation.

The duration of reproductive ontogeny in pigeonpea is generally less variable than the duration of the vegetative phase, so that in field environments, crop duration, i.e., the time from sowing to maturity of the first flush of pods, tends to be strongly correlated with time to flowering (Akinola and Whiteman, 1975a). Thus it is possible to classify genotypes (Sharma *et al.*, 1981) into maturity groupings which largely reflect genotypic differences in flowering response. One consequence of the relatively greater effect of photothermal regime on the duration of vegetative growth, is that the relative duration of reproductive growth (as a proportion of total crop duration), increases in those photothermal regimes that favour early flowering; i.e., in autumn and winter sowings, particularly of earlier flowering genotypes. For example, in the case of the four genotype × eight sowing date combinations of Akinola and Whiteman (1975a), (Figure 7.1), the percentage of total crop cycle spent in reproductive growth increased inversely as the time to flowering decreased (Figure 8.4), from around 15% for late genotypes sown in summer, to around 50% for early genotypes sown late, in winter.

Nonetheless, there are genotypic and environmental effects on the duration of reproductive ontogeny. Flowering, and subsequently, pod and seed development, are more synchronous in the more-determinate genotypes, so that reproductive ontogeny is compressed into a shorter period than in indeterminate genotypes. Likewise, reproductive ontogeny is more synchronous, and of shorter duration in early-flowering genotypes, and in later genotypes where the photothermal regime is favourable to early flowering i.e., in the short-day/moderate temperature conditions of dry-season crops in the tropics (Narayanan and Sheldrake, 1979), or as late-sown crops in the subtropics (Wallis *et al.*, 1981). Conversely, under long-day conditions marginal for induction, flowering may be very sporadic and pod set sparse.

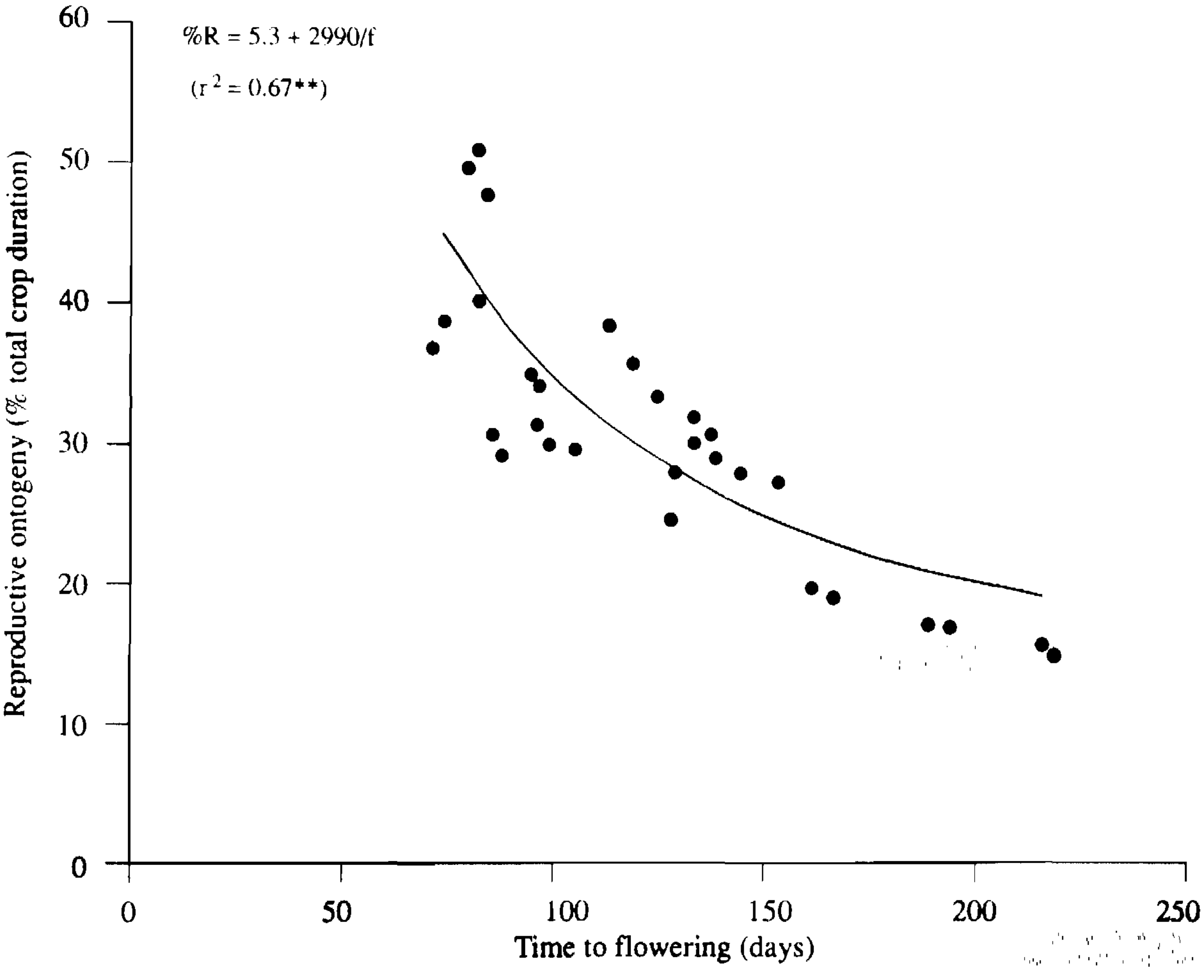


Figure 8.4. Relationship between pigeonpea reproductive ontogeny, expressed as a percentage of total crop duration, and days to flowering, as influenced by genotype and sowing date.

Source: Akinola and Whiteman, 1975a and see also Figure 7.1.

Development of Reproductive Sinks

Most pigeonpeas are more or less indeterminate in flowering habit, with axillary flowering racemes forming along the apical portions of branches (Summerfield and Roberts, 1985). Flowering proceeds acropetally within both inflorescences and branches. Some genotypes, mainly of short duration, are morphologically determinate and basipetalous, although within racemes, flowers open sequentially. Determinate genotypes generally have fewer racemes but more flowers (and ultimately pods) per raceme (Sheldrake and Narayanan, 1979), and so the duration of flowering in individual racemes may be longer than in indeterminate types. Flowering may still be polycarpic, punctuated by periods of renewed vegetative growth, so that determinateness does not confer the potential loss of homeostasis that is characteristic of monocarpic plants. However, vulnerability to insect damage may be increased through the physical proximity of the inflorescences (Meekin *et al.*, 1987). Intermediate forms (semi-determinate) have also been described (Remanandan *et al.*, 1988).

Flowering may be confined to a 3-week period or may continue for several months, depending on genotype, environmental conditions, and sowing density. High populations reduce branching and increase the sychrony of flowering, particularly in the more determinate types, and if the setting of the first flush of pods is not restricted by drought stress or insect damage, further flowering may be largely inhibited (Sheldrake *et al.*, 1979; Meekin *et al.*, 1987). Conversely, the flowering period is generally longer in indeterminate genotypes and may be extended in less dense sowings, and under long-day/warm temperature conditions, and environmental conditions that increase floral abortion such as heat waves, intermittent drought stress, or overcast weather. However severe drought stress will restrict both the duration and extent of flowering.

Pods grow exponentially after anthesis, with growth largely confined to the pod wall for the first 15 days, after which seed growth predominates and the biomass of pod walls increases slowly (Grover *et al.*,1985; Khatra *et al.*, 1986). Individual seeds progressively accumulate sugars, starch, soluble nitrogen and protein, although at different rates for each constituent, so that the relative proportions vary with time (Singh *et al.*, 1980). The greatest concentrations of sugars, soluble nitrogen, and proteins occur early in seed growth, while the starch concentration increases to around 60% by midway during seed growth and remains constant or declines somewhat thereafter. The final composition of pigeonpea seed varies with genotype and environmental conditions, but the major constituents are starch (45-55%) and protein (19-23%) (Table 8.4). Lines with high seed protein content (around 30%) and promising agronomic features have been developed at ICRISAT from crosses with *Cajanus albicans* (Faris *et al.*, 1987).

Table 8.4. Composition of pigeonpea seed.

Crude protein (%)	19 –23
Starch (%)	45 –55
Soluble sugars (%)	3 – 5
Fat (%)	1 – 2
Crude fibre (%)	1 – 5
Ash (%)	3 – 4
Lysine (%)	1.2– 1.4
Methionine (%)	0.1– 0.3
Cystine (%	0.3– 0.5
Gross energy (MJ kg^{-1})	16 –18

Source: Various authors.

Depending on genotype, pigeonpea pods contain between 2 and 9 ovules, of which up to half may abort, particularly in large-seeded genotypes, and seed size (measured as 100-seed mass) varies from 28 to 224 mg (Remanandan *et al.*, 1988). Pod number per plant (or per unit area) is the component through which variation in seed yield due to growing conditions is predominantly expressed. Both seeds per pod and seed size may be reduced by treatments or environmental conditions that restrict the supply of assimilates during the respective growth phases, although rarely by more than 50% (seeds per pod) or 20% (seed size) (Akinola and Whiteman, 1975a; Sheldrake *et al.*, 1979).

Most flowers are shed without setting pods (Sheldrake *et al.*, 1979; Summerfield and Roberts, 1985), a fact which has aroused considerable interest. The physical removal of flowers and young pods stimulates flower production, but has no effect on final yield (Sheldrake *et al.*, 1979; Pandey and Singh, 1981; Grover *et al.*, 1985), except through the effects of an induced delay in maturity. The effects may be positive, e.g., in an early genotype at sub-optimal density (Tayo, 1980), or negative, as when maturity is delayed into progressively harsher environmental conditions (Sheldrake *et al.*, 1979). The ability of the plant to produce new pods is progressively reduced as pods are removed later in plant ontogeny, and because the potential for compensation in terms of seeds per pod and seed size is limited, seed yield declines (Tayo, 1980; Thirathon *et al.*, 1987c).

The number of pods per plant is strongly related to assimilation during early pod growth, through effects on pod formation, for the first 2 weeks after anthesis, and on pod retention, for the next 2 weeks (Thirathon *et al.*, 1987a). Nevertheless, that study and several others have concluded that a proportion of the carbon assimilated during pod growth is diverted to stems and other storage organs (Rawson and Constable, 1981; Deshpande and Nimbalkar, 1982; Setter *et al.*, 1984) and thus that pigeonpea plants should be able to set more pods than they do (Sheldrake and Narayanan, 1979). Being intrinsically perennial, pigeonpea may also conserve a proportion of the assimilates produced during reproductive growth to support subsequent root and shoot growth (Sheldrake and Narayanan, 1979; Setter *et al.*, 1984). It has been suggested that there may be vascular limitations to the supply of assimilates to the pods during the peak pod-setting period (Rawson and Constable, 1981), but this is not supported by the observations of Thirathon *et al.* (1987a), noted above.

Plants of early and late cultivars in India were described by Roxburgh in 1832 as yielding "one hundred-fold" and "six hundred-fold", respectively, which would indicate yields of around 1 t ha^{-1} if densities were even conservatively comparable to those in use today. If so, progress during the last 150 years has been very limited. World yields, according to FAO estimates, averaged 722 kg ha^{-1} between 1980 and 1987, albeit with an increasing trend over that period of approximately 2% per year. The many influences on seed yield are described in detail in this and many other chapters of this book, but could be summarized as genetic, climatic, edaphic, and biological (including inter-plant competition). The selection of data from high-yielding crops presented in Table 8.5 is evidence that as those various limits are overcome, the yield potential of pigeonpea is many times greater than suggested by either the world average, or the yield level reached in many experiments.

Table 8.5. Examples of maximum experimental dry seed yields in pigeonpea.

Crop duration	Maximum dry seed yield (t ha^{-1})	Cultural conditions	Reference
Short	3.53	Irrigated, late summer	Panwar and Yadav, 1981
Short	3.98	Irrigated, dense stands	Hughes and Keatinge, 1983
Short	8.88	Irrigated, dense stands	Wallis *et al.*, 1983
Medium	2.22	Irrigated, mid-summer	Venkataratnam and Sheldrake, 1985
Medium	4.22	Irrigated, late summer	Sharma *et al.*, 1981
Long	6.15	Rainfed, "high input"	Singh and Kush, 1981.

Table 8.6. Estimates of harvest index (HI) in pigeonpeas of varying crop duration, contrasted with soybean.

HI	Crop duration	Location	Sowing season	Basis of estimate	Reference
Pigeonpea					
0.12-0.17	Long	Punjab, India	Early summer	Standing biomass	Dahiya *et al.*, 1974
0.20-0.25	Long	Punjab, India	Mid-summer	Standing biomass	Dahiya *et al.*, 1974
0.15-0.26	Long	ICRISAT Center, India	Summer	Excl. fallen leaves	Sheldrake and Narayanan, 1979
0.11-0.19	Long	ICRISAT Center, India	Summer	Incl. fallen leaves	Sheldrake and Narayanan, 1979
0.22-0.35	Various	ICRISAT Center, India	Autumn	Excl. fallen leaves	Narayanan and Sheldrake, 1979
0.19-0.27	Various	ICRISAT Center, India	Autumn	Incl. fallen leaves	Narayanan and Sheldrake, 1979
0.19	Long	ICRISAT Center, India	Summer (sole crop)	Excl. fallen leaves	Natarajan and Willey, 1980a, b
0.31-0.34	Long	ICRISAT Center, India	Summer (intercrop)	Excl. fallen leaves	Natarajan and Willey, 1980a, b
0.17-0.24	Long	ICRISAT Center, India	Summer (sole crop)	Excl. fallen leaves	Rao and Willey, 1983
0.23-0.29	Long	ICRISAT Center, India	Summer (intercrop)	Excl. fallen leaves	Rao and Willey, 1983
0.30-0.43	Short	ICRISAT Center, India	Early summer	Excl. fallen leaves	Chauhan *et al.*, 1987[1]
0.40-0.48	Short	ICRISAT Center, India	Late summer	Excl. fallen leaves	Chauhan *et al.*, 1987[1]
0.24-0.31	Medium	ICRISAT Center, India	Early summer	Excl. fallen leaves	Chauhan *et al.*, 1987[1]
0.22-0.28	Medium	Hisar, India	Early summer	Excl. fallen leaves	Chauhan *et al.*, 1987[1]
0.10-0.24	Various	SE Queensland, Australia	Summer	Excl. fallen leaves	B.Singh, unpublished.[1]
0.40	Short	Ord River, Australia	Autumn (irrigated)	Excl. fallen leaves	Chapman and Muchow, 1985
0.31	Short	Ord River, Australia	Autumn (rainfed)	Excl. fallen leaves	Chapman and Muchow, 1985
0.52	Short	Trinidad, West Indies	Winter	Excl. fallen leaves	Hughes and Keatinge, 1983
0.40	Short	Trinidad, West Indies	Winter (rainfed)	Excl. fallen leaves	Hughes and Keatinge, 1983
0.21	Medium	Hisar, India	Summer (in pots)	Incl. roots and fallen leaves	Rao *et al.*, 1984
Soybean					
0.32-0.39		SE Queensland, Australia	Summer	Incl. roots and fallen leaves	Lawn, in press

1. See also **Figure 8.5.**

Partitioning and Harvest Index

Harvest index (HI) or the proportion of total plant biomass harvested as seed of pigeonpea, is very variable, ranging from around 10 to 52% depending on; genotype, environment, and agronomic management (Table 8.6). However, the method of estimation of HI, in particular total biomass, is also extremely variable between studies. Thus, while valid comparisons may be possible between treatments within studies, extreme caution must be exercised in attempting to draw comparisons across studies. For example, in some cases estimates of total biomass do not include fallen leaves, etc., or roots. Fallen leaves, petioles, and flowers represent around 25-36% of the total biomass of the crop (Narayanan and Sheldrake, 1979; Sheldrake and Narayanan, 1979), and HI based on standing biomass only is therefore underestimated to that extent. Roots may represent about another 15% of total biomass at maturity (Rao *et al.*, 1984).

Notwithstanding these difficulties, several generalisations are possible. Most importantly, the HI of pigeonpea is low relative to those of the cereals, and even of other grain legumes such as soybean. This is particularly so for the long-duration pigeonpeas traditionally grown in India. Even where fallen leaves and roots are not included, HI of these genotypes rarely exceeds 25% (Table 8.6). In contrast, HI for soybeans (with roots and fallen leaves etc. included) approaches 40%, a comparison which is even more unfavourable for pigeonpea if the different chemical compositions of the seeds are considered. Soybean seed contains around 6-7% nitrogen (N), and 18-22% oil, compared with around 3-4% N, and negligible oil, in pigeonpea (Table 8.4). Conversely, HI in pigeonpea tends to be greater in earlier-flowering, shorter-duration genotypes, and also, where the crop is sown in autumn or even winter. Interestingly, when the long-duration pigeonpea genotypes are grown as an intercrop, their HI is much improved (Table 8.6), even though their absolute seed yield is lower than that of equivalent sole crops, commonly by 20-50% (Natarajan and Willey, 1980a,b; Sivakumar and Virmani, 1980; Rao and Willey, 1983).

In many ways, these responses are consistent with those of other tropical grain legumes (Lawn, in press). In these crops, HI is a function of the relative durations of the vegetative and reproductive phases, and, during the reproductive phase, the relative partitioning of current assimilate, and the degree of remobilization of stored assimilate, to seeds. Thus, HI (in the absence of the confounding effects of stress) is particularly enhanced where the duration of reproductive growth represents a large proportion of total growth, i.e., in early-flowering genotypes and late sowings which, because of strongly inductive photothermal conditions, encourage precocious flowering (Figure 8.4). An analogous situation exists with the intercrop, where the early vegetative development which occurs in the sole crop is suppressed by the companion crop (Figure 8.2).

In several of the tropical grain legumes, the photothermal regime after the start of flowering also directly influences the relative partitioning of current assimilate into vegetative as opposed to reproductive growth. As such, photothermal regime can alter the level of "indeterminateness", or the extent to which vegetative growth persists concurrently with reproductive development after flowering has commenced (Lawn and Williams, 1987). Generally, relatively short-day/moderate temperature conditions which encourage precocious flowering, also stimulate the partitioning of assimilates into reproductive growth and enhance the intensity and synchrony of reproductive development. Given that similar conditions induce analogous developmental effects in pigeonpea, it is probable that there are direct effects of photothermal regime on assimilate partitioning in this species also, but the point remains to be experimentally demonstrated.

In several species, the direct effects of photothermal regime on assimilate partitioning after the start of flowering, combine with its indirect effects on the relative duration of reproductive growth (Figure 8.4), to ensure that HI is maximized when crops are grown under photothermal conditions which favour rapid ontogenetic development (Lawn, in press). The result is that there is frequently a generalized negative relationship between HI and crop duration, that can also be demonstrated in pigeonpea (Figure 8.5).

A corollary of the relationship shown in Figure 8.5 is that the proportion of seed biomass

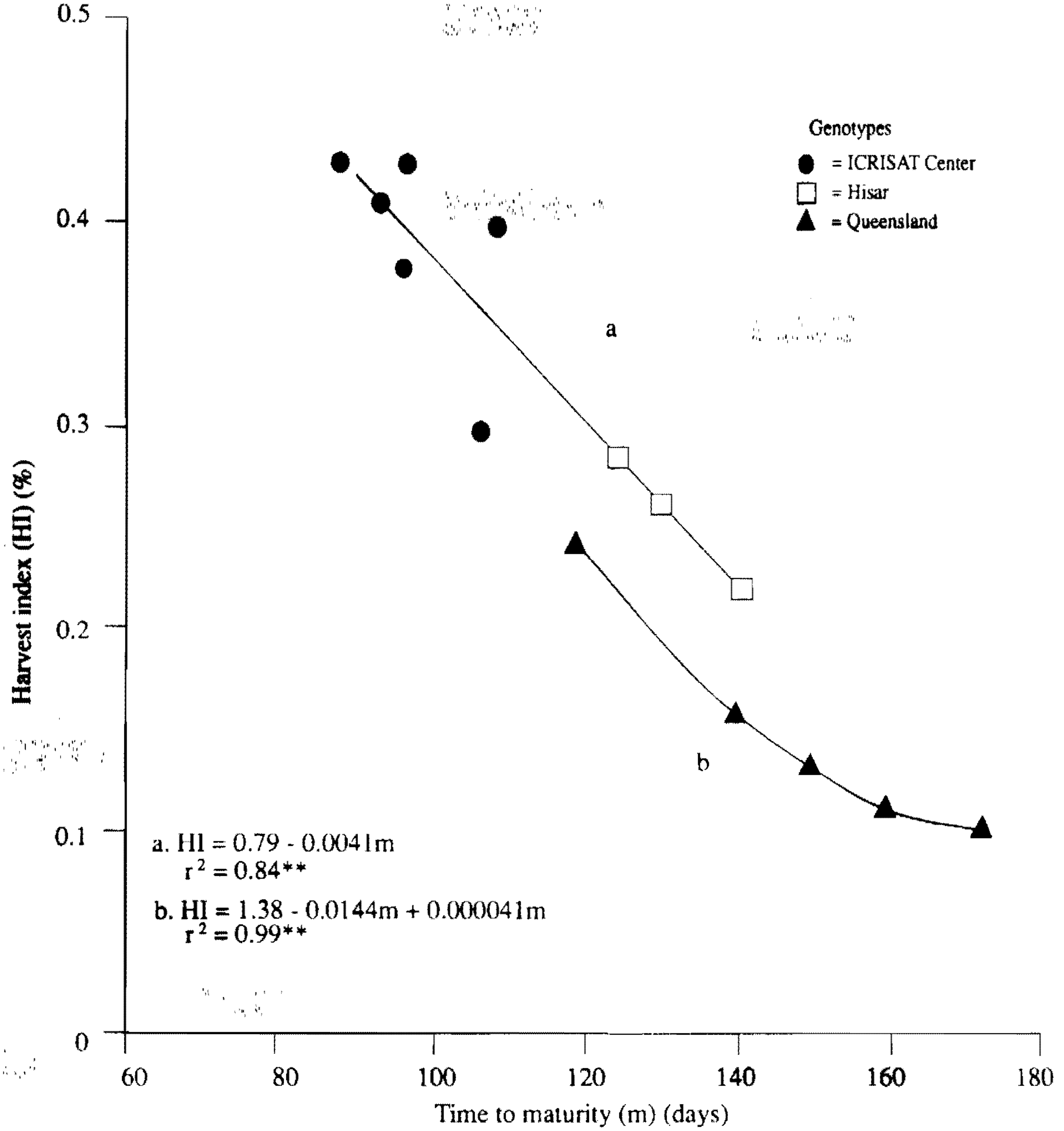


Figure 8.5. Relationship between harvest index (HI) and days to maturity (m) in pigeonpea.

a. Data for three genotypes, sown on two different dates at ICRISAT Center and one at Hisar, India.

Source: Chauhan *et al.*, 1987.

b. Data for five diverse genotypes grown in southern Queensland, Australia.

Source: Baldeo Singh, University of Queensland, unpublished.

derived from current assimilation, as opposed to that derived from assimilation prior to flowering, and subsequently remobilized from vegetative structures, is necessarily greater in earlier-flowering genotypes of pigeonpea. In long-duration pigeonpeas, however, a substantial proportion of the carbon (C) and nitrogen (N) requirements for seed can be satisfied by remobilization of previously fixed assimilate. For example, half of the N requirement of seed in a 120-day line was derived through remobilization from leaf and stem (Rao *et al.*, 1984), while Sheldrake and Narayanan (1979) observed that the gross remobilization of N from vegetative structures in very long duration genotypes exceeded that recovered in seed. The efficiency of re-remobilization however, is low, with much of both the and to a lesser extent the N, effectively immobilized in structural material.

Additionally at maturity in pigeonpea, 30-40% of total plant biomass can remain as green stem, 5-10% as attached leaves, and 15% as roots (Sheldrake and Narayanan, 1979; Rao *et al.*, 1984), reflecting the short-lived perennial nature of the species. Genotypes differ in their propensity to ratoon and in the timing of regrowth relative to maturity of the initial flush of pods (Wallis *et al.*, 1981). It is unclear to what extent differences in ratoonability may be related to differences in the relative distribution of C and N at maturity.

NITROGEN ECONOMY

Sources and Seasonal Profiles of Nitrogen Uptake

Temporal profiles of the uptake of shoot N closely reflect those of shoot biomass accumulation, except that the rate of N accumulation declines earlier, usually during pod or seed growth (Sheldrake and Narayanan, 1979; Dalal, 1980; Rao *et al.*, 1984; De Vries, 1986). This pattern is reflected in a gradual decline in shoot N concentration over the growing period (e.g., from approximately 3.3 to 2.0% in whole shoots (Kumar Rao and Dart, 1987), and from 4-5% to 3-3.5% in leaves, and from 1.5 to 1.0% in stems (Sheldrake and Narayanan, 1979; Dalal, 1980; De Vries, 1986).

Extensive variation is also likely in seasonal patterns of nodulation and N_2 fixation, through the influence of the many biological and environmental factors listed earlier. Thus maximum nodule biomass and nitrogenase activity have been observed to occur at various stages of ontogeny e.g., at or before flowering in greenhouse (Luthra *et al.*, 1983a) and field (De Vries, 1986) studies, or during pod or seed growth (Quilt and Dalal, 1979; Rao *et al.*, 1984, both greenhouse studies). In two field studies, nodule biomass (Sheldrake and Narayanan, 1979) and N_2 fixation (S. Karsono *et al.*, MARIF, unpublished) did not decline until immediately prior to seed maturity. In the study of Kumar Rao and Dart (1987), nodule biomass continued to increase with time, while nitrogenase activity peaked around flowering in the earliest lines, and somewhat later in time, but always before flowering, in later lines.

For more details on nitrogen fixation see Chapter 10.

Partitioning and Nitrogen Harvest Index

Experimental data indicate that between 28 and 56% of the N accumulated by pigeonpea shoots is recovered in the seeds (Table 8.7). The recovery of N (or Nitrogen Harvest Index - NHI) is less with longer-duration crops, presumably because of the relatively smaller HI in such crops (Table 8.6) and the relatively greater amount of N immobilized in stems, roots, and fallen leaves (Kumar Rao and Dart, 1987; Table 8.7). Remobilization of N from leaves can account for a major proportion of the N required for seed protein (Sheldrake and Narayanan, 1979; Kumar Rao and Dart, 1987), with some variation among genotypes in the residual N content of abscised material (Kumar Rao and Dart, 1987). For example, two genotypes extracted N to 1.23 and 1.40%, compared to the mean value of 1.58% for the other nine. Likewise, Rao *et al.* (1984) showed that remobilized N was sufficient to fully meet the requirements of the seed of their greenhouse-grown plants, with surplus N remaining at maturity in both living and abscised vegetative organs.

Table 8.7. Estimates of nitrogen harvest index (NHI) of pigeonpea, and concentration (%) of residual nitrogen (N_r) in abscised material (leaves and petioles combined), contrasted with soybean.

NHI	N_r (%)	Crop duration	Location	Sowing season	Basis of estimate	Reference
Pigeonpea			Australia			
0.62	na[1]	Short	Ord River	Autumn (irrigated)	Excl. fallen leaves	Chapman and Muchow, 1985
0.54	na	Short	Ord River	Autumn (rainfed)	Excl. fallen leaves	Chapman and Muchow, 1985
			India			
0.43	1.51	Long	ICRISAT Center	Summer (Vertisol)	Incl. fallen leaves	Sheldrake and Narayanan, 1979
0.30	1.31	Long	ICRISAT Center	Summer (Alfisol)	Incl. fallen leaves	Sheldrake and Narayanan, 1979
0.56	1.63	Short	ICRISAT Center	Summer	Incl. fallen leaves	Kumar Rao and Dart, 1987
0.40	1.48	Medium	ICRISAT Center	Summer	Incl. fallen leaves	Kumar Rao and Dart, 1987
0.28	1.48	Long	ICRISAT Center	Summer	Incl. fallen leaves	Kumar Rao and Dart, 1987
0.48	2.12	Medium	Hisar	Summer (in pots)	Incl. roots and fallen leaves	Rao *et al.*, 1984
Soybean						
0.60	1.33		SE Queensland, Australia	Summer	Incl. roots and fallen leaves	Lawn, in press; R.J. Lawn, unpublished

1. na = data not available.

PHYSIOLOGICAL CONSTRAINTS TO YIELD IMPROVEMENT

Opportunities are available for agronomic and genetic improvement of seed yield in pigeonpea through; overcoming inherent physiological constraints to yield potential in the species, and minimizing environmental constraints to expression of that potential. In the absence of stress, physiological constraints to seed yield can be considered in terms of constraints to; biomass production, and efficiency of conversion of biomass to seed, i.e., HI. The opportunities for yield improvement in pigeonpea through greater HI are far more promising in the shorter term, in common with the other "unimproved" tropical grain legumes (Lawn, in press). Nonetheless, there are several areas where opportunities exist to enhance yield in pigeonpea by improving biomass production.

Optimizing Biomass Production

Radiation falling on bare ground is wasted energy, and as suggested earlier, a key constraint to early crop growth rate in pigeonpea is its poor E_i. While of less importance where pigeonpea is grown as an intercrop, this constraint is potentially a major limitation to its exploitation as a sole crop, and most particularly, to the use of early-flowering, photoperiod-insensitive genotypes. There is therefore a need for improvement research to focus on selection of genotypes with enhanced E_i and faster initial crop growth rates, and as a prerequisite, for a more definitive understanding of the phyiological basis of the slow leaf area development in pigeonpea seedlings. At the same time, however, caution will need to be exercised such that any selection for greater E_i during early crop growth does not compromise the low extinction coefficients whereby incident PAR is dispersed over a large leaf area within the closed pigeonpea canopy.

To some extent, the low E_i of present genotypes can be partly offset by agronomic means. Equidistant spatial arrangements and higher plant populations, which enhance early LAI development and PAR interception, also enhance early vegetative growth and so reduce the time from sowing until canopy closure when essentially all the incident PAR is intercepted. For example, maximum LAI may be attained within 7 weeks in dense sowings, or require 12 weeks or longer in sparse sowings (Sheldrake and Narayanan, 1979; Rowden *et al.*, 1981; Chauhan *et al.*, 1987). Even so, with very-short-duration crops (such as late sowings and/or very early genotypes), the duration of vegetative growth may be too short to enable canopy closure even at very high plant populations (Chauhan *et al.*, 1987).

Plant populations and spatial arrangements which maximize biomass production may not necessarily maximize seed yield, even in the absence of stresses such as drought. While rapid canopy closure tends to maximize biomass production, continued vegetative growth beyond the time of canopy closure represents energy which might more efficiently be assimilated directly into seed, so that optimum biomass production may be somewhat less than the maximum. At best, excessive vegetative growth (particularly the stem fraction) may serve as a temporary, and largely inefficient, storage reserve for subsequent re-translocation to seed during reproductive ontogeny. A significant proportion is likely to be shed in the form of senescent leaves as subsequent growth shades the lower leaves. For example, Sheldrake and Narayanan (1979) recorded biomass losses through leaf senescence prior to pod fill of up to 1 t ha^{-1}. Thus ideally, the agronomy of the crop should be such that canopy closure is achieved prior to pod filling, to ensure maximum interception of incident PAR during reproductive ontogeny, but after the start of flowering, to avoid excessive vegetative growth. This need to optimize biomass production and LAI provides the basis of genotype × sowing date/latitude × sowing density interactions frequently observed in pigeonpea and other phenologically plastic species (Wallis *et al.*, 1981; Lawn and Williams, 1987).

There is little reliable information available concerning the extent of genotypic differences in carbon exchange capacity within pigeonpea leaves, but in view of the general lack of success in other species, together with the fact that E_c values for pigeonpea are comparable for other species, it seems unlikely that attempts to select for greater leaf photosynthetic rates would lead to greater seed yields in the short term. However, the consequences for E_c of absorption of PAR by reproductive tissues remain to be evaluated in pigeonpea. Actively growing pods of cowpea (Littleton *et al.*, 1981) can recycle much of the CO_2 evolved by respiring seed, but appear incapable of net uptake of CO_2, even in full sunlight, and the same appears likely for developing pods in pigeonpea (Luthra *et al.*, 1983b). The absorption of PAR by non-photosynthetic tissues such as flowers and ripe pods clearly represents wasted energy. There is evidence (Lawn and Williams, 1987) that in mung bean another top-podding species, E_c may be reduced through the interception of PAR by reproductive structures during reproductive growth. There is also one report in pigeonpea (Thirathon *et al.*, (1987b) that E_c declined from 1.62 to 1.18 g MJ^{-1} between early and late reproductive growth.

Improving Harvest Index

The key physiological constraint to potential productivity in pigeonpea is undoubtedly the relatively low HI of most cultivars, at least as grown in traditional production systems, and it follows that selection for greater HI is a priority area for improvement research (Lawn, in press). Support for this course can be drawn from the fact that the HI of most pigeonpeas is very low compared with such species as soybean (Table 8.6) and groundnut, and that much of the genetic advance made in the latter species has been due to improvements in HI. The prospects for analogous advance in pigeonpea are even more optimistic when it is considered that; 1. because of the low N concentration of pigeonpea seed relative to soybean and groundnut, its NHI compares even less favourably, 2. because of its negligible oil content, the energy concentration in pigeonpea seed is relatively lower, and 3. the present loss of C and N in senescent leaves, petioles, and stems in pigeonpea would be sufficient to sustain much greater seed yield without any need for improved N or C productivity.

In the short term, the manipulation of photothermal sensitivity offers the most powerful tool for improving HI in pigeonpea, because of the relationships apparent in Table 8.6 and Figure 8.5. There are several successful applications exemplifying this approach (Byth *et al.*, 1981; Wallis *et al.*, 1981; Chauhan *et al.*, 1987), which relies on the fact that under strongly inductive photothermal conditions, time to flowering is shortened, plants are less vegetative and less prone to loss of biomass through senescence of shaded leaves, stems, etc. In large part, although not always (Chauhan *et al.*, 1987), reduced biomass per plant is compensated by greater HI and the use of dense stands. Nonetheless, the heaviest seed yields recorded for pigeonpea come from this approach (Whiteman *et al.*, 1985).

The fact that HI in pigeonpea is influenced by photothermal regime necessarily raises questions about using the trait as a selection criterion in a breeding programme (Lawn, in press). Most obvious of these is that unless genotypic comparisons are made under the same conditions of location/sowing date, the effects of photothermal regime will confound and probably obscure any inherent genotypic variations for the trait. Likewise, comparisons will need to be made within material of similar phenology, or selection for HI will merely favour early-maturing genotypes. Also, the sensitivity of HI to environmental stresses such as water deficits (Table 8.6) raises specific problems in selection. Genotypic differences in HI are confounded, and thus selection efficiency is lowered, in environments where the nature, timing, and intensity of stresses are uncontrolled and unpredictable.

There will inevitably be some costs associated with improvements in the HI for seed yield of pigeonpea. Larger HI for seed yield may well compromise the use of pigeonpea for many of the other purposes for which it has traditionally been grown, since any improvement in HI will necessarily be achieved at the expense of the quantity of vegetative biomass. Thus the potential to use stems for fuel, or the N-rich residues for incorporation into the soil, or for composting would be reduced. Further, it is possible that the presently large homeostatic capacity of the plant to compensate for the effects of stresses, and/or ratoonability, may be reduced to the extent that stem reserves of assimilates are mobilized to sustain a relatively larger seed load. Although, as noted above, the quantity of DM and C already sloughed as senescent leaves and petioles offers substantial scope for improvement without compromising either homeostasis or ratoonability. Indeed, the very large yields already obtained from short-duration genotypes did not inhibit ratooning (Wallis *et al.*, 1981).

PHYSIOLOGICAL RESPONSE TO CLIMATIC STRESSES

Drought

Pigeonpea has a reputation as a crop well-adapted to drought-prone environments. In India, where some 90% of world production occurs, pigeonpea is sown mainly as a rainy-season crop, and grown through to maturity in the subsequent dry season on stored soil water. Almost all the crop is rainfed, and as such, is exposed to periods of transient drought during much of its vegetative ontogeny, followed by a terminal drought during most, if not all, of its reproductive ontogeny. There is ample evidence however, that as for most mesophytic crop plants, the productivity of pigeonpea is enhanced where water deficits can be avoided (Hughes and Keatinge, 1983; Chauhan *et al.*, 1987). There is also some evidence that, notwithstanding its drought-tolerant status, there may be opportunities for further productivity improvement.

The main effects of water deficit on productivity in pigeonpea can be summarized in terms of consequences for the efficiencies of interception (E_i) and conversion (E_c) of PAR to biomass, and the partitioning of biomass to seed (Lawn and Williams, 1987). Water deficits can variously reduce E_i through; 1. relative reductions in LAI, due to slower rates of leaf initiation and/or smaller leaflet areas, and/or reduced leaf area duration through faster leaf senescence, and 2. decreases in *k* as a consequence of paraheliotropic leaf movement and leaf rolling (Hughes and Keatinge, 1983; Muchow, 1985a). Reductions in E_c can be induced through slower carbon exchange rates, presumably because of reduced stomatal conductance, but perhaps also because of direct effects on photosynthesis. Reductions in partitioning efficiency, reflected in lower HI (see Table 8.6), can arise because the duration and/or rate of reproductive growth is reduced, or because of the excessive abscission of pod and seed sinks induced by a severe stress.

The relative effects of water deficit on each of these components of productivity depend mainly on timing relative to crop ontogeny, duration, and intensity. For example, where water deficit develops gradually after sowing, the reduction in E_i may be greater than that in E_c (Muchow, 1985b). However, where deficits develop relatively rapidly, as in an advanced crop with limited soil water reserves, effects on E_c may be comparable with, or exceed those on E_i. The extent to which any of these effects are translated into losses of seed yield depend on their severity and timing. In general, pigeonpea has proven remarkably resilient to water deficits prior to flowering. Water deficits subsequent to flowering can variously induce the abscission of flower buds and small pods, or, if they occur later toward maturity, promote premature leaf loss and reduce seed size. In addition to constraints on the C economy of the crop, symbiotic N_2 fixation in pigeonpea is sensitive to water deficits (De Vries, 1986), and N accumulation can be reduced under drought conditions (Chapman and Muchow, 1985). Thus, where pigeonpea crops are grown into the dry season, the tendency for longer-duration genotypes to have smaller HI and NHI (Tables 8.6, 8.7) would be accentuated to the extent that water deficit increases as the dry season progresses.

While pigeonpea is responsive to irrigation, the opportunities for using irrigation are in practice very limited, farmers preferring to use scarce water resources on more profitable crops. Attempts to improve the performance of pigeonpea in drought-prone environments must therefore focus on agronomic and genetic opportunities to maximize productivity in rainfed agriculture. Under rainfed conditions, where water is the main limitation, it is convenient to consider productivity in terms of water use, rather than of PAR. Thus, in water-limiting conditions, productivity can be expressed in terms of three components; the total water used, its efficiency of use in producing biomass (WUE), and HI. In pigeonpea, the main emphasis should be on maximizing the use of available water by the crop, since this in turn maximizes the potential biomass of the crop, minimizing drought constraints to partitioning, and to improving HI. It remains to be demonstrated whether any significant gains can be made through increasing the physiological efficiency of water use (Lawn, 1988).

Physiological mechanisms or traits which might conceivably be manipulated to enhance productivity of pigeonpea in rainfed environments are listed in Table 8.8. The most important overall strategy, and one already widely in practice where pigeonpea matures on residual soil water, is to seek to escape the effects of drought by using genotypes whose duration matches the available water supply (Lawn and Williams, 1987). A related escape mechanism, that is particularly useful where the water supply may be variable year to year, is phenological plasticity, whereby the plant can adjust duration, particularly of the reproductive phase, to water supply. Given the wide variation in pigeonpea for flowering time, and the existence of more- and less- determinate types, there is much scope for breeders to exploit these traits in matching the crop to specific rainfed environments.

Several mechanisms contribute to the short-term survival of pigeonpea plants during periods of transient drought, with greater or lesser effects on productivity during and after the drought (Table 8.8). Low epidermal conductance (g_e), stomatal closure, leaf rolling and paraheliotropic leaf movements, less rapid rates of leaf area development, leaf abscission/shorter leaf area duration, all contribute to reduced energy interception and/or slower rates of water loss, and prolong the period the plant can survive on a limited water supply, but with successively greater impacts on productivity once the stress is relieved. The deep-rooting ability of pigeonpea is a particularly important factor enhancing the plant's ability to make most effective use of stored soil water. Pigeonpea also has particularly low g_e relative to other tropical grain legumes (Sinclair and Ludlow,

Table 8.8. Physiological mechanisms or traits potentially contributing to drought escape or drought survival in pigeonpea.

Strategy	Mechanism/trait	Reference
Escape	Matching phenology to water supply (phenological adjustment, plasticity)	Lawn, 1981, 1988
Survival		
Reduced water use	Stomatal closure	Sinclair and Ludlow, 1986
	Slower leaf development	Sinclair and Ludlow, 1986
	Shorter leaf area duration	Muchow, 1985a
	Paraheliotropic movement, leaf rolling	Muchow, 1985a
	Low epidermal conductance	Sinclair and Ludlow, 1986
Improved water uptake	Deep rooting	Sheldrake and Narayanan, 1979
Dehydration tolerance	Osmotic adjustment	Flower and Ludlow, 1986, 1987
	Low critical relative water content	Sinclair and Ludlow, 1986

1986), while leaf rolling is very strongly expressed (Muchow, 1985a). Unfortunately however, there are few reliable data documenting the extent of genotypic variation for any of these traits in pigeonpea, and their potential remains unexploited in any systematic way in improvement programmes.

Two mechanisms, which may be related, and which contribute to strong tolerance of tissue water deficits in pigeonpea, are high levels of osmotic adjustment and low critical or lethal relative water contents (RWC_c) of leaves (Flower and Ludlow, 1986; Sinclair and Ludlow, 1986). Genotypic variation has been demonstrated in the levels of osmotic adjustment (Flower and Ludlow, 1987), although the range among the genotypes tested was relatively small, and the potential for further improvement remains uncertain.

While the various mechanisms which postpone leaf and/or plant mortality are of greatest potential value in the context of transient drought, they are also potentially of importance in a terminal stress situation, because any prolonged survival could conceivably enable greater partitioning of assimilate to seed before the crop is dried off, and thus minimize the effects of drought on HI. Comparative studies across species suggest that there is a strong interrelation between the various mechanisms listed in Table 8.8, and that several may operate "in concert", perhaps causally, to give rise to "strategies" of response (Ludlow and Muchow, 1988). The interaction of several crop species is illustrated in terms of their effects on plant survival times (Table 8.9), following the exhaustion of transpirable water. The combination of a low RWC_c and a low g_e assisted pigeonpeas to survive 18 days after all transpirable water had been used, compared to only 2 days for soybean, that had both high RWC_c and high g_e. In turn, both the lower RWC_c, and the greater water extraction of pigeonpea relative to the other species may have been partly due to its greater osmotic adjustment capacity.

Table 8.9. Differences in plant survival time (days) following exhaustion of transpirable water, relative amount of water transpired, dehydration tolerance as indicated by the critical relative water content (RWC_c) when plants die, and epidermal conductance (g_e) of droughted leaves, of pigeonpea and other tropical grain legumes grown in pots.

Crop species	Survival time (days)	Relative transpiration	RWC_c (%)	g_e (mm s^{-1})
Pigeonpea (*Cajanus cajan*)	18	100	32	0.03
Cowpea (*Vigna unguiculata*)	>24	88	40	0.05
Black gram (*Vigna mungo*)	14	85	46	0.09
Soybean (*Glycine max*)	2	91	50	0.14

Source: Sinclair and Ludlow, 1986.

Waterlogging

Pigeonpea is very susceptible to waterlogging, which is perhaps consistent with its adaptation to drier environments. In India, exposure of pigeonpea to waterlogging is most likely, and most detrimental, during seedling growth in cracking clay soils, when monsoon rains lead to short-term flooding. Waterlogging damages the root system through anoxia and, possibly, the effects of ethylene, and produces symptoms of water deficit (Chauhan, 1987). Plants are also extremely vulnerable to attack by the fungus *Phytophthora drechsleri* f. sp *cajani* that causes blight, and to N deficiency through the inhibition of N_2 fixation (Thompson *et al.*, 1981).

Evidence of genotypic differences in response to waterlogging has been reported by Chauhan (1987) and Dubey and Asthana (1987). Average survival after 6 days of waterlogging was 96% in a tolerant genotype, and 28% in a susceptible genotype (Chauhan, 1987). During 2 years of testing, 27 genotypes out of 123 consistently survived inundation, and wide variation for seed yield was observed among these (Dubey and Asthana, 1987). Combined tolerance to waterlogging and salinity has also been identified (Chauhan, 1987).

Temperature

Pigeonpea is a warm-season plant, best adapted to the lower altitude regions of the tropics and subtropics (Chapter 7), and studies suggest that growth of pigeonpea is generally superior at warmer temperatures, but may be poor under cooler temperatures. In laboratory tests, for example, germinability of several pigeonpea genotypes was high over a relatively broad temperature range (19-43°C), while germination was rapid and even over the range 26-43°C (de Jabrun *et al.*, 1981). The optimal range for rate of hypocotyl elongation was narrower (29-36°C). No germination occurred at 7.1°C or 46.5°C, and the rate of germination was markedly reduced below 19°C. Studies of field emergence suggest that, like groundnut, pigeonpeas have both a warmer base temperature, and a greater thermal sum requirement for emergence, relative to other tropical grain legumes (Table 8.10). As a consequence, emergence is relatively slow at cooler soil temperatures. Sensitivity to cool soil temperature and its consequent effects on plant stand have been suggested as a constraint to utilization of pigeonpea at higher altitudes in eastern Africa (Khan and Ashley, 1975). Likewise, cool temperatures have been suspected as the cause of slower crop growth rates during winter (Akinola and Whiteman, 1975a; Narayanan and Sheldrake, 1979). Controlled environment studies showed that various growth processes such as rates of leaf appearance, leaf area per plant, and plant height all increased over the temperature range 20-28°C (McPherson *et al.*, 1985). However, there is little reliable evidence of genotypic differences within pigeonpea for sensitivity of growth processes to temperature. Nonetheless, given the experience with other species and the generally broad adaptation of pigeonpea as a species, comprehensive searches among the pigeonpea germplasm are likely to be successful in identifying sources of tolerance to both warm and cool temperature extremes.

Table 8.10. Relative sensitivity of pigeonpea to temperature during emergence. Estimated time (days) to emergence at mean temperatures of 18°C and 25°C for pigeonpea and other tropical grain legumes, based on experimental estimates of base temperatures (T_b), and thermal time to emergence (day degrees $>T_b$).

	Days to emergence		Base temperature	Thermal time (day degrees
Crop species	18°C	25°C	(T_b) (°C)	$>T_b$)
Pigeonpea (*Cajanus cajan*)	11.2	4.8	12.8	58.2
Cowpea (*Vigna unguiculata*)	6.1	3.1	11.0	43.0
Green/black gram (*Vigna radiata/mungo*)	6.9	3.5	10.8	49.6
Navy bean (*Phaseolus vulgaris*)	7.0	3.6	10.6	52.1
Soybean (*Glycine max*)	8.7	3.6	9.9	70.5
Groundnut (*Arachis hypogaea*)	16.2	6.5	13.3	76.3

Source: Angus *et al.*, 1981.

FUTURE

Many of the physiological processes of yield formation in pigeonpea reflect the species' long history of immensely successful exploitation in various traditional subsistence production systems of the Indian subcontinent. Thus attributes such as: slow initial growth combined with late-season vegetative vigour; extreme plasticity of branching; profligate production of flower buds; indeterminateness; photosensitivity and long duration; strong ratoonability; low HI; and poor seed yield but strong homeostasis in stressful environments — all of which are characteristic of so many traditional cultivars — simultaneously contribute to, and derive from, the broad adaptation of those cultivars within low-input, labour-intensive, mixed cropping systems, and the crops' multipurpose use for fuel and forage as well as seed. For the foreseeable future, the bulk of pigeonpea will continue to be produced and consumed in India. Pigeonpea will therefore continue to play an important role as a subsistence crop, and many of these unique physiological attributes will necessarily be conserved to fulfil that role. Yet, not all of these attributes are simultaneously essential to that role, either within existing production systems, or for all end-uses for the crop. Thus, as indicated throughout this chapter, there are opportunities to improve productivity either by sacrificing the multipurpose role of the crop, or by more closely tailoring genotypes to the constraints of their environments and so exploiting more purposefully the opportunities for specific adaptation within the species.

Neither are these traditional attributes ubiquitous within pigeonpea. Indeed, there exists a wealth of largely untapped variability within the pigeonpea germplasm, which together with strategies for manipulating response to the environment (Spence and Williams, 1972), offers immense potential to transform pigeonpea into a high-yielding grain crop, suited even to mechanized agriculture (Wallis *et al.*, 1981). Increasingly, it is inevitable, indeed necessary that pigeonpea will be developed and exploited as a more productive grain crop, and in physiological terms, the most direct route to achieve this objective is through an improvement in HI. There are some opportunities for improvement that are relevant to pigeonpea as both a subsistence crop and a high-yielding grain crop, particularly where genetic approaches to minimizing environmental constraints involve improving stress resistance. However, in many cases, an increasing emphasis on improving seed-yield potential will compromise some of the attributes valuable to subsistence agriculture. Thus, choices will have to be made in the objectives of improvement programmes to reflect the relative priority to be given to stability of yield *vs* yield potential (Lawn, in press).

Regardless of whether pigeonpea is being bred for stability of performance, for yield potential, or some optimum combination of the two, the process will be assisted by a more comprehensive understanding of the physiology of yield formation than is presently available. Areas where further understanding is particular needed include: research to define quantitatively and predictively the environmental control of reproductive ontogeny in pigeonpea so that cultivars can be better matched to their environments; research to critically evaluate environmental and physiological constraints to partitioning of biomass and N to seed, so that the very poor HI of the crop can be raised; and research to explore the opportunities for exploiting physiological traits which assist survival during drought, so that the drought resistance of pigeonpea can be further enhanced.

Acknowledgement

The authors appreciate the assistance of Mr A.R. Watkinson in figure preparation.

REFERENCES

Akinola, J.O. and Whiteman, P.C. (1975a) Agronomic studies on pigeonpea (*Cajanus cajan* (L.) Millsp.). I. Field responses to sowing time. *Australian Journal of Agricultural Research* 26, 43-56.

Akinola, J.O. and Whiteman, P.C. (1975b) Agronomic studies on pigeonpea (*Cajanus cajan* (L.) Millsp.). II. Responses to sowing density. *Australian Journal of Agricultural Research* 26, 57-66.

Angus, J.F., Cunningham, R.B., Moncur, M.W. and MacKenzie, D.H. (1981) Phasic development in field crops I. Thermal response in the seedling phase. *Field Crops Research* 3, 365-378.

Ariyanayagam, R.P. (1981) Pigeonpea breeding in the Caribbean Regional Programme. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 415-426.

Brakke, M.P. and Gardner, F.P. (1987) Juvenile growth in pigeonpea, soybean, and cowpea in relation to seed and seedling characteristics. *Crop Science* 27, 311-316.

Byth, D.E., Wallis, E.S. and Saxena, K.B. (1981) Adaptation and breeding strategies for pigeonpea. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 450-465.

Chapman, A.L. and Muchow, R.C. (1985) Nitrogen accumulated and partitioned at maturity by grain legumes grown under different water regimes in a semi-arid tropical environment. *Field Crops Research* 11, 69-79.

Charles-Edwards, D.A. (1982) *Physiological Determinants of Crop Growth.* Academic Press, Sydney, 161 pp.

Chauhan, Y.S. (1987) Screening for tolerance to salinity and waterlogging: case studies with pigeonpea and chickpea. In: *Adaptation of Chickpea and Pigeonpea to Abiotic Stresses. Proceedings of the Consultants' Workshop, 19-21 December 1984, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 93-103.

Chauhan, Y.S., Venkataratnam, N. and Sheldrake, A.R. (1987) Factors affecting growth and yield of short-duration pigeonpea and its potential for multiple harvests. *Journal of Agricultural Science, Cambridge* 109, 519-529.

Dahiya, B.S., Brar, J.S. and Kaul, J.N. (1974) Changes in growth habit of pigeon-peas (*Cajanus cajan* (L.) Millsp.) due to late sowing. *Journal of Agricultural Science, Cambridge* 83, 379-380.

Dalal, R.C (1980) Nutrient element concentration and dry matter production by field grown pigeonpea (*Cajanus cajan* (L.) Millsp.). *Tropical Agriculture (Trinidad)* 57, 107-112.

de Jabrun, P.L.M., Byth, D.E. and Wallis, E.S. (1981) Imbibition by and effects of temperature on germination of mature seed of pigeonpea. In: *Proceedings of the International Workshop on Pigeonpeas, volume 2, 15-19 December 1980, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 181-187.

Deshpande, R. and Nimbalkar, J.D. (1982) Effect of salt-stress on translocation of photosynthates in pigeonpea. *Plant and Soil* 65, 129-132.

De Vries, J.D. (1986) Water relations and nitrogen fixation of three grain legumes during water stress. MSc thesis, University of Florida, USA, 107 pp.

Dubey, S.D. and Asthana, A.N. (1987) Selection of plant type for resistance to waterlogging in pigeonpea. In: Wallis, E.S. and Byth, D.E. (eds), *Food Legume Improvement for Asian Farming Systems: Proceedings of an International Workshop held in Khon Kaen, Thailand, 1-5 September 1986. ACIAR Proceedings no. 18.* ACIAR, Canberra, p. 311.

Faris, D.G., Saxena, K.B., Singh, U. and Reddy, L.J. (1987) The promise of high protein pigeonpea. In: Wallis, E.S. and Byth, D.E. (eds), *Food Legume Improvement for Asian Farming Systems: Proceedings of an International Workshop held in Khon Kaen, Thailand, 1-5 September 1986. ACIAR Proceedings no. 18.* ACIAR, Canberra, pp. 311-312.

Flower, D.J. and Ludlow, M.M. (1986) Contribution of osmotic adjustment to the dehydration tolerance of water-stressed pigeonpea (*Cajanus cajan* (L.) Millsp.) leaves. *Plant, Cell and Environment* 9, 33-40.

Flower, D.J. and Ludlow, M.M. (1987) Variation among accessions of pigeonpea (*Cajanus cajan*) in osmotic adjustment and dehydration tolerance of leaves. *Field Crops Research* 17, 229-243.

Giri, A.N., Yadav, M.V., Bainade, S.S. and Jondhale, S.G. (1981) Intercropping studies with pigeonpea. In: *Proceedings of the International Workshop on Pigeonpeas, volume 2, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 257-261.

Grover, A., Koundal, K.R. and Sinha, S.K. (1985) Senescence of attached leaves: regulation by developing pods. *Physiologia Plantarum* 63, 87-92.

Hegde, D.M. and Saraf, C.S. (1978) Light relations in pigeon pea as affected by intercroppingng and phosphorus fertilisation. *Indian Journal of Agronomy* 23, 379-380.

Hughes, G. and Keatinge, J.D.H. (1983) Solar radiation interception, dry matter production and yield in pigeonpea (*Cajanus cajan* (L.) Millspaugh). *Field Crops Research* 6, 171-178.

Hughes, G., Keatinge, J.D.H. and Scott, S.P. (1981) Pigeon pea as a dry season crop in Trinidad, West Indies. II–Interception and utilization of solar radiation. *Tropical Agriculture (Trinidad)* 58, 191-199.

ICRISAT (1978) *Pulse Physiology Progress Report 1977-1978, Part 1, Pigeonpea Physiology. Progress Report Pulse Physiology–2*. Patancheru, A.P., India: Legumes Program, ICRISAT, pp. 88-90 (Limited distribution).

Kay, D.E. (1979) *Crop and Product Digest no. 3–Food Legumes*. Tropical Products Institute, London, pp. 322-347.

Khan, T.N. and Ashley, J.M. (1975) Factors affecting plant stand in pigeon pea. *Experimental Agriculture* 11, 315-322.

Khatra, S.S., Kumar, V. and Sidhu, P.S. (1986) Pattern of dry matter accumulation in developing fruit parts of early- and late-maturing pigeonpeas (*Cajanus cajan* (L.) Millsp.). *Biologia Plantarum* 28, 297-302.

Kumar Rao, J.V.D.K. and Dart, P.J. (1987) Nodulation, nitrogen fixation and nitrogen uptake in pigeonpea (*Cajanus cajan* (L.) Millsp.) of different maturity groups. *Plant and Soil* 99, 255-266.

Lawn, R.J. (1981) The potential contribution of physiological research to pigeonpea improvement. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 151-164.

Lawn, R.J. (1988) Interpretive summary of Part 4: Breeding for improved plant performance in drought-prone environments. In: Bidinger, F.R. and Johansen, C. (eds), *Drought Research Priorities for the Dryland Tropics*. Patancheru, A.P., India: ICRISAT, pp. 213-219.

Lawn, R.J. (in press) Agronomic and physiological constraints to the productivity of tropical grain legumes, and opportunities for improvement. *Experimental Agriculture*.

Lawn, R.J. and Williams, J.H. (1987) Limits imposed by climatic factors. In: E.S. Wallis and D.E. Byth (eds), *Food Legume Improvement for Asian Farming Systems: Proceedings of an International Workshop held in Khon Kaen, Thailand, 1-5 September 1986. ACIAR Proceedings no. 18*. ACIAR Canberra, pp. 83-98.

Littleton, E.J., Dennett, M.D., Elston, J. and Monteith, J.L. (1981) The growth and development of cowpeas (*Vigna unguiculata*) under tropical field conditions. *Journal of Agricultural Science, Cambridge* 97, 539-550.

Ludlow, M.M. and Muchow, R.C. (1988) Critical evaluation of the possibilities for modifying crops for high production per unit of precipitation. In: Bidinger, F.R. and Johansen, C. (eds), *Drought Research Priorities for the Dryland Tropics*. Patancheru, A.P., India: ICRISAT, pp. 179-211.

Luthra, Y.P., Sheoran, I.S. and Singh, R. (1983a) Ontogenetic interactions between photosynthesis and symbiotic nitrogen fixation in pigeonpea. *Annals of Applied Biology* 103, 549-556.

Luthra, Y.P., Sheoran, I.S. and Singh, R. (1983b) Relative photosynthetic efficiency of subtending leaves, podwalls and seeds of pigeonpea. *Photosynthetica* 17, 210-215.

McPherson, H.G., Warrington, I.J. and Turnbull, H.L. (1985) The effects of temperature and daylength on the rate of development of pigeonpea. *Annals of Botany* 56, 597-611.

Meekin, J.S., Troedson, R.J., Wallis, E.S. and Byth, D.E. (1987) Pigeonpea: a new summer legume crop. *Queensland Agricultural Journal* 113, 117-122.

Muchow, R.C. (1985a) Canopy development in grain legumes grown under different soil water regimes in a semi-arid tropical environment. *Field Crops Research* 11, 99-109.

Muchow, R.C. (1985b) An analysis of the effects of water deficits on grain legumes grown in a semi-arid tropical environment in terms of radiation interception and its efficiency of use. *Field Crops Research* 11, 309-323.

Narayanan, A., Saxena, N.P. and Sheldrake, A.R. (1981) Varietal differences in seed size and seedling growth of pigeonpea and chickpea. *Indian Journal of Agricultural Sciences* 51, 389-393.

Narayanan, A. and Sheldrake, A.R. (1979) Pigeonpea (*Cajanus cajan*) as a winter crop in peninsular India. *Experimental Agriculture* 15, 91-95.

Natarajan, M. and Willey, R.W. (1980a) Sorghum-pigeonpea intercropping and the effects of plant population density 1. Growth and yield. *Journal of Agricultural Science, Cambridge* 95, 51-58.

Natarajan, M. and Willey, R.W. (1980b) Sorghum-pigeonpea intercropping and the effects of plant population density 2. Resource use. *Journal of Agricultural Science, Cambridge* 95, 59-65.

Pandey, R.K. and Singh, V.B. (1981) Influence of source and sink size on flower drop and seed yield of pigeonpea. *Indian Journal of Agricultural Sciences* 51, 185-188.

Panwar, K.S. and Yadav, H.L. (1981) Response of short-duration pigeonpea to early planting and phosphorus levels in different cropping systems. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 37-44.

Quilt, P. and Dalal, R.C. (1979) Effect of soil mineral N levels and inoculation on nodulation, nitrogenase activity, and grain yield of pigeonpea. *Agronomy Journal* 71, 450-452.

Rao, A.S., Luthra, Y.P., Sheoran, I.S. and Singh, R. (1984) Partitioning of carbon and nitrogen during growth and development of pigeonpea (*Cajanus cajan* L.) *Journal of Experimental Botany* 35, 774-784.

Rao, M.R. and Willey, R.W. (1983) Effects of pigeonpea plant population and row arrangements in sorghum/pigeonpea intercropping. *Field Crops Research* 7, 203-212.

Rao, M.R., Willey, R.W., Sharma, D. and Green, J.M. (1981) Pigeonpea genotype evaluation for intercropping. In: *Proceedings of the International Workshop on Pigeonpeas, volume 2, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 263-270.

Rawson, H.M. and Constable, G.A. (1981) Gas exchange of pigeonpea: a comparison with other crops and a model of carbon production and its distribution within the plant. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 175-189.

Remanandan, P., Sastry, D.V.S.S.R. and Mengesha, M.H. (1988) *ICRISAT Pigeonpea Germplasm Catalog: Evaluation and Analysis*. Patancheru, A.P., India: ICRISAT, 90 pp.

Rowden, R., Gardiner, D., Whiteman, P.C. and Wallis, E.S. (1981) Effects of planting density on growth, light interception and yield of a photoperiod insensitive pigeonpea (*Cajanus cajan*). *Field Crops Research* 4, 201-213.

Roxburgh, W. (1832) *Flora Indica: Descriptions of Indian Plants*. W. Thacker and Co., Calcutta, and Parbury, Allen and Co., London.

Sardar Singh and Russell, M.B. (1981) Water use by a maize/pigeonpea intercrop on a deep Vertisol. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 271-282.

Setter, T.L., McDavid, C.R. and Lopez, F.B. (1984) Photosynthate partitioning in pigeonpea in response to defoliation and shading. *Crop Science* 24, 221-224.

Sharma, D., Reddy, L.J., Green, J.M. and Jain, K.C. (1981) International adaptation of pigeonpeas. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 71-81.

Sheldrake, A.R. and Narayanan, A. (1979) Growth, development and nutrient uptake in pigeonpea (*Cajanus cajan*). *Journal of Agricultural Science, Cambridge* 92, 513-526.

Sheldrake, A.R., Narayanan, A. and Venkataratnam, N. (1979) The effects of flower removal on the seed yield of pigeonpeas (*Cajanus cajan*). *Annals of Applied Biology* 91, 383-390.

Sinclair, T.R. and Ludlow, M.M. (1986) Influence of soil water supply on the plant water balance of four tropical grain legumes. *Australian Journal of Plant Physiology* 13, 329-341.

Singh, D.N. and Kush, A.K. (1981) Effect of population density on growth pattern and yielding ability in pigeonpea. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 165-174.

Singh, H.P. and Saxena, M.C. (1981) Effect of date of planting on the time of flowering in greengram, blackgram, cowpea and pigeonpea. *Indian Journal of Agricultural Sciences* 51, 33-37.

Singh, U., Jambunathan, R. and Narayanan, A. (1980) Biochemical changes in developing seeds of pigeonpea (*Cajanus cajan*). *Phytochemistry* 19, 1291-1295.

Sivakumar, M.V.K. and Virmani, S.M. (1980) Growth and resource use of maize, pigeonpea and maize/pigeonpea intercrop in an operational research watershed. *Experimental Agriculture* 16, 377-386.

Snaydon, R.W. and Harris, P.M. (1981) Interactions belowground–the use of nutrients and water. In: *Proceedings of the International Workshop on Intercropping, 10-13 January 1979, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 188-201.

Spence, J.A. and Williams, S.J.A. (1972) Use of photoperiod response to change plant design. *Crop Science* 12, 121-122.

Summerfield, R.J. and Roberts, E.H. (1985) *Cajanus cajan*. In: Halevy, A.H. (ed), *CRC Handbook of Flowering, volume 1*. CRC Press, Inc., Boca Raton, Florida, pp. 83-91.

Summerfield, R.J. and Roberts, E.H. (1987) Effects of illuminance on flowering in long- and short-day grain legumes: a reappraisal and unifying model. In: Atherton, J.G. (ed), *Manipulation of Flowering*. Butterworths, London, pp. 203-223.

Summerfield, R.J., Roberts, E.H. and Lawn, R.J. (1989) Measurement and prediction of flowering in soybean on fluctuating field environments. In: Pascale, A.J. (ed), *Proceedings, World Soybean Research Conference IV*. Asociacion Argentina de la Soja, Buenos Aires, Argentina, pp. 82-87.

Tayo, T.O. (1980) Compensatory growth and yield of pigeonpea (*Cajanus cajan*) following pod removal at different stages of reproductive growth. *Journal of Agricultural Science, Cambridge* 95, 487-491.

Thirathon, A., Byth, D.E., Fischer, K.S. and Whiteman, P.C. (1987a) Effect on sink development of changes in assimilate supply during different growth stages of short-season pigeonpea. In: Wallis, E.S. and Byth, D.E. (eds), *Food Legume Improvement for Asian Farming Systems: Proceedings of an International Workshop held in Khon Kaen, Thailand, 1-5 September 1986. ACIAR Proceedings no. 18*. ACIAR, Canberra, p. 252.

Thirathon, A., Byth, D.E., Fischer, K.S. and Whiteman, P.C. (1987b) Relationship between leaf area, radiation interception and dry matter production after flowering in short-season pigeonpea. In: Wallis, E.S. and Byth, D.E. (eds), *Food Legume Improvement for Asian Farming Systems: Proceedings of an International Workshop held in Khon Kaen, Thailand, 1-5 September 1986. ACIAR Proceedings no. 18*. ACIAR, Canberra, pp. 252-253.

Thirathon, A., Byth, D.E., Fischer, K.S. and Whiteman, P.C. (1987c) Compensatory ability of pigeonpea to a reduction in sink capacity. In: Wallis, E.S. and Byth, D.E. (eds), *Food Legume Improvement for Asian Farming Systems: Proceedings of an International Workshop held in Khon Kaen, Thailand, 1-5 September 1986. ACIAR Proceedings no. 18*. ACIAR, Canberra, p. 253.

Thompson, J.A., Kumar Rao, J.V.D.K. and Dart, P.J. (1981) Measurement of inoculation response in pigeonpea. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 249-253.

Turnbull, L.V. and Ellis, M.L. (1987) Effect of incandescent and fluorescent lighting used in photoperiod extension on the vegetative growth and floral development of four lines of pigeonpea. *Field Crops Research* 17, 25-36.

Turnbull, L.V., Whiteman, P.C. and Byth, D.E. (1981) The influence of temperature and photoperiod on floral development of early flowering pigeonpea. In: *Proceedings of the International Workshop on Pigeonpeas, volume 2, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 217-222.

Venkataratnam, N. and Sheldrake, A.R. (1985) Second harvest yields of medium duration pigeonpeas (*Cajanus cajan*) in peninsular India. *Field Crops Research* 10, 323-332.

Wallis, E.S., Byth, D.E. and Whiteman, P.C. (1981) Mechanized dry seed production of pigeonpea. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 51-60.

Wallis, E.S., Byth, D.E., Whiteman, P.C. and Saxena, K.B. (1983) Adaptation of pigeonpea (*Cajanus cajan*) to mechanized culture. In: Driscoll, C.J. (ed), *Proceedings of the Australian Plant Breeding Conference, Adelaide, South Australia, 14-18 February, 1983*. University of Adelaide, South Australia, pp. 142-145.

Whiteman, P.C., Byth, D.E. and Wallis, E.S. (1985) Pigeonpea (*Cajanus cajan* (L.) Millsp.). In: Summerfield, R.J. and Roberts, E.H. (eds), *Grain Legume Crops*. Collins Professional and Technical Books, London, pp. 658-698.

Willey, R.W. and Rao, M.R. (1981) Genotype studies at ICRISAT. In: *Proceedings of the International Workshop on Intercropping, 10-13 January 1979, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 117-127.

Chapter 9

PIGEONPEA: MINERAL NUTRITION

C. JOHANSEN

Principal Agronomist, Legumes Program, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Andhra Pradesh 502 324, India.

INTRODUCTION

It is generally observed that pigeonpea responds less to fertilizers than other comparable crops of the semi-arid tropics. This apparent lack of nutritional problems has perhaps resulted in fewer in-depth studies of the mineral nutrition characteristics of this crop than is warranted. Most nutritional studies have been done on the traditional, longer-duration varieties that are normally grown in intercrops or mixed cropping situations. However, the recent development of short-duration genotypes, normally used as sole crops and given higher levels of management, has necessitated a comprehensive examination of the mineral nutrition characteristics of this essentially new plant type. This chapter summarizes previous work, and discusses recent research developments on the response of pigeonpea to essential plant nutrients as well as to elements that could be toxic. The nitrogen nutrition of pigeonpea is covered in Chapters 10 and 11 and thus will not be referred to in any detail here, except in terms of effects of other elements on nitrogen fixation activity.

RECORDED DEFICIENCIES

Pigeonpea is comparatively less responsive to phosphorous (P) application than other non-legume crops that are usually grown in the same season (Figure 9.1), but responds similarly to other tropical grain legumes (Nandal *et al.*, 1987). There are many recorded instances of this nutrient limiting pigeonpea growth, mainly in India where most pigeonpea is grown and most experimentation done. Kulkarni and Panwar (1981) summarized the data to 1980 and concluded that responses to 17-26 kg ha^{-1} P application ranged from 300 to 600 kg ha^{-1} grain yield on farmers' fields in the majority of experiments. However, large responses have been recorded. For example, Ramanathan *et al.* (1977) showed that grain yield of cultivar Co 2 on a calcareous soil at Coimbatore in southern India at the optimum P level of 22 kg ha^{-1} was 250% of that where no P was applied. In summarizing the results of 503 trials measuring P response of pigeonpea in India, Tandon (1987) calculated a mean increase in yield of 310 kg ha^{-1} over an unfertilized control yield of 480 kg ha^{-1}, up to an application level of 17 kg ha^{-1} P. Again, the biologically optimum P application rate appeared to be in the range 17-26 kg ha^{-1} P but some responses to 43 kg ha^{-1} P were reported.

Large P responses have been reported for growth of pigeonpea in Africa, where P deficiency is widespread and severe among most crops (e.g., Ogunwale and Olaniyi, 1978; Rhodes, 1987). In the Caribbean, little response of pigeonpea to P fertilizer was reported from several studies (e.g., Pietri *et al.*, 1971; Morton *et al.*, 1982; Ariyanayagam and Griffith, 1987). However large P responses in this region have been found in other studies on acid soils. For example, Dalal and Quilt (1977) found that P application almost doubled grain yield on a Trinidad soil of pH 5.2 and Hernandez and Focht (1985) reported that P application could increase grain yield five-fold in Panama.

It has also been demonstrated that P deficiency delays flowering and maturity of short-duration pigeonpea (Y.S. Chauhan, ICRISAT, unpublished). This has implications for fitting pigeonpea into crop rotations where there are time constraints for the cropping period allocated to pigeonpea, an example being the pigeonpea-wheat rotation practised in northern India.

Responses of pigeonpea to potassium (K) fertilizer are marginal at most, but significant

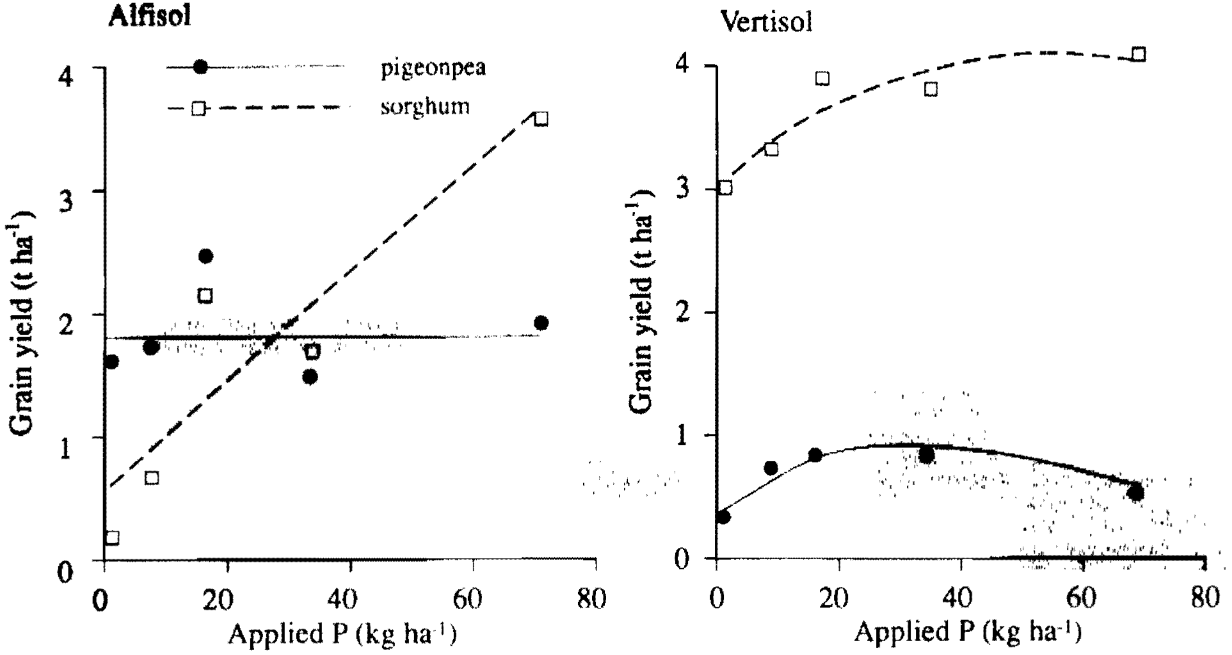


Figure 9.1. Response of pigeonpea (ICPL 87) and sorghum (CSH 5) to phosphorous (kg ha^{-1}) in field experiments on an Alfisol and a Vertisol, ICRISAT Center, rainy season, 1987/88.

Source: ICRISAT, 1989.

responses have been recorded in India (Kulkarni, 1980; Kulkarni and Panwar, 1981; Tandon and Sekhon, 1988). Responses are only up to about 20 kg ha^{-1} K and boost yields to usually no more than 20% above the control. Also, in recent studies in Andhra Pradesh, where K deficiency in pigeonpea is the most common in India (Tandon and Sekhon, 1988), foliar application of K almost doubled the grain yield of medium-duration pigeonpea (Ravindranath *et al.*, 1985).

In view of the extent of sulphur (S) deficiency in field crops in India (Tandon, 1986), it is surprising that no instances of response to S by field-grown pigeonpea have been reported. However, in pot trials, Oke (1969) showed significant responses of pigeonpea growth and nodulation to S application. Similarly, in pot trials with a Vertisol at ICRISAT Center, omission of S fertilizer reduced growth of short-duration cultivar ICPL 87 to about half that in a fully fertilized treatment, with classic S deficiency symptoms apparent. By contrast, no S response was obtained when this cultivar was grown at a field site near where the soil for pot experiments was obtained (ICRISAT, unpublished). This may be an indication of the deep-rooting ability of pigeonpea in being able to exploit S at depth, as available S normally increases with soil depth (Probert and Jones, 1977).

Recorded responses of pigeonpea to trace elements are rare. Shukla and Raj (1980) reported large responses of pigeonpea to zinc (Zn) in a potted Entisol at Hisar, northern India. These Zn responses occur on both normal and saline Entisols (Gupta *et al.*, 1985). Responses of field-grown pigeonpea to Zn application have also been reported, e.g., those in the sandy loam soils of West Bengal, India (Puste and Jana, 1988). Raj (1987) reported that seed application of cobalt (Co) at a rate of 500 mg cobalt nitrate kg^{-1} seed significantly increased grain yield of ICPL 1 and ICPL 87 by 30% in an Alfisol field at Hyderabad, central India. This is an interesting and unusual finding in that, although it is known that traces of Co are essential for nitrogen (N) fixation in legumes, reports of significant responses of any legumes to application of this element in soils are very rare. Although limitations of other trace elements, such as molybdenum (Mo), for pigeonpea in various soils have been sought (e.g., Subbian and Ramiah, 1982), no reports of significant responses can be found.

MINERAL TOXICITIES

Salinity

Pigeonpea is normally grown in semi-arid regions that are prone to salinity, particularly in India, and this can pose a major constraint to crop production (Chauhan, 1987). Among tropical legumes, Keating and Fisher (1985) found that pigeonpea cultivars Hunt and Royes were less salt-tolerant than sesbania, guar *(Cyamopsis tetragonoloba)*, cowpea, and soybean, but more so than green gram (mung bean). They found that electrical conductivity (EC) of saturated soil extracts at half-maximal growth were 5.4 dS m^{-1} for Hunt and 4.9 dS m^{-1} for Royes. Johansen *et al.* (in press) similarly found that half-maximal growth of 40-45 day-old seedlings of a range of pigeonpea genotypes growing in sand or solution culture occurred at 5-7 dS m^{-1}. In a saline Vertisol, this critical range corresponded to 1.5-3 dS m^{-1} in a 1:2 soil-water extract.

Among cultivated pigeonpea genotypes, ICPL 227 is relatively salt-tolerant and Hy 3C salt-sensitive, but these differences do not seem large enough to warrant a programme of genetic enhancement of salinity tolerance utilizing only crosses between cultivated genotypes (Johansen *et al.*, in press). Subbarao (1988) has demonstrated substantial sources of salinity tolerance among wild relatives of pigeonpea, *Cajanus platycarpus* and *C. albicans*. These species can grow, flower, and set pods at 10 dS m^{-1} and thus offer the extent of salinity tolerance needed for significant genetic enhancement in cultivated pigeonpea. Only *C. albicans* readily crosses with cultivated pigeonpea and the F_1 hybrids of such a cross exhibit the level of salinity tolerance of the tolerant, wild-type parent, indicating that the salinity tolerance syndrome is genetically dominant (Subbarao, 1988).

Subbarao (1988) has further shown that the salinity tolerance mechanism in pigeonpea involves exclusion of sodium (Na) and chlorine (Cl) ions from the shoot, and maintenance of high K levels. Although replacement of Na with Ca in the ambient solution enhances plant growth at a constant salinity level, relative differences in salinity response between genotypes remain unchanged.

Soil Acidity

Although it is predominantly grown in the neutral to alkaline soils of India, pigeonpea can grow and fix N_2 in acid soils, in the pH range 4.5 to 5.5 (Dalal and Quilt, 1977; Edwards, 1981; Abruna *et al.*, 1984) but not below pH4 (Chong *et al.*, 1987). However, in common with other legumes, the N_2-fixation activity seems more sensitive to acidity than plant growth itself (Edwards, 1981). Liming can alleviate acid soil effects but high rates of lime (e.g., 5 t ha^{-1}) may lead to induced Zn

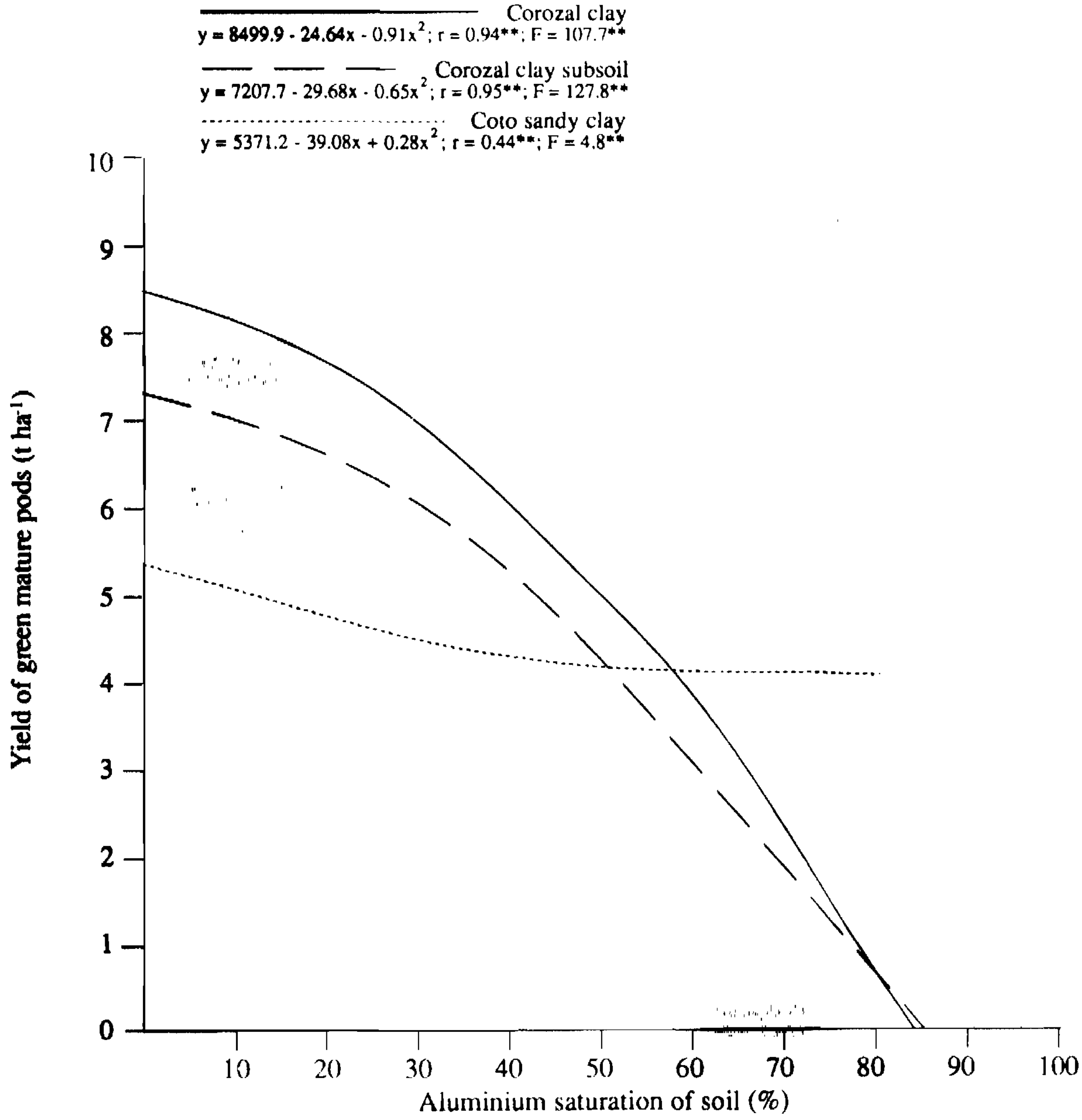


Figure 9.2. Relationship between yield of green mature pods of vegetable pigeonpea (t ha^{-1}) and aluminium saturation (%) of two Ultisols and one Oxisol from Puerto Rico.

Source: Abruna *et al.*, 1984

deficiency (Dalal and Quilt, 1977; Edwards, 1981; Sahu and Pal, 1987). Although Edwards (1981) attributed acid soil effects on pigeonpea primarily to Ca deficiency, aluminium (Al) toxicity is usually implicated in growth reduction on acid soils (Abruna *et al.*, 1984). Figure 9.2 illustrates the yield response of pigeonpea to Al saturation on three acid soils amended with lime. This data indicates that the critical Al-saturation level for pigeonpea, where yield is reduced to 90% of maximum, is about 20%. In solution culture, 20 ppm Al was determined as a critical level for pigeonpea, with distorted root growth occurring at higher concentrations (Narayanan and Syamala, in press). In this study differences among pigeonpea genotypes in their response to Al were also recorded.

PLANT REQUIREMENTS

Symptoms

Symptoms provide an initial indication of any imbalance of mineral elements in plant tissue. The nutrient deficiency symptoms of pigeonpea are generally similar to those observed in other tropical legumes (Table 9.1) but they have not been characterized in such detail as for other legumes e.g., mung bean (Smith *et al.*, 1983). Pigeonpea seedlings can be particularly sensitive to excessive levels of mineral elements in their tissues. This sensitivity may result when pigeonpea is either grown on saline soils, or excessive fertilizer applications are placed near seedlings. Salinity damage is characterized by sudden necrosis of the entire lamina and rapid plant death (Subbarao, 1988). At advanced growth stages, salinity symptoms can also appear as the soil dries out and salt concentrations in the soil solution increase. There is necrosis of the leaf margins, primarily of old leaves but also of intermediately placed leaves (ICRISAT, unpublished observations).

It needs to be emphasized that symptoms can only provide an approximate guide to nutrient imbalances. Symptoms of nutrient imbalance can be similar to those of other biotic and abiotic stresses and their expression is controlled by various environmental factors. Further, they often only appear when plant growth has already been severely impaired by the particular deficiency or toxicity (Robson and Snowball, 1986).

Critical Concentrations in Plant Tissue

Internal nutrient requirements are conceptually best defined in terms of critical nutrient concentrations or ranges (Smith, 1986), below which growth is limited by an inadequate supply of a particular nutrient. The limited data available for pigeonpea are summarized in Table 9.2. However, as for symptoms, considerable care is required in interpreting these values as they are influenced by the plant part sampled, plant growth stage, interactions with other nutrients, growth environment, and genotype (Bates, 1971; Smith, 1986). Scaife (1988) goes further to suggest that critical nutrient concentrations are only interpretable and useful when internal nutrient concentrations are related to crop growth dynamics. There appear to be no marked variations of critical levels reported for pigeonpea from those established for other tropical legumes (Table 9.2; Reuter, 1986; Smith, 1986).

Measurement of compounds resulting from disturbed metabolism due to nutrient imbalance may also be used to detect nutrient imbalance. One such case is the accumulation of putrescine in leaves when K is deficient, and this has been found to apply in pigeonpea (Madhava Rao and Venkateswara Rao, 1984).

Table 9.1. Description of nutrient deficiency symptoms recorded on pigeonpea.

Nutrient element	Deficiency symptoms	Reference[1]
N	Classical yellowing of older leaves, as for most legumes	1
P	No distinct foliar symptoms, plants stunted, foliage remains dark green, old leaves eventually shed	1,2
K	Yellowing, then necrosis of outer margins of old leaves	2
Ca	Stem weakness leading to prostrate growth habit. Random light-green patches in marginal interveinal regions of terminal leaves. These patches eventually become necrotic and leaves abscise	2,3,4
S	Even yellowing across lamina of mainly youngest leaves, but older leaves also eventually become yellow	1
Mg	Beginning in oldest leaves, in-rolling of leaf margins, interveinal regions lighter green, mesophyll of interveinal regions becomes bronzed, eventual necrosis	2
Zn	Yellowish-white interveinal chlorosis on youngest leaves, leaflets narrowed, then chlorotic areas become reddish-brown and leaves abscise. Plants stunted with shortened internodes	3,4,5
Fe	Distinct interveinal chlorosis of youngest leaves	2,4
Mn	Leaf spotting and shedding of younger leaves	4
B	Deformed youngest leaves resulting in dieback, rosetting, and multiple branching	3,4

1. Reference	Growth medium
1. ICRISAT, unpublished	Potted soil
2. Nichols, 1964	Sand culture
3. Reddy *et al.*, 1978	Potted soil
4. D.G. Edwards, University of Queensland, unpublished	Solution culture
5. Shukla and Raj, 1980	Potted soil

Uptake Pattern

Uptake patterns of P in medium-duration pigeonpea in the peninsular Indian environment have been established by Sheldrake and Narayanan (1979). Essentially, total accumulation increases throughout the growing period but, during the reproductive phase, there is a decline in leaf and stem P fractions (Figure 9.3), implying retranslocation to reproductive structures. As for other plants, P concentrations in all plant tissues decrease with plant age (Table 9.2; Sheldrake and Narayanan, 1979). Similar patterns are also observed for K uptake in intercropped and sole-cropped medium-duration pigeonpea in this environment (Natarajan and Willey, 1980).

AVAILABILITY IN SOIL

Uptake of a mineral nutrient into plant roots ultimately depends on the concentration of the ionic species adjacent to the root surface. In flowing nutrient solution culture, where it is possible to

Table 9.2. Concentrations of nutrients in plant tissue of pigeonpea determined as being either inadequate, critical for deficiency, or adequate for plant growth.

	Nutrient concentration						
Nutrient	Inadequate	Critical	Adequate	Plant part	Growth stage	Medium	Reference[1]
P (%)	0.08		0.24	Laminae	91 DAS[2]	Sand	1
			0.35-0.38	Laminae	30 DAS	Field	2
			0.30-0.33	Laminae	60 DAS	Field	2
			0.19-0.28	Laminae	90-100 DAS	Field	2
			0.15-0.20	Laminae	120-130 DAS	Field	2
			0.15-0.18	Laminae	160-165 DAS	Field	2
	<0.07	0.10	0.12	YMB[3]	Early fl[4]	Solution	3
		0.22		YMB	96 DAS	Field	4
		0.11		All leaves	92 DAS	Potted soil	5
		0.08		All leaves	132 DAS	Potted soil	5
K (%)	0.81		1.72	Laminae	91 DAS	Sand	1
		0.78		YMB	Early fl	Solution	3
Ca (%)	0.13		1.32	Laminae	91 DAS	Sand	1
		0.84		YMB	Early fl	Solution	3
Mg (%)	0.26		>0.26	Laminae	91 DAS	Sand	1
		0.17		YMB	Early fl	Solution	3
S (%)			0.16-0.32	YMB	Early fl	Solution	3
Zn (mg kg^{-1})		20-30		Whole shoot	42 DAS	Potted soil	6
			7-48	YMB	Early fl	Solution	7
Cu (mg kg^{-1})	1-10	10	10-12	YMB	Early fl	Solution	7
Mn (mg kg^{-1})	<17	18	19-25	YMB	Early fl	Solution	7
			78-300	Whole shoot	Vegetative	Flowing solution	8
Fe (mg kg^{-1})	50-69		126	Laminae	91 DAS	Sand	1
	<166	151	151-191	YMB	Early fl	Solution	7
B (mg kg^{-1})	<10	10	10-52	YMB	Early fl	Solution	7
Mo (kg ha^{-1})			0.23-0.39	YMB	Early fl	Solution	7

1. Reference: Source for all references except 4 and 5 is Reuter, 1986.
   1. Nichols, 1965
   2. Sheldrake and Narayanan, 1979
   3. P.A. Rosbrook and D.G. Edwards, University of Queensland, unpublished data from Reuter, 1986
   4. Rhodes, 1987
   5. Ogata *et al.*, 1988
   6. Shukla and Raj, 1980
   7. A.F. Burton and D.G. Edwards, University of Queensland, unpublished data from Reuter, 1986
   8. Edwards and Asher, 1982
2. DAS = days after sowing
3. YMB = youngest mature leaf blade
4. Early fl = early flowering

maintain nutrient concentrations at defined low levels of the order found in soil solutions, Fist *et al.* (1987) found that maximum growth of the medium-duration pigeonpea cultivar Royes required an external P concentration maintained at 1.0 μM. Comparative critical external P concentrations (in μM) were 0.8 for cowpea and soybean, 2.0 for mung bean, and 3.0 for guar. Actual nutrient concentrations adjacent to the root surface in soils are, of course, very difficult to estimate as they vary spatially and temporally, and fluctuate according to exchange equilibria between soil colloids and the soil solution, and rate of uptake by roots. However, soil chemical tests have been developed that attempt to estimate immediately available and potentially available nutrients for plant uptake. For many crops, although many soil analyses may have been done for the purpose of predicting nutrient sufficiency, there is often inadequate field calibration relating plant growth or yield to soil test value. Thus reliable estimates of soil test critical values are rare.

In India, where responses of pigeonpea to P are frequent but of low magnitude, there seem to be no soil P test critical levels developed specifically for pigeonpea (Tandon, 1987). There are such critical levels available for many other crops in India, developed in both pot and field studies (Tandon, 1987), but these should not be considered applicable for pigeonpea as critical values differ between crops and agroecological situations. To illustrate this, in a study using ^{32}P-labelled superphosphate, soybean was found to be more efficient than pigeonpea, cowpea, or green gram in utilizing native soil P in comparison with fertilizer P (Dahama *et al.*, 1984). Based on ICRISAT experience, responses of pigeonpea to P fertilizer would not be expected in soils with more than 5 mg kg^{-1} P extractable by Olsen's bicarbonate extraction; although lower values would not necessarily predict a response.

Rhodes (1987) calibrated a soil P test to response of field-grown pigeonpea in an acid (pH 4.8) soil in Sierra Leone. He found the critical level to be an equilibrium soil concentration of 0.26 μM P.

As few field responses of pigeonpea to nutrients other than P (or N - see Chapter 10) have been recorded, soil test calibrations for other nutrients are also rare. Using Cate and Nelson (1971) separations of soils responsive or non-responsive to Zn, for pigeonpea grown in potted soil, Gupta *et al.* (1984) measured a critical DPTA-extractable Zn level of 0.48 mg kg^{-1}. However, it should be emphasized that such values need to be verified against field response data before they can be used with any reliability to predict the response of pigeonpea to Zn in the field.

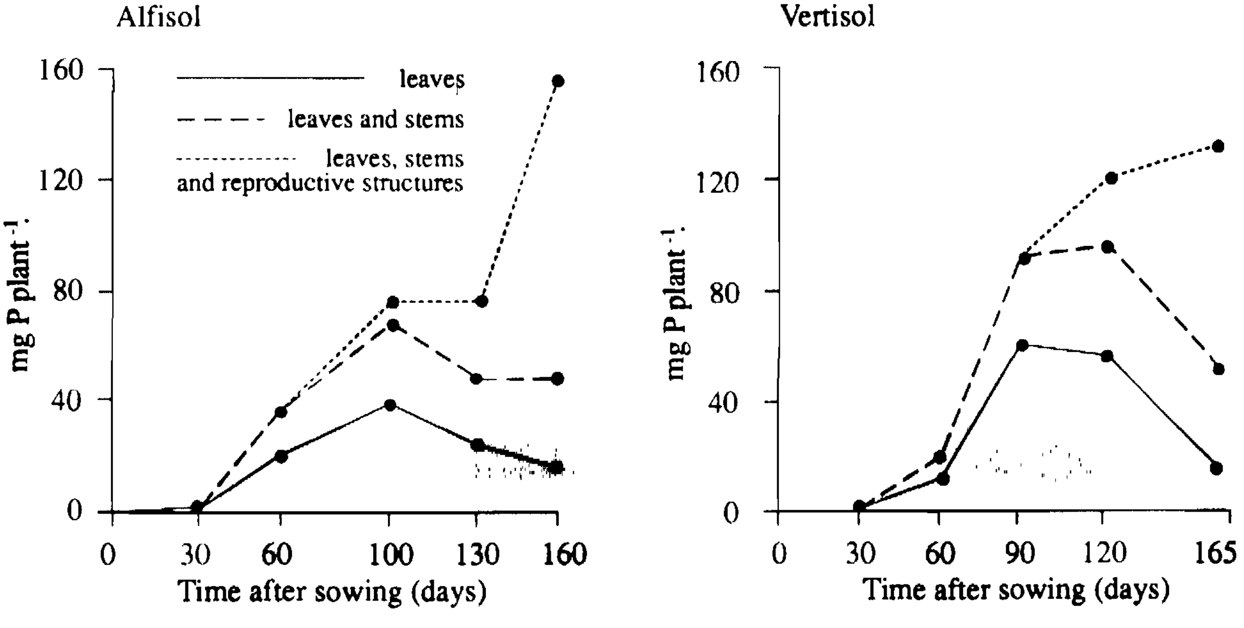


Figure 9.3. Uptake pattern of phosphorous (mg P plant^{-1}) in organs of the medium-duration pigeonpea cultivar ICP 1 grown on an Alfisol and a Vertisol, ICRISAT Center, 1976.
Source: Sheldrake and Narayanan, 1979.

NUTRIENT UPTAKE MECHANISMS

Root Distribution

A first consideration of nutrient availability to field-grown plants is the distribution of roots in the soil profile in relation to the nutrients in question. Chauhan (in press) has summarized current knowledge on pigeonpea root systems. Again, most studies have been done on longer-duration, traditional pigeonpea genotypes and they have a typical perennial legume rooting habit; namely, strong tap root development, deep-rooting ability, strong primary lateral root development, and most roots formed in the top 60 cm of the soil profile (Sheldrake and Narayanan, 1979). Root development can continue well into the reproductive phase, provided soil moisture is adequate (Chauhan, in press).

Although distribution of total root mass in deep-rooting crops like pigeonpea is difficult to estimate, it is even more difficult to estimate distribution of the roots that are active in nutrient uptake. Nye and Foster (1961) attempted this for long-duration pigeonpea grown in Ghana by injecting ^{32}P into different parts of the rooting zone and measuring resultant radioactivity in the shoots. The relative values are shown in Table 9.3 and they illustrate changes in the effective rooting pattern over time. It is noteworthy that most uptake occurs in the 0-25 cm zone. Pigeonpea differed from millet and maize, examined in the same study, by feeding closer to its base (stem).

Table 9.3. Relative uptake (%) of soil phosphorous from different compartments of the root zone of pigeonpea.

		Distance from base (cm)			
Age of crop (days)	Depth (cm)	0-20	20-40	40-60	0-60
20	0 -12.5 (22)[1]	75	8	-	83
	12.5-25 (13)	15	-	-	15
	25 -37.5 (8)	2	-	-	2
	37.5-50 (6)	-	-	-	-
	0 -50	92	8	-	100
34	0 -12.5	59	3	-	62
	12.5-25	34	2	-	36
	25 -37.5	2	-	-	2
	37.5-50	-	-	-	-
	0 -50	95	5	-	100
55	0 -12.5	34	10	4	48
	12.5-25	27	11	10	48
	25 -37.5	2	1	1	4
	37.5-50	-	-	-	-
	0 -50	63	22	15	100
80	0 -12.5	19	18	12	49
	12.5-25	13	10	17	40
	25 -37.5	2	2	5	9
	37.5-50	-	1	1	2
	0 -50	34	31	35	100

1. Numbers in parentheses indicate ^{32}P-exchangeable P (mg kg^{-1} soil).

Source: Nye and Foster, 1961.

The predominance of surface uptake in this study, despite the established deep-rooting ability of pigeonpea, may have been caused by the much greater P availability at 0-25 cm than at deeper soil layers.

Preliminary observations with short-duration pigeonpeas suggest that their root systems are less extensive than longer-duration genotypes (ICRISAT, unpublished), perhaps because of an earlier cessation of root growth due to the earlier maturity. This appeared to be the case in a comparison of the root systems of the extra-short-duration cultivar Prabhat with those of the longer-duration Pusa Ageti and P 4785, where the latter cultivars had better root development and more profuse nodulation (Ahlawat and Saraf, 1982). This apparently restricted rooting ability of short-duration pigeonpea may limit its potential to access soil nutrients and water. As this type of pigeonpea is now being more widely cultivated (Chapters 12 and 15) there is a pressing need for more definitive studies of its root development and activity.

Mycorrhizal Associations

For most higher plant species examined, mycorrhizae have been shown to be beneficial in enhancing plant nutrient uptake, primarily by the mycorrhizal hyphae acting as an extension of the nutrient absorptive area (Mosse, 1981). Pigeonpea is no exception, and is indeed strongly mycorrhizal-dependent in low-nutrient media (Figure 9.4). Responses of pigeonpea to vesicular arbuscular mycorrhizae (VAM) have also been obtained in nonsterilized soil, against a background of native mycorrhizal infection (Manjunath and Bagyaraj, 1984; J.V.D.K. Kumar Rao, ICRISAT, personal communication). Differences among VAM species in their ability to stimulate pigeonpea growth in nonsterilized soil of low nutrient status have also been found (J.V.D.K. Kumar Rao, ICRISAT, personal communication). However, prospects for large-scale field inoculation of pigeonpea to improve nutrient or water acquisition characteristics appear bleak, primarily because of difficulties of mass culturing inoculum, as VAM cannot yet be axenically cultured (Mosse, 1981; Hepper, 1987).

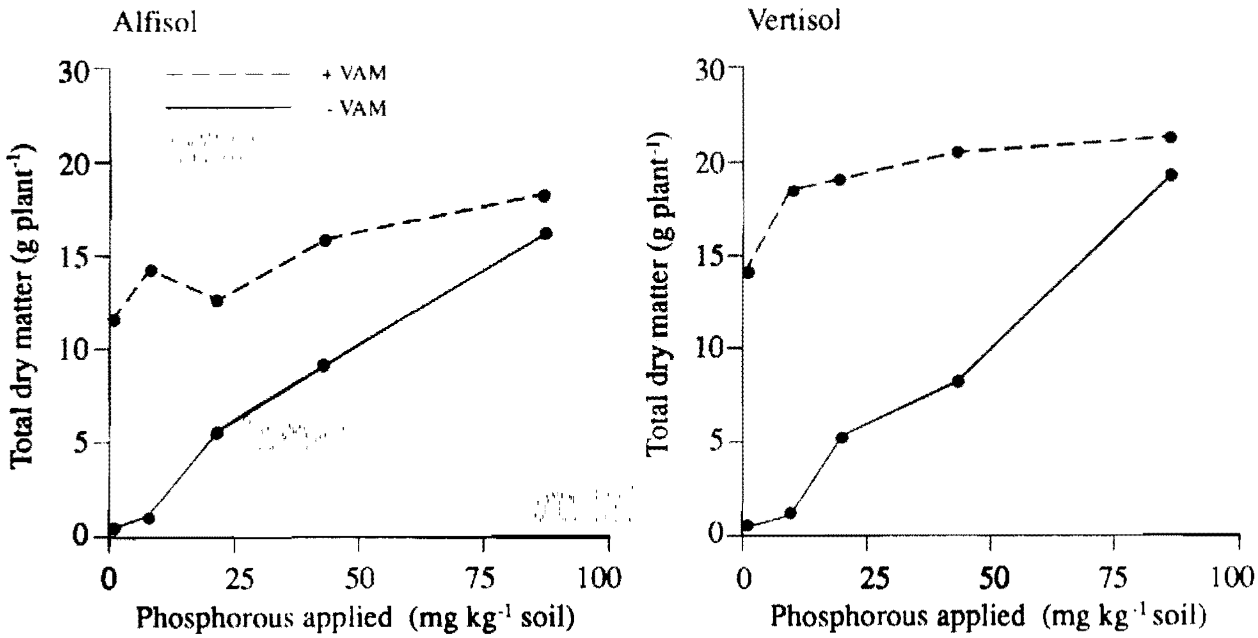


Figure 9.4. The effect of VAM and applied phosphorous (mg kg^{-1} soil), on growth expressed as total dry matter (g plant^{-1}) of pigeonpea in a sterilized Alfisol and a Vertisol in pots, ICRISAT Center, 1987.
Source: ICRISAT, 1988.

Absorption Kinetics

The process of active nutrient absorption into roots may also be a rate-limiting step to nutrient accretion by the plant. Itoh (1987) found that kinetic parameters, such as maximum uptake rate (Imax), Michaelis constant (Km) and relative uptake parameter (Imax/Km), for P uptake into roots of pigeonpea seedlings were of the same order as found in such other crop species as soybean, chickpea, and maize, even though responsiveness to P fertilizer in the field may differ markedly for these crops. Fist *et al.* (1987) similarly showed that the potential of roots to absorb P, as measured in kinetic studies at non-limiting external concentrations, was similar between pigeonpea (Royes), cowpea, mung bean, soybean, and guar. However, they suggested that pigeonpea had a higher Km than the other legumes.

Root Exudates

Pigeonpea is better able to utilize P bound to the iron (Fe) fraction of soil (Fe-P) than chickpea, sorghum, soybean, or maize (N. Ae, ICRISAT, personal communication). This may explain why it responds less to P than these crops when grown on an Alfisol, where Fe-P is high, than on a Vertisol, which is dominated by calcium-bound P (Ca-P) (Figure 9.1). Examination of exudates from pigeonpea roots has revealed fractions, not present in other crop species, that are able to solubilize P from Fe-P (N. Ae, ICRISAT, personal communication). Thus pigeonpea appears to have a particular adaptation allowing it to better utilize P in soils high in Fe-P. The effect of specific root exudates on availability of other nutrients is yet to be examined.

Pigeonpea roots also exude organic acids, primarily citric acid, which act to solubilize P from Ca-P in the rhizosphere of alkaline soils, such as Vertisols (N. Ae, ICRISAT, personal communication). This acidification of the rhizosphere (Ae *et al.*, 1988) may also increase the availability of such nutrients as Zn and Fe, which are likely to be deficient in alkaline soils.

Interactions with Other Limiting Factors

Nutrient uptake processes interact strongly with various environmental factors and plant growth processes and this needs to be recognized when interpreting plant nutrient status. When soil water is limiting, plants are less responsive to fertilizer because of the reduced plant demand for nutrients, due to water deficit limiting plant growth, and reduced nutrient availability because of drying of soil zones from whence the nutrient could be absorbed. For example, pigeonpea is less responsive to P under limiting soil moisture conditions than when adequate water is available (Bhowmik *et al.*, 1983). Conversely, P application may enhance water use efficiency, as is found in many crops in India (Tandon, 1987). Pigeonpea fertilized with P could extract twice as much water from 60-90 cm soil depth than an unfertilized crop (Singh *et al.*, 1983b), a consequence of P stimulating root production and extension. The P × water interaction is given only as an example since any environmental factor reducing plant growth will decrease nutrient demand, and hence decrease responsiveness to nutrient application if nutrient supply is marginal.

Nutrients also interact among themselves. The P × Zn interaction is a common one among crop plants, particularly on alkaline soils prone to Zn deficiency. In pigeonpea also, P application has been shown to depress Zn uptake (Gupta *et al.*, 1985).

The functioning of nodules in symbiotic nitrogen fixation is also markedly influenced by nutrient supply, particularly of those nutrients specifically required for nitrogen fixation such as P and Mo. The beneficial effects of P (Ogata *et al.*, 1988) and Co (Raj, 1987) on pigeonpea growth can be interpreted as a primary effect of these elements in improving nitrogen fixation.

DIAGNOSIS OF NUTRITIONAL IMBALANCES

Multilocational fertilizer experiments conducted over many seasons in the major pigeonpeagrowing areas, primarily in India, have given some indications of the extent of nutrient limitation in specific regions, and provided a basis for fertilizer recommendations. Nevertheless, for a given site, even on any research station, considerable uncertainty remains as to pigeonpea nutrient status, and continued quantification of this seems warranted. This particularly applies to areas where cropping systems involving pigeonpea are changing markedly, such as those where sole crops of short-duration pigeonpea are replacing traditional long-duration pigeonpea intercropping systems. There are several possible methods of identifying nutrient imbalances that are applicable to pigeonpea, but they have differing degrees of precision in the information that they can offer.

To diagnose the nutritional status of pigeonpea in order to prescribe appropriate corrective measures, whether for the introduction of the crop into new areas, or its re-evaluation in traditional pigeonpea-growing areas, a stepwise use and combined interpretation of the various possible methods is recommended. These are described as follows, in approximately increasing order of precision of the information that they can provide.

Soil and Geological Maps

Examination of these gives a first approximation as to possible nutrient imbalances for a given region; for example, they would indicate the likelihood or otherwise of acid soil problems.

Symptoms

As discussed earlier, foliar symptoms can give an indication of nutrient imbalances, but their limitations in terms of interaction of symptom expression with other factors, and their appearance only after considerable plant growth inhibition must be borne in mind. Of course, it is best if the symptoms are observed on pigeonpea itself but, in the absence of this crop, symptoms on other plants can also provide a clue to potential problems for pigeonpea. Some symptoms, such as N or K deficiency, are less ambiguous to recognize than others, such as Zn deficiency. Nevertheless, ameliorative recommendations should not be based on manifestation of symptoms alone, but on plant growth response in field experiments. However, symptoms can provide guidelines to designing plant growth tests by suggesting type and severity of nutrient imbalances.

Soil Analysis

The dearth of appropriate calibration of soil chemical tests for pigeonpea, and determination of critical levels, limits their usefulness in diagnosing nutrient imbalances of this crop. For pigeonpea as for other crops, critical levels are likely to vary according to soil type, cropping system, and sampling and analysis procedures. In the case of P, about which there is considerable information on critical soil P values for crops other than pigeonpea, only broad generalizations can be made for pigeonpea; viz. an Olsen-P value above 5 mg kg^{-1} would indicate that a response is highly unlikely, 1-5 mg kg^{-1} P would be a zone of uncertainty, and below 1 mg kg^{-1} P responses would be probable. For S, as the available fraction normally increases with soil depth, it would be necessary to conduct profile analyses and give weightings according to root distribution (Probert and Jones, 1977). Among secondary and trace elements, critical soil test values only seem to have been determined for pigeonpea in the case of Zn (Gupta *et al.*, 1984).

Soil chemical tests are most useful in identifying soil chemical toxicities, rather than nutrient deficiencies; the critical values for salinity and acidity have already been discussed.

Development and calibration of soil tests appropriate for pigeonpea would be difficult due to its deeper rooting habit than other crops, necessitating profile sampling, and the ability of its root exudates to modify the rhizosphere, rendering standard measures of soil availability suspect. Perhaps this explains why few such attempts have been made for traditional pigeonpea. Prospects may be better for short-duration pigeonpea because of its shallower rooting habit, and of the need for more precise soil testing capability for this crop because of its potentially greater nutrient demands and thus fertilizer requirements. However, even with appropriate development and calibration of soil tests specifically for pigeonpea, fertilizer recommendations should not be based on these alone, but on field fertilizer rate trials in which yield response functions are quantified.

Plant Analysis

Although we have some knowledge of critical nutrient concentrations in pigeonpea tissue (Table 9.2), their interpretation is complicated by the many factors referred to earlier in this chapter. Plant analysis is most useful in intensive cropping systems where phenology and growth pattern are reasonably constant between seasons, and thus standard times and plant parts can be chosen for sampling for chemical analysis. Traditional pigeonpea with its indeterminate growth habit, long duration, and growth fluctuations that are dependant on soil moisture availability and other environmental factors does not fit these criteria. On the other hand, plant analysis may be more feasible for monitoring the nutrient status of short-duration, determinate sole crops of pigeonpea grown under assured soil moisture regimes. Nevertheless, it is not likely to be sufficiently precise to allow formulation of optimum fertilizer practises.

Plant analysis may be used as the next step in interpreting the apparently ambiguous symptoms of nutrient disorder. For example, chlorosis of pigeonpea leaves, particularly younger ones, often appears on pigeonpea growing on alkaline calcareous soils under conditions of high soil moisture. Growth reductions are usually associated with this chlorosis. Chemical analysis has revealed that this is likely to be due to reduced levels of Fe^{2+} in leaves under these conditions, rather than to disorders associated with Zn, manganese (Mn), or copper (Cu) (Gupta *et al.*, 1986). However, plant growth tests will be required to confirm whether this common problem of pigeonpea is indeed primarily attributable to disturbed Fe nutrition.

As for soil tests, plant analyses are more useful in identifying toxicities rather than deficiencies. For example, Na levels above 0.5% or Cl levels above 3.5% in pigeonpea leaves would indicate growth reduction due to salinity (Subbarao, 1988).

Pot Tests

Pot trials conducted in a greenhouse can provide information as to the potential of a particular soil to supply all of the nutrients essential for growth of a particular plant species (Andrew and Fergus, 1976). Plants are grown in as non-limiting an environment as possible so as to maximize chances of expression of any nutrient imbalance. Omission or factorial designs can be used, testing the effect of presence or absence of each element that could possibly be limiting. Actual treatments and treatment levels are best decided on the basis of preliminary soil tests. Omission designs (adding all possible nutrients except one) are simplest to interpret and demonstrate, but they cannot detect nutrient interactions, and give little information if there are soil toxicities. Factorial designs overcome these limitations.

In one-half replicated factorial pot tests to determine potential nutrient limitations to short-

Table 9.4. Effect of phosphorus (P) and sulphur (S) application on shoot dry matter (g plant^{-1}) of pigeonpea genotype ICPL 87 in nutrient screening trials in pots containing soils from ICRISAT Center (Vertisol, Alfisol) and Gwalior (Inceptisol), ICRISAT Center greenhouses, 1985 and 1986.

Treatment		Vertisol 1985		Vertisol 1986		Alfisol 1985		Inceptisol 1986	
S	P	–P	+P	–P	+P	–P	+P	–P	+P
–S		0.19	0.77	0.32	1.05	4.23	5.32	4.00	4.86
+S		0.17	1.67	0.30	2.08	4.42	5.47	4.84	5.32
SE		±0.092		±0.055		±0.246		±0.087	
Response[1]		P^{***},S^{***},PxS**		P^{***},S^{***},PxS***		P^{***}		P^{***},S^{***}	

1. The significance of responses to application of phosphorus (P), sulphur (S) and their interaction (PxS), are indicated as ** for P<0.01, and *** for $P<0.001$ probability levels.

Source: ICRISAT, 1987.

duration pigeonpea genotype ICPL 87 in recently unfertilized soils from ICRISAT Center, Gwalior, and Hisar, presence and absence of P, K, S, lime ($CaCO_3$), Zn, Cu, boron (B), Fe, Mo, and Co (several of the elements least likely to be deficient were combined into one treatment) were tested. The plants were inoculated with *Rhizobium* so as to ensure their dependence on symbiotic nitrogen fixation. Only P and S deficiencies could be detected in the soils from ICRISAT Center and Gwalior in Madhya Pradesh and there were strong P × S interactions (Table 9.4). No nutrient limitation could be detected in the Entisol from Hisar.

It should be noted that, for pigeonpea, only the response of the vegetative growth phase can be measured in such pot tests because reproductive growth under greenhouse conditions results in inferior pod development, as compared with field conditions, for reasons not yet fully understood. Thus, any nutrient disorders that only express themselves in the reproductive phase would not be detected. It should also be realized that a response found in pot tests may not necessarily express itself in the field because of the interaction of other growth-limiting factors, and the greater volume of soil for roots to explore and exploit nutrients in the field. This is illustrated by the previously mentioned ICRISAT experience of finding a large S response of pigeonpea in pots but not in the field.

Field Trials

Using as much information as is available from the above-mentioned diagnostic methods, field fertilizer trials can then be efficiently designed. Efficiency of design in terms of choosing appropriate treatments and treatment levels is important as field trials are costly in terms of time and resources, and difficult to run. It is necessary to establish plant growth and yield response functions under field conditions if biological and economic optimum rates of fertilizer or amendment application are to be precisely known. It is necessary to conduct such fertilizer rate trials over several seasons and at different sites before an accurate picture of fertilizer requirement is established. This is because of the various growth and yield limitations interacting with nutrient response. The soil moisture × nutrient interaction is particularly important for pigeonpea as the crop normally grows in drought-prone environments.

Where some knowledge exists of the nutrient status and fertilizer requirements of particular fields, small-plot field trials can be effectively used to monitor nutrient status; for example, to check whether fertilizer recommendations are indeed correct. At ICRISAT Center, such trials have been used to demonstrate that pigeonpea does not require P fertilizer in fields where P is regularly applied to other crops in the rotation. Indeed, it is suggested that such small-plot trials (e.g., plot size of 8 rows 4-m long for short-duration pigeonpea sole crops) should supplement soil analyses in monitoring the status of nutrients likely to be in marginal supply.

ALLEVIATION OF IMBALANCES

Genetic Enhancement

Genetic enhancement of crop tolerance to imbalanced nutrient supply offers better prospects for overcoming soil chemical toxicities than nutrient deficiencies. This is mainly because the use of fertilizers to correct soil nutrient deficiencies is generally feasible and cost-effective, but correcting soil chemical toxicities by management is often difficult and costly. A first consideration for genetic enhancement within a crop species is the demonstrated existence of substantial genotypic differences in response, such that achievement of a satisfactory level of tolerance in the desired genetic background appears feasible. This criterion seems to be satisfied in the case of salinity response of pigeonpea, where related wild species *Cajanus platycarpus* and *C. albicans* have substantial levels of tolerance (Subbarao, 1988). It is yet to be assessed whether the genotypic differences in Al tolerance reported for pigeonpea (Cowie et al., 1987; Narayanan and Syamala, in press), are large enough to warrant genetic enhancement of this trait in pigeonpea.

Although the breeding of crop species to better tolerate sub-optimal nutrient supply is advocated (e.g., Gerloff and Gabelman, 1983), at this stage this only appears to be worth considering for P for pigeonpea as this is by far the most frequently occurring mineral nutrient deficiency. Manjhi *et al.* (1973) have demonstrated genotypic differences in P response between pigeonpea genotypes: variety Sarada appears to reach a yield plateau at lower P application rates than T 21 or AS 10. Additional studies will be required to; examine the extent of genotypic difference in P response in pigeonpea, understand the physiological basis, and assess the feasibility of genetic enhancement of P use efficiency. Shukla and Raj (1980) and Mehrotra *et al.* (1983) have also detected differences among pigeonpea genotypes in response to Zn.

Appropriate Fertilizers and Amendments

In India, diammonium phosphate (DAP) is the most commonly used form of P fertilizer for pigeonpea (Tandon, 1987) in the rare instances that any fertilizer is indeed used for this crop. At the normally recommended rate for pulses of 100 kg ha^{-1}, it supplies about 18 kg ha^{-1} each of P and N which is in the range most commonly determined as optimum for pigeonpea for each of these nutrients. The next most commonly available P fertilizer in India for use with pigeonpea would be single superphosphate (about 7% P). This has the advantage of containing S and may prevent potential, but transient and difficult to detect, S deficiencies. Rock phosphate can also supply P to pigeonpea and would be a feasible low-cost source of P for pigeonpea on acid soils, as it is for other tropical legumes (Kerridge, 1978).

Where S deficiency needs to be corrected either single superphosphate, calcium sulphate (gypsum), or elemental sulphur are the most commonly available fertilizers. For pigeonpea, if it responds to S similarly to other tropical legumes (Andrew, 1977), rates of 10-20 kg ha^{-1} S should suffice. Gypsum and elemental sulphur can also lower soil pH in alkaline soils, thus correcting nutrient imbalances associated with high pH.

When use of K fertilizer is considered necessary, care must be taken in application of the most commonly used K fertilizer, muriate of potash (KCl), as pigeonpea seedlings are prone to Cl toxicity if this fertilizer is placed too close to the seed row. Zinc deficiency is usually corrected with zinc sulphate application at rates of 4-8 kg ha^{-1} Zn (Tandon, 1989). Use of compound trace element fertilizers is not recommended for pigeonpea unless there is evidence that each of the component nutrient elements are indeed required. For trace elements required in small amounts, such as Co, seed application can be effective (Raj, 1987).

To improve pigeonpea growth on acid soils, use can be made of lime (calcium carbonate), on the faster-reacting quick (calcium oxide) or slaked (calcium hydroxide) lime. The amounts required to substantially improve growth may be of the order of 1-10 t ha^{-1}, depending on the degree and nature of the acidity (e.g., Al saturation).

Timing and Placement

Fertilizer is usually applied to pigeonpea at sowing. However, in the case of ratoon-harvested pigeonpea there is preliminary evidence that, although there may be no response of the first-flush grain yield to P application, the second flush may respond by the order of 45% e.g., ICPL 87 grown on an Alfisol in 1986 (ICRISAT, unpublished). The additional nutrient requirements of ratooning and other perennial pigeonpea systems need closer examination. However, any top-dressing of fertilizer, additional to an application at sowing, would require that the top soil be moist in order for the applied fertilizer to become available for uptake by roots. Another alternative for nutrient addition to established crops is use of foliar sprays. It is sometimes reported that application of DAP as a foliar spray at about the time of flowering improves pigeonpea grain yield, but the causal factor, N or P, is not differentiated. Foliar application of K can be effective (Ravindranath *et al.*, 1985).

For predominantly rainfed crops such as pigeonpea, lack of responsiveness to fertilizers can be at least partly attributed to drying of the surface soil, to which fertilizer is normally applied, and the resulting reduced availability of added nutrients during dry periods. In this case, deep placement of fertilizer should enhance its availability. This has been demonstrated for short-duration pigeonpea T 21 grown in Punjab, India (Pannu and Sawhney, 1975). Placement of P fertilizer at a depth of 10 or 15 cm increased yield over broadcast application by 35%. Arihara and Ae (1988) similarly found that placement of P at 15 cm was superior to broadcasting and mixing in the surface soil for rainfed short-duration genotype ICPL 87 in central India. However, for an irrigated crop they found that mixing P in the top 15 cm of soil was superior to placement in terms of growth, yield, and P uptake. In this case there was more functional root proliferation in the top 15 cm of soil than occurred under rainfed conditions. Thus it appears that the most appropriate mode of fertilizer placement for P will be determined by the likely soil moisture status in the soil profile during crop growth.

NUTRIENT MANAGEMENT IN PIGEONPEA CROPPING SYSTEMS

Type of Cropping System

In considering the nutrient needs of pigeonpea it is necessary to define the total cropping system in which it is grown, since these systems are widely varied (Chapter 12). The nutrient demand of pigeonpea is determined by its biomass production potential in the system, which in turn is determined by the various biotic and abiotic stresses affecting the crop. Nutrient supply to pigeonpea can be reduced by competition for uptake by companion crops or weeds.

In intercrops, total uptake of nutrients would be reduced in pigeonpea, as compared to sole-crop pigeonpea, primarily due to its reduced growth in the intercrop (e.g., Dalal, 1974; Asokaraja and Ramiah, 1987). Direct competition for nutrients is only indicated when nutrient concentrations are lower in intercropped than sole-crop pigeonpea, as in the case of P in a pigeonpea/sorghum intercrop (Natarajan and Willey, 1980), or where there is a bigger response of intercropped than sole-crop pigeonpea to nutrient application, as in the case of P uptake in a pigeonpea/pearl millet intercrop (Palaniappan *et al.*, 1984).

On the basis of trials conducted by the All India Coordinated Agronomic Research Project (Ahlawat *et al.*, 1986), it seems that the fertilizer requirement of an intercrop would be the sum of the requirements of the individual components when grown as sole crops at similar spacings as in the intercrop. However, care must be taken in adding N to the cereal component of an intercrop with pigeonpea, as excessive N application will favour vigorous cereal growth at the expense of the initially slow-growing pigeonpea (Narain *et al.*, 1980). Thus split application of N in cereal/pigeonpea cropping systems is highly desirable, with no more than half of the total N being applied at sowing (Ahlawat *et al.*, 1986).

In pigeonpea sole crops, where higher plant densities are used than for intercropped pigeonpea, there would be a higher biomass potential and thus a higher nutrient demand than for pigeonpea grown as an intercrop component. This is illustrated by the data of Table 9.5 where a positive interaction between plant density and P fertilizer rate is apparent. Although Rathi *et al.* (1974) did not find such a positive interaction, they did show that P response was increased as the sowing of pigeonpea at Meerut, Uttar Pradesh, India, was progressively delayed from 10 June to 10 July, even though total yields declined with sowing date. This is contrary to expectations of increased P response with increased biomass production. The possible additional P requirements of ratooned pigeonpea sole crops have been discussed earlier in this chapter.

Table 9.5. Interaction between plant density and rate of phosphorous (P) application on grain yield (t ha^{-1}) of pigeonpea. Mean of three cultivars; Pusa Ageti, P 4785, and Prabhat.

Plant density (plants m^{-2})	P applied (kg ha^{-1}) 0	17	34
5	0.96	1.41	1.41
10	1.05	1.75	1.75
15	0.99	1.72	1.73
LSD	(P = 0.05) = 0.10		

Source: Ahlawat and Saraf, 1981.

Residual Effects

Application of P to pigeonpea often has residual benefits to a following wheat crop (Pannu and Sawhney, 1975; Singh *et al.*, 1983a; Ahuja, 1984; Dahama and Sinha, 1985). This can primarily be attributed to P fertilizer stimulating pigeonpea growth and nitrogen fixation such that more residual fixed N is made available to the subsequent wheat crop. However, data on P uptake by wheat indicate that P applied to the preceding wheat crop is absorbed by wheat (Singh *et al.*, 1983a;

Dahama and Sinha, 1985). Rao and Bhardwaj (1981) found little effect of P application to a previous pigeonpea crop, even though pigeonpea itself responded to P, in stimulating wheat yields; but found that P applied to wheat stimulated subsequent pigeonpea yields. They concluded that, for their particular wheat-pigeonpea rotation, the best strategy was to fertilize each crop with 18 kg ha^{-1} P.

Residual effects of P have also been measured in a rotation of a sorghum/pigeonpea intercrop with castor under rainfed conditions on an Alfisol (Venkateswarlu *et al.*, 1986). The castor could benefit from P applied to the prior sorghum/pigeonpea intercrop to the extent that the P fertilizer recommendation for this system was 22 kg ha^{-1} P applied only to the intercrop. There was also an indication (data not significant) that pigeonpea could benefit from P applied to a prior castor crop.

For pigeonpea cropping systems, more detailed studies are needed to allow calculation of rates of decay (e.g., half-life) in availability of P, and any other limiting nutrients, over time. Possible methodologies for doing this are discussed by Russell (1978). This approach should lead to the optimum allocation of fertilizer to any particular cropping system.

Enhancing Nutrient Availability to Other Crops

Pigeonpea may be considered as an asset in enhancing the overall nutrient use efficiency of the entire cropping system, in addition to its effects of contributing fixed N to the system (Kushwaha and Ali, 1988). Some pigeonpea researchers claim that the deep-rooting ability of pigeonpea allows it to recycle nutrients absorbed at deeper soil layers to the soil surface, thus making them available to subsequent crops on decomposition of pigeonpea residues. However, quantification of this effect is awaited. The ability of pigeonpea root exudates to solubilize iron-bound soil P, which is normally unavailable to other crops (N. Ae, ICRISAT, personal communication), suggests that pigeonpea is adding to the available P pool of the total cropping system. Likewise, the strong mycorrhizal associations with pigeonpea would permit more widespread capture of soil P for recycling in the organic components of the cropping system.

Nutrient Budgets

In order to understand and optimize the long-term nutrient requirements of cropping systems involving pigeonpea, a nutrient budgeting approach of the type discussed by Tandon (1987) for P is desirable. This would require data from long-term experiments measuring gains, losses, and transformations between available and unavailable forms of the nutrient in question. Although P is likely to be the most limiting nutrient (apart from N) in most pigeonpea-based cropping systems, and therefore should be monitored for budgeting purposes, intensive cropping is likely to result in additional nutrient limitations, and their appearance should be carefully watched for. A simplified nutrient budgeting approach for cropping systems involving pigeonpea has been developed by the All India Coordinated Research Project on Soil Test - Crop Response Correlation, utilizing the concept of fertilizer application for targeted yields (Velayutham *et al.*, 1985). Although calculations of fertilizer requirement by this methodology rely on gross assumptions about nutrient availability from fertilizer and soil, it is reported to be useful in framing fertilizer recommendations and in promoting understanding of, and stimulating research in, nutrient cycling in particular cropping systems.

FUTURE

There is a need to develop soil tests, primarily for P, appropriate to the different types of pigeonpea, keeping in view the problems posed by deep rooting, and modification of rhizosphere chemistry by root exudates. Critical levels need to be determined on the basis of field response data. For determinate, short-duration pigeonpea grown as sole crops, it would be worthwhile to examine the feasibility of tissue testing as a diagnostic technique for detecting mineral nutrient deficiencies.

The finding of substantial sources of salinity tolerance in wild species related to pigeonpea suggests that it could be worthwhile to attempt genetic enhancement of salinity tolerance in cultivated pigeonpea. As it is possible that pigeonpea cultivation will be extended to areas of the tropics with acid soil problems, further studies are needed into the extent of genotypic differences in pigeonpea in response to acid soil problems. Basic studies of pigeonpea root growth in acid soil profiles are also required.

In view of the possible increasing importance of P limitations to pigeonpea growth and yield in more intensive cropping systems, there is now a need to more closely examine genotypic differences in P response, both between and within maturity groups. Traits possibly contributing to P response that deserve particular attention are; rooting characteristics, mycorrhizal associations, root exudates, and the ability to retranslocate and reutilize absorbed P. Such studies would provide a basis for assessing the scope for genetic enhancement of P use efficiency in pigeonpea.

There is a need to systematically monitor nutrient status of pigeonpea in the major cropping systems in which it is grown. This would need to rely heavily on field response data in view of the uncertainties currently associated with soil tests for pigeonpea. In intensive systems involving pigeonpea, particular care should be taken to identify any new nutrient deficiencies that may appear as a result of increased extraction of nutrients by other crops. When pigeonpea is introduced into new areas, it is recommended that the nutrient disorder diagnostic procedure outlined in this chapter be systematically followed, so that undetected disorders do not mask evaluation of the crop's genetic potential. Nutrient budgets or models should be developed for the known limiting nutrients for the major cropping systems involving pigeonpea, so as to rationalize and optimize fertilizer usage. As fertilizer is likely to become a relatively more costly agricultural input in future, determination of biological and economic optimum levels of input should proceed in unison. This requires sound knowledge of nutrient response functions under field conditions.

REFERENCES

Abruna, F., Rivera, E. and Rodgriguez Garcia, J.A. (1984) Crop response to soil acidity factors in Ultisols and Oxisols in Puerto Rico. X. Pigeonpeas. *Journal of Agriculture of the University of Puerto Rico* 68, 433-443.

Ae, N., Arihara, J. and Ohwaki, Y. (1988) Estimation of available phosphorus in Vertisols in view of root effects on rhizosphere soil. In: *Phosphorus in Indian Vertisols: Summary Proceedings of a Workshop, 23-26 Aug 1988, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, p. 21.

Ahlawat, I.P.S., Ali, M., Pal, M. and Singh, A. (1986) Research needs and directions on pigeonpea based cropping systems. In: Pal, M.(ed), *Proceedings of the National Symposium on Cropping Systems, 3-5 April 1985, Central Soil Salinity Research Institute, Karnal, Haryana*. ICAR and Indian Society of Agronomy, New Delhi, India, pp. 183-209.

Ahlawat, I.P.S. and Saraf, C.S. (1981) Response of pigeonpea (*Cajanus cajan* (L.) Millsp.) to plant density and phosphorus fertilizer under dryland conditions. *Journal of Agricultural Science, Cambridge* 97, 119-124.

Ahlawat, I.P.S. and Saraf, C.S. (1982) Rooting and nodulation pattern in pigeonpea under differing plant densities and phosphate fertilization. *Indian Journal of Agronomy* 27, 149-155.

Ahuja, K.N. (1984) II. Economics of pigeonpea-wheat rotation. *Indian Journal of Agronomy* 29, 335-340.

Andrew, C.S. (1977) The effect of sulphur on the growth, sulphur and nitrogen concentrations, and critical sulphur concentrations of some tropical and temperate pasture legumes. *Australian Journal of Agricultural Research* 28, 807-820.

Andrew, C.S. and Fergus, I.F. (1976) Plant nutrition and soil fertility. In: Shaw, N.H. and Bryan, W.W. (eds), *Tropical Pasture Research, Principles and Methods. Bulletin 51, Commonwealth Bureau of Pastures and Field Crops, Hurley.* Commonwealth Agricultural Bureaux, Farnham Royal, England, pp. 101-133.

Arihara, J. and Ae, N. (1988) Response of chickpea, pigeonpea and sorghum to method of phosphorus application in a Vertisol. In: *Phosphorus in Indian Vertisols: Summary Proceedings of a Workshop, 23-26 Aug 1988, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 22-23.

Ariyanayagam, R.P. and Griffith, S.M. (1987) Soil and climatic environment in the Caribbean region: yield reductions in pigeonpea due to drought, salinity, acidity, and alkalinity. In: *Adaptation of Chickpea and Pigeonpea to Abiotic Stresses. Proceedings of the Consultants' Workshop, 19-21 December 1984, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 149-158.

Asokaraja, N. and Ramiah, S. (1987) Effect of redgram based intercropping system on growth analysis, nutrient uptake and yield of redgram. *Madras Agricultural Journal* 74, 252-254.

Bates, T.E. (1971) Factors affecting critical nutrient concentrations in plants and their evaluation: a review. *Soil Science* 112, 116-130.

Bhowmik, N.N., Ghosh, N. and Chowdhury, P.B. (1983) Effect of irrigation and phosphorus on growth and yield of pigeonpea (*Cajanus cajan* L.). *Indian Agriculturalist* 27, 343-347.

Cate, R.B. Jr. and Nelson, L.A. (1971) A simple statistical procedure for partitioning soil test correlation data into classes. *Soil Science Society of America Proceedings* 35, 658-660.

Chauhan, Y.S. (1987) Screening for tolerance to salinity and waterlogging: case studies with pigeonpea and chickpea. In: *Adaptation of Chickpea and Pigeonpea to Abiotic Stresses. Proceedings of the Consultants' Workshop, 19-21 December 1984, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 93-103.

Chauhan, Y.S. (in press) The root system of pigeonpea. In: Abdul Salam, M. and Wahid, P.A. (eds), *Rooting Pattern of Tropical Crops.* Tata McGraw Hill Publishing Co., Ltd., New Delhi.

Chong, K., Wynne, J.C., Elkan, G.H. and Schneeweis, T.J. (1987) Effects of soil acidity and aluminium content on *Rhizobium* inoculation, growth and nitrogen fixation of peanuts and other grain legumes. *Tropical Agriculture (Trinidad)* 64, 97-104.

Cowie, A.L., Rayment, G.E. and Chand, V. (1987) Responses of pigeonpea to lime on an Oxisol in Fiji. In: Wallis, E.S. and Byth, D.E. (eds), *Food Legume Improvement for Asian Farming Systems: Proceedings of an International Workshop held in Khon Kaen, Thailand, 1-5 September 1986. ACIAR Proceedings no. 18.* ACIAR, Canberra, pp. 258-259.

Dahama, A.K. and Sinha, M.N. (1985) Residual and cumulative effects of *kharif* grain legumes and P applied to them on succeeding wheat: A study on NP concentration and their uptake. *Indian Journal of Agronomy* 30, 422-428.

Dahama, A.K., Sinha, M.N. and Rai, R.K. (1984) Relative efficiency of grain legumes in utilizing soil phosphorus. *Annals of Agricultural Research* 5, 156-160.

Dalal, R.C. (1974) Effects of intercropping maize with pigeon peas on grain yield and nutrient uptake. *Experimental Agriculture* 10, 219-224.

Dalal, R.C. and Quilt, P. (1977) Effects of N, P, liming, and Mo on nutrition and grain yield of pigeonpea. *Agronomy Journal* 69, 854-857.

Edwards, D.G. (1981) Development of research on pigeonpea nutrition. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 205-211.

Edwards, D.G. and Asher, C.J. (1982) Tolerance of crop and pasture species to manganese toxicity. In: *Plant Nutrition 1982. Proceedings of the Ninth International Colloquium, volume 1.* Warwick University, England, pp. 145-150.

Fist, A.J., Smith, F.W. and Edwards, D.G. (1987) External phosphorus requirements of five tropical grain legumes grown in flowing-solution culture. *Plant and Soil* 99, 75-84.

Gerloff, G.C. and Gabelman, W.H. (1983) Genetic basis of inorganic plant nutrition. In: Lauhchli, A. and Bieleski, R.L. (eds), *Inorganic Plant Nutrition.* Pirson, G.A. and Zimmermann, H.M.H. (eds) *Encyclopedia of Plant Physiology. New Series, volume 15B.* Springer-Verlag, Berlin, pp. 453-480.

Gupta, V.K., Potalia, B.S. and Laura, R.D. (1986) Micronutrient contents of chlorotic and normal plants of pigeonpea (*Cajanus cajan*). *International Journal of Tropical Agriculture* 4, 297-299.

Gupta, V.K., Raj, H. and Singh, B. (1984) Pigeonpea response to Zn and critical Zn levels. *International Pigeonpea Newsletter* 3, 32-33.

Gupta, V.K., Yadav, S.S., Potalia, B.S. and Laura, R.D. (1985) Effect of salinity, zinc and phosphorus on growth, Zn and P nutrition of pigeonpea (*Cajanus cajan*). *International Journal of Tropical Agriculture* 3, 98-104.

Hepper, C.M. (1987) VAM spore germination and hyphal growth *in vitro*–prospects for axenic culture. In: Sylvia, D.M., Hung, L.L. and Graham, J.H. (eds), *Mycorrhizae In The Next Decade–Practical Applications And Research Priorities: Proceedings of the 7th North American Conference on Mycorrhizae, 3-8 May 1987, Gainesville, Florida, USA.* Institute of Food and Agricultural Sciences, University of Florida, Gainesville, USA, pp. 172-174.

Hernandez, B.S. and Focht, D.D. (1985) Effects of phosphorus, calcium, and Hup and Hup' rhizobia on pigeonpea yields in an infertile tropical soil. *Agronomy Journal* 77, 867-871.

ICRISAT (1987) *Annual Report 1986.* Patancheru, A.P., India: ICRISAT, pp. 190-191.

ICRISAT (1988) *Annual Report 1987.* Patancheru, A.P., India: ICRISAT, p. 200.

ICRISAT (1989) *Annual Report 1988.* Patancheru, A.P., India: ICRISAT, p. 97.

Itoh, S. (1987) Characteristics of phosphorus uptake of chickpea in comparison with pigeonpea, soybean, and maize. *Soil Science and Plant Nutrition* 33, 417-422.

Johansen, C., Saxena, N.P., Chauhan, Y.S., Subbarao, G.V., Pundir, R.P.S., Kumar Rao, J.V.D.K. and Jana, M.K. (in press) Genotypic variation in salinity response of chickpea and pigeonpea. In: *Proceedings of the International Congress of Plant Physiology, 15-20 February 1988, New Delhi, India.* Society for Plant Physiology and Biochemistry, New Delhi, India.

Keating, B.A. and Fisher, M.J. (1985) Comparative tolerance of tropical grain legumes to salinity. *Australian Journal of Agricultural Research* 36, 373-383.

Kerridge, P.C. (1978) Fertilization of acid tropical soils in relation to pasture legumes. In: Andrew, C.S. and Kamprath, E.J. (eds), *Mineral Nutrition of Legumes in Tropical and Subtropical Soils.* CSIRO, Melbourne, Australia, pp. 395-415.

Kulkarni, K.R. (1980) Scope for increasing production of pulses through use of fertilizers under rainfed conditions and its economics. *Fertilizer News* 25(8), 3-6.

Kulkarni, K.R. and Panwar, K.S. (1981) Response of pigeonpea to fertilizers in India: a critical review. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 212-220.

Kushwaha, B.L. and Ali, M. (1988) Effect of Kharif legumes on productivity and nitrogen economy in succeeding wheat. *Indian Journal of Pulses Research* 1, 12-17.

Madhava Rao, K.V. and Venkateswara Rao, K. (1984) Putrescine content as an indicator of potassium deficiency in pigeonpea. *International Pigeonpea Newsletter* 3, 33-36.

Manjhi, S., Chowdhury, S.L. and Kavitkar, A.G. (1973) Influence of varieties, planting rates, row spacings and fertilizer nutrients on the yield and yield components of pigeonpea (*Cajanus cajan* (L.) Millsp.). *Indian Journal of Agricultural Sciences* 43, 998-1001.

Manjunath, A. and Bagyaraj, D.J. (1984) Response of pigeonpea and cowpea to phosphate and dual inoculation with vesicular arbuscular mycorrhiza and *Rhizobium. Tropical Agriculture (Trinidad)* 61, 48-52.

Mehrotra, N.K., Dube, B.K. and Agarwala, S.C. (1983) Effect of zinc deficiency on uptake of Zn, Mn and P, and activity of some enzymes in four pigeonpea genotypes. *Indian Journal of Agricultural Sciences* 53, 30-37.

Morton, J.F., Smith, R.E., Lugo-López, M.A. and Abrams, R. (1982) *Pigeonpeas (Cajanus cajan Millsp.): A Valuable Crop of the Tropics.* Special Publication of the College of Agricultural Sciences, Department of Agronomy and Soils, University of Puerto Rico, Mayaguez, Puerto Rico, 123 pp.

Mosse, B. (1981) Vesicular-arbuscular mycorrhiza research for tropical agriculture. *Research Bulletin of Hawaii Institute of Tropical Agriculture and Human Resources.* University of Hawaii, USA.

Nandal, D.P., Malik, D.S. and Singh, K.P. (1987) Effect of phosphorus levels on dry matter accumulation of kharif pulses. *Legume Research* 10, 31-33.

Narain, P., Verma, B. and Singhal, A.K. (1980) Nitrogen economics through intercropping of pigeonpea in rainfed sorghum. *Indian Journal of Agronomy* 25, 190-196.

Narayanan, A. and Syamala, R. (in press) Response of pigeonpea (*Cajanus cajan* (L.) Millsp.) genotypes to aluminium toxicity. In: *Proceedings of the International Congress of Plant Physiology, 15-20 February 1988, New Delhi, India.* Society for Plant Physiology and Biochemistry, New Delhi, India.

Natarajan, M. and Willey, R.W. (1980) Sorghum-pigeonpea intercropping and the effects of plant population density. 2. Resource use. *Journal of Agricultural Science, Cambridge* 95, 59-65.

Nichols, R. (1964) Studies on the major-element deficiencies of the pigeon pea (*Cajanus cajan*) in sand culture. I. Foliar symptoms of the major-element deficiencies. *Plant and Soil* 21, 377-387.

Nichols, R. (1965) Studies on the major-element deficiencies of the pigeon pea (*Cajanus cajan*) in sand culture. II. The effects of major element deficiencies on nodulation, growth and mineral composition. *Plant and Soil* 22, 112-126.

Nye, P.H. and Foster, W.N.M. (1961) The relative uptake of phosphorus by crops and natural fallow from different parts of their root zone. *Journal of Agricultural Science, Cambridge* 56, 299-306.

Ogata, S., Adu-Gyamfi, J. and Fujita, K. (1988) Effect of phosphorus and pH on dry matter production, dinitrogen fixation and critical phosphorus concentration in pigeon pea (*Cajanus cajan* (L.) Millsp.). *Soil Science and Plant Nutrition* 34, 55-64.

Ogunwale, J.A. and Olaniyi, J.K. (1978) Responses of pigeon pea (*Cajanus cajan* (L.) Millsp.) to phosphorus on a phosphorus-marginal soil in Nigeria. *East African Agricultural and Forestry Journal* 43, 274-280.

Oke, O.L. (1969) Sulphur nutrition of legumes. *Experimental Agriculture* 5, 111-116.

Palaniappan, S.P., Sudhakara Rao, R. and Soundar Rajan, D. (1984) Studies on nutrient uptake by pigeonpea as influenced by intercropping and P fertilization. *Madras Agricultural Journal* 71, 791-794.

Pannu, J.S. and Sawhney, J.S. (1975) Effect of arhar on the nitrogen requirements of the succeeding wheat in an intensive rotation. *Indian Journal of Genetics and Plant Breeding* 35, 253-256.

Pietri, R., Abrams, R. and Julia, F.J. (1971) Influence of fertility level on the protein content and agronomic characters of pigeonpeas in an Oxisol. *Journal of Agriculture of the University of Puerto Rico* 55, 474-477.

Probert, M.E. and Jones, R.K. (1977) The use of soil analysis for predicting the response to sulphur of pasture legumes in the Australian tropics. *Australian Journal of Soil Research* 15, 137-146.

Puste, A.M. and Jana, P.K. (1988) Effect of phosphorus and zinc on growth patterns of pigeonpea (*Cajanus cajan* (L.) Millsp.) grown during winter season. *Indian Journal of Plant Physiology* 31, 243-247.

Raj, A.S. (1987) Cobalt nutrition of pigeonpea and peanut in relation to growth and yield. *Journal of Plant Nutrition* 10, 2137-2145.

Ramanathan, G., Pajanisamy, N. and Krishnamoorthy, K.K. (1977) Response of Co.2 red gram to "P" application. *Madras Agricultural Journal* 64, 671-672.

Rao, M.R. and Bhardwaj, R.B.L. (1981) Direct, residual and cumulative effect of phosphorus in wheat-pigeonppea rotation. *Indian Journal of Agricultural Sciences* 51, 96-102.

Rathi, S.S., Singh, D. and Malik, R.S. (1974) Response of short duration arhar to dates of sowing, row spacing and phosphate application. *Fertilizer News* 19(2), 27 and 31.

Ravindranath, N.N.V.S., Satynarayana, N.V., Prasad, P. and Madhava Rao, K.V. (1985) Foliar application of potassium on the growth and yield components of pigeonpea (*Cajanus cajan* (L.) Millsp.). *Proceedings of the Indian Academy of Sciences (Plant Sciences)* 94, 671-676.

Reddy, P.R., Subba Rao, I.V. and Madhusudhan Rao, L. (1978) Nutritional disorders in pigeon pea (*Cajanus cajan* (L.) Millsp.) cv. HY-3C and remedial measures. *Science and Culture* 44, 36-37.

Reuter, D.J. (1986) Temperate and sub-tropical crops. In: Reuter, D.J. and Robinson, J.B. (eds), *Plant Analysis: An Interpretation Manual.* Inkata Press, Melbourne, Australia, pp. 38-99.

Rhodes, E.R. (1987) Critical phosphorus levels in equilibrium soil extract and index leaf for pigeonpea. *Communications in Soil Science and Plant Analysis* 18, 709-714.

Robson, A.D. and Snowball, K. (1986) Nutrient deficiency and toxicity symptoms. In: Reuter, D.J. and Robinson, J.B. (eds), *Plant Analysis: An Interpretation Manual.* Inkata Press, Melbourne, pp. 13-19.

Russell, J.S. (1978) Residual value of fertilizers. In: Andrew, C.S. and Kamprath, E.J. (eds), *Mineral Nutrition of Legumes in Tropical and Subtropical Soils.* CSIRO, Melbourne, Australia, pp. 361-376.

Sahu, S.K. and Pal, S.S. (1987) Direct and residual effect of paper mill sludge and limestone on crop yield under three different crop rotations on an acid red soil. *Journal of the Indian Society of Soil Science* 35, 46-51.

Scaife, A. (1988) Derivation of critical nutrient concentrations for growth rate from data from field experiments. *Plant and Soil* 109, 159-169.

Sheldrake, A.R. and Narayanan, A. (1979) Growth, development and nutrient uptake in pigeonpeas (*Cajanus cajan*). *Journal of Agricultural Science, Cambridge* 92, 513-526.

Shukla, U.C. and Raj, H. (1980) Zinc response in pigeon pea as influenced by genotypic variability. *Plant and Soil* 57, 323-333.

Singh, A., Ahlawat, I.P.S. and Lal, R.B. (1983a) Effect of planting pattern, intercropping and application of phosphate on the yields of pigeonpea and the succeeding crop of wheat. *Indian Journal of Agricultural Sciences* 53, 556-562.

Singh, A., Prasad, R. and Saraf, C.S. (1983b) Effect of variety, row spacing and phosphate fertilization on yield and moisture extraction pattern in pigeonpea. *Indian Journal of Agronomy* 28, 33-36.

Smith, F.W. (1986) Interpretation of plant analysis: Concepts and principles. In: Reuter, D.J. and Robinson, J.B. (eds), *Plant Analysis: An Interpretation Manual.* Inkata Press, Melbourne, pp. 1-12.

Smith, F.W., Imrie, B.C. and Pieters, W.H.J. (1983) *Foliar Symptoms of Nutrient Disorders in Mung Bean (Vigna radiata). Technical Paper no. 24.* Division of Tropical Crops and Pastures, CSIRO, Australia, 11 pp.

Subbarao, G.V. (1988) Salinity tolerance in pigeonpea (*Cajanus cajan* (L.) Millsp.) and its wild relatives. PhD thesis, Indian Institute of Technology, Kharagpur, India, 217 pp.

Subbian, P. and Ramiah, S. (1982) Influence of phosphorus, molybdenum and rhizobial seed inoculation on growth and grain yield of redgram. *Madras Agricultural Journal* 69, 23-32.

Tandon, H.L.S. (1986) *Sulphur Research and Agricultural Production in India.* 2nd edition. Fertilizer Development and Consultation Organization, New Delhi, India, 76 pp.

Tandon, H.L.S. (1987) *Phosphorus Research and Agricultural Production in India.* Fertilizer Development and Consultation Organization, New Delhi, India, 160 pp.

Tandon, H.L.S. (1989) *Secondary and Micronutrient Recommendations for Soils and Crops: A Guide Book.* Fertilizer Development and Consultation Organization, New Delhi, India, 104 pp.

Tandon, H.L.S. and Sekhon, G.S. (1988) *Potassium Research and Agricultural Production in India.* Fertilizer Development and Consultation Organization, New Delhi, India, 144 pp.

Velayutham, M., Reddy, K.C.K. and Sankar, G.R.M. (1985) All India Coordinated Research Project on soil test–crop response correlation and its impact on agricultural production. *Fertilizer News* 30(4), 81-95.

Venkateswarlu, J., Das, S.K. and Rao, U.M.B. (1986) Phosphorus management for castor-sorghum ± red gram intercropping rotation in semi-arid Alfisol. *Journal of the Indian Society of Soil Science* 34, 799-802.

Chapter 10

PIGEONPEA: NITROGEN FIXATION

J.V.D.K. KUMAR RAO

Crop Physiologist, Legumes Program, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Andhra Pradesh 502 324, India.

INTRODUCTION

Even though 78% of the earth's atmosphere consists of elemental nitrogen (N), the demand for fixed nitrogen by the biosphere exceeds its availability. This is because all animals and most plants can not assimilate gaseous nitrogen. The majority of crop plants depend on nitrate or ammonium for their nitrogen source, but many legumes that form root nodules can reduce atmospheric nitrogen in symbiosis with rhizobia, and hence can grow better than cereals in soils low in nitrogen.

In pigeonpea, nodules are produced by a wide spectrum of rhizobial strains belonging to the "cowpea group" (Allen and Allen, 1981). Although based on area pigeonpea is the fifth most important pulse crop in the world, work on biological nitrogen fixation in this crop has been relatively limited. Some important aspects of the legume-*Rhizobium* symbiosis, with particular emphasis on the current understanding of nodulation and nitrogen fixation in pigeonpea are discussed in this chapter.

ROOT NODULE FORMATION

Pigeonpea Rhizobia

Leguminous root nodules are highly specialized structures formed as a result of a sequence of interactions between the host plant and the invading rhizobia. Pigeonpea is nodulated by rhizobia belonging to the "cowpea-miscellany" that nodulate legumes of mostly tropical or sub-tropical origin. Pigeonpea rhizobia can nodulate cowpea and soybean but not legumes belonging to other cross-inoculation groups (Jadhav and Moniz, 1972). Rhizobia isolated from soybean nodules (Singh and Subba Rao, 1981) or *Sesbania* sp and groundnut nodules (J.V.D.K. Kumar Rao and M. Usha Kiran, unpublished) are able to nodulate pigeonpea.

There is certainly diversity in growth characteristics among pigeonpea rhizobia (Bromfield and Kumar Rao, 1983). Pigeonpea rhizobia are generally slow-growing, but fastgrowing rhizobia have also been isolated from pigeonpea nodules. According to the Bergey's Manual of Systematic Bacteriology, slow-growing rhizobia have been placed in a new genus i.e., *Bradyrhizobium* (Jordon, 1984). The author has opted not to distinguish *Rhizobium* and *Bradyrhizobium* in this Chapter, mainly because all pigeonpea rhizobia have not been thoroughly examined for symbiotic relationships. The fast-growing *Rhizobium* species utilize a wider range of carbon sources than the slow-growing isolates. In culture, slow-growing isolates produce a near-neutral to alkaline reaction whereas fast-growers produce an acidic reaction.

Some pigeonpea rhizobia can induce leaf-roll on the host plant, that has symptoms similar to those of a virus infection (Figure 10.1) (Kumar Rao *et al.*, 1984). The mechanism of leaf-roll induction by *Rhizobium* is not fully understood (Upadhayaya *et al.*, 1985).

Root Colonization

The first step in nodule formation is proliferation of rhizobia in the rhizosphere of legumes (Broughton, 1978). In general, growth of microorganisms is known to be stimulated in the rhizosphere of crop plants, including pigeonpea (Bagyaraj and Rangaswami, 1966; Sethunathan, 1970). Once rhizobia migrate to the rhizosphere their growth is supported better by legumes than non-legumes. There is a marked rhizosphere effect of pigeonpea on cowpea group rhizobia — rhizobial numbers increased from 1.3×10^3 g^{-1} in bulk soil to 9.1×10^4 g^{-1} in the rhizosphere (Nambiar *et al.*, 1988). It is not known if this population of *Rhizobium* in the rhizosphere of pigeonpea is adequate for maximum nodulation of pigeonpea. Toomsan (1981) observed no clear-cut specificity in root colonization by rhizobia, since chickpea *Rhizobium* species, that do not form nodules on groundnut or pigeonpea, colonize the roots of all the three legumes to more or less the same extent.

A given *Rhizobium* strain should be able to overcome antagonism from other microorganisms and competition from other rhizobia if it is to succeed in nodulating the host plant (Alexander, 1982). Very little is known about antagonistic effects of soil microorganisms on pigeonpea *Rhizobium*.

Recognition and Infection

The discrimination that host legume and rhizobia display during nodule initiation suggests that cellular recognition is important to the development of this symbiosis. An understanding of the mechanisms involved in cellular recognition might explain unusual specificities among tropical legumes in infection, and lead to solutions for such problems as inter-strain competition for nodule sites, and the inhibitory effects of combined N on root nodulation. The most promising lectin - recognition hypothesis is that recognition at infection sites involves the binding of specific legume lectins (carbohydrate-binding proteins) to particular carbohydrates found exclusively on the surface of the appropriate rhizobial symbiont (Bauer, 1981; Dazzo and Hubbell, 1982; Dazzo *et al.*, 1985; Dudman, 1984). One of the possible consequences of lectin/polysaccharide interaction would be that the rhizobial cell could attach and then firmly adhere to the target host cell. By mediating the adhesion of specific cells the lectin could also function as a "cell-recognition molecule" influencing cells which associate in sufficient proximity to the root hairs so that subsequent recognition steps can occur.

The mechanism operating in selective recognition of a specific *Rhizobium* strain by pigeonpea is not known. In pigeonpea the *Rhizobium* infects through root hairs by forming an infection thread (Kapil and Kapil, 1971). The curling of root hairs after infection with rhizobia is the first obvious response of the host. It is not clear which substances from the rhizobia induce curling, even though this response was described by Ward as early as 1887 (cited in Dart, 1977). Even the function of curling in the infection process is a matter of conjecture. The epidermal cells forming root hairs

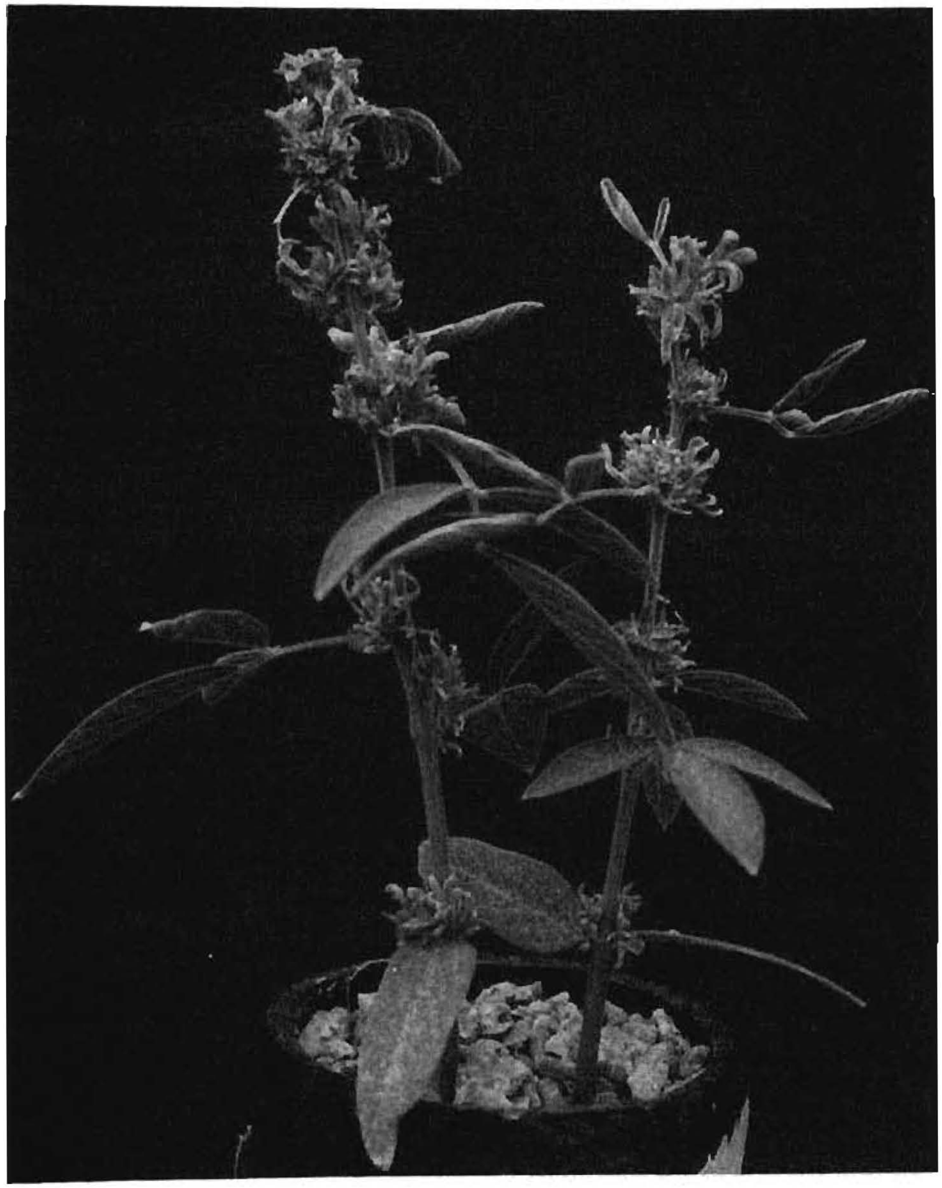


Figure 10.1. Some pigeonpea rhizobia cause 'leaf roll' symptoms on pigeonpea.
Photo: ICRISAT.

develop thickened walls, enlarge, and form infection spots. The infection thread has a branched and multiple nature in the root hair itself. The infection thread grows into the root cortex towards the site of nodule initiation through narrow, elongated cortical cells with dense cytoplasmic contents. The passage of the infection thread from the root hair to the inner cortex is clearly marked. Infection threads have not been observed to penetrate the endodermis but, in all instances, they caused proliferation of the cells of the middle region of the cortex while the two inner cortical layers remained uninfected. The root nodules, therefore, originate exogenously in the cortex.

Nodule Development and Structure

The development and structure of pigeonpea nodules has been very well described by Kapil and Kapil (1971). Proliferation of the root cells is dependent upon the release of the rhizobia from the infection thread, and this release occurs by pinocytosis (Stewart, 1967). At the same time, the invaded and uninvaded neighbouring cortical cells undergo rapid divisions leading to a hypertrophy that is meristematic and without much tissue specialization. Some isolated cells at the edge of the recently formed nodular tissue develop thickening and mature into sclerids. The enlarging nodule ruptures the root epidermis and protrudes well beyond the original root boundary. A mature nodule shows a well-marked bacteroid zone, an apical meristem, and a vascular zone. The tissues of the nodule differentiate and mature acropetally. The multilayered, thin-walled, densely cytoplasmic cells of the meristem vary in size and shape. Adjacent to the nodule cortex, the cells are smaller, elongated, and form transverse spindles resulting in radial divisions. The daughter cells remain small and uninfected. Towards the inner side of the meristem, the cells are larger and more densely cytoplasmic, and their spindles are oriented in a plane more or less parallel to the longitudinal axis of the nodule. The resulting daughter cells mature into the bacteroid region. The parenchymatous cells adjacent to the bacteroid zone contain large starch grains and, some of them, contain calcium oxalate crystals.

In pigeonpea the number of vascular strands entering the nodule is constant. The arrangement of phloem and xylem in the vascular bundles of the nodule is variable. The vascular bundles may be collateral, inversely collateral, or bicollateral. In the bacteroid zone about 80% of the cells are uninfected and full of starch.

In young nodules the infected cells are small. As the nodules increase in size, the vacuoles seen in the early stages of elongation are not apparent later when the cells become filled with rhizobia.

The bacteroid zone of pigeonpea nodules may be pink, due to the presence of leghaemoglobin, but it may also be brown in colour. It is not known if brown nodules are less active in nitrogen fixation than pink nodules. In some strain-cultivar combinations there is a deep purple to black pigmentation in the bacteroid zone (Thompson *et al.*, 1981). With the onset of senescence a green pigment develops from the base of the nodule, and small vacuoles arise in the large bacteroid cells. Their contents soon appear mottled and are absorbed. Thus, large, empty, duct-like cells are seen in the infected zone of old nodules.

Unlike freely nodulating plants such as groundnut, where nodules arise in the axils of lateral roots, pigeonpea has a comparatively low intensity of nodulation per unit of root length, much lower than for *Vigna* spp. when grown under the same conditions (Thomspon *et al.*, 1981). The nodules differ in size and shape; the size may vary from less than 2 mm to more than 2 cm, and the shape may be spherical, oval, elongate, or branched (Figure 10.2). The presence of nodules of varying size on a given plant suggests that they are of different ages. Occasionally, several nodules form close together on lateral roots.

Nodule formation and development are affected by the soil type, the season, and the duration of the cultivar (Kumar Rao and Dart, 1979; Thompson *et al.*, 1981). Nodulation in pigeonpea is rapid, with about 25 nodules per plant formed in an Alfisol within 15 days after sowing (DAS), and about half of these formed on the primary root. Nodules on the primary root usually have a short life span (<60 days). Nodules continue to form up to 120 DAS on plants grown in both Alfisols and Vertisols. However, nodule senescence starts from about 30 DAS. Further, the nodules are prone to damage by a Dipteran larva, *Rivellia angulata* Hendel (Siddapaji and Gowda, 1980; Sithanantham *et al.*, 1981). Nodule damage by *R. angulata* is much higher in Vertisols than in Alfisols. Both nodule senescence and nodule damage result in a loss of active nodules which increases with plant age. Most nodules are formed on the secondary roots, the majority are located in the top 30 cm of the soil profile. Small nodules are frequent in the 120-150 cm soil zone and may occur at even greater depths (Kumar Rao and Dart, 1987).

In general, a greater mass of, and more than twice as many, nodules were found during the rainy season in Alfisols than in Vertisols, but after the rains ceased there was more nodule formation in the Vertisols. Pigeonpea sown in the postrainy season formed few nodules, presumably because of the lower moisture availability and the lower temperatures (Thompson *et al.*, 1981).

In a field study on the seasonal pattern of nodulation and nitrogen fixation of 11 pigeonpea cultivars belonging to different maturity groups, Kumar Rao and Dart (1987) reported that in all cultivars the nodule number and mass increased to a maximum around 60-80 DAS and then declined. The nodule number and mass of medium- and late-maturing cultivars was greater than

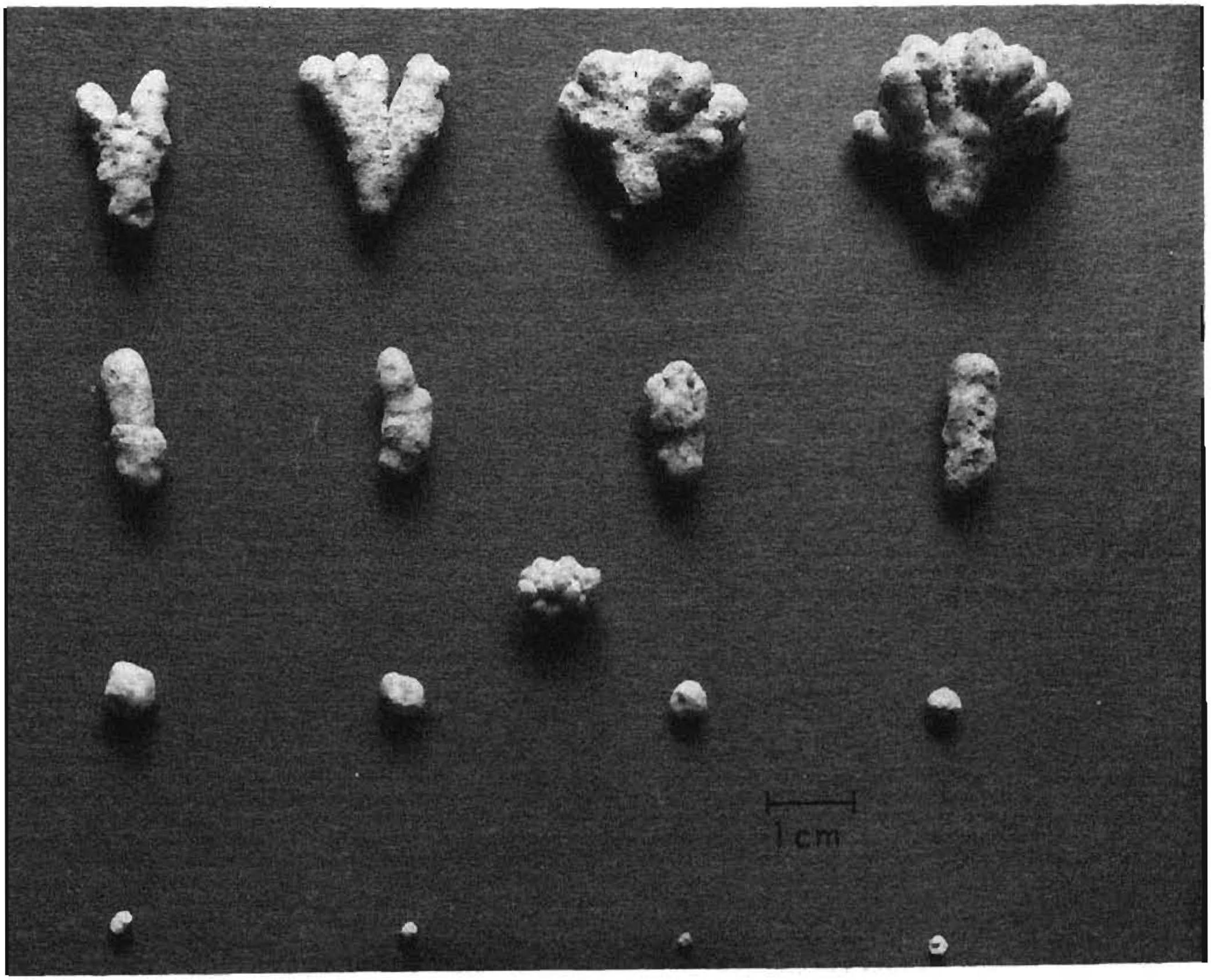


Figure 10.2. Nodules of different sizes and shapes form a pigeonpea plant grown in an Alfisol at ICRISAT Center.
Photo: ICRISAT.

that of early-maturing cultivars (Figure 10.3). The nitrogenase activity per plant increased to 60 DAS and declined thereafter, with little activity at 100 DAS when the crop was flowering (Figure 10.4). However, this decline also generally coincides with a decline in soil moisture availability.

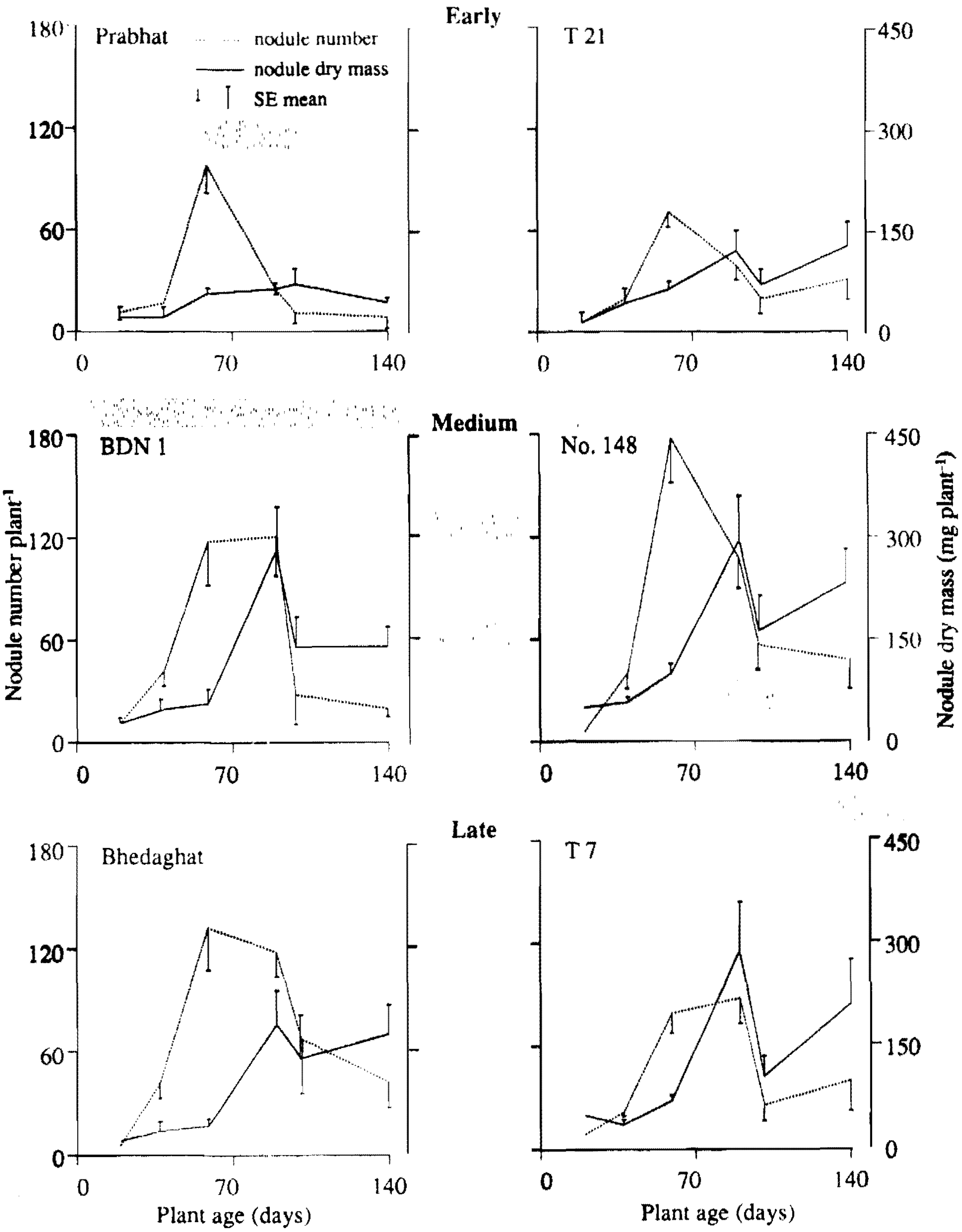


Figure 10.3. Nodule number and dry mass (mg plant^{-1}) over time of pigeonpea cultivars of different maturities.

Source: Kumar Rao and Dart, 1987.

At later stages of plant growth nodules formed down to 90 cm below the soil surface, but those at greater depth appeared less active than those near the soil surface.

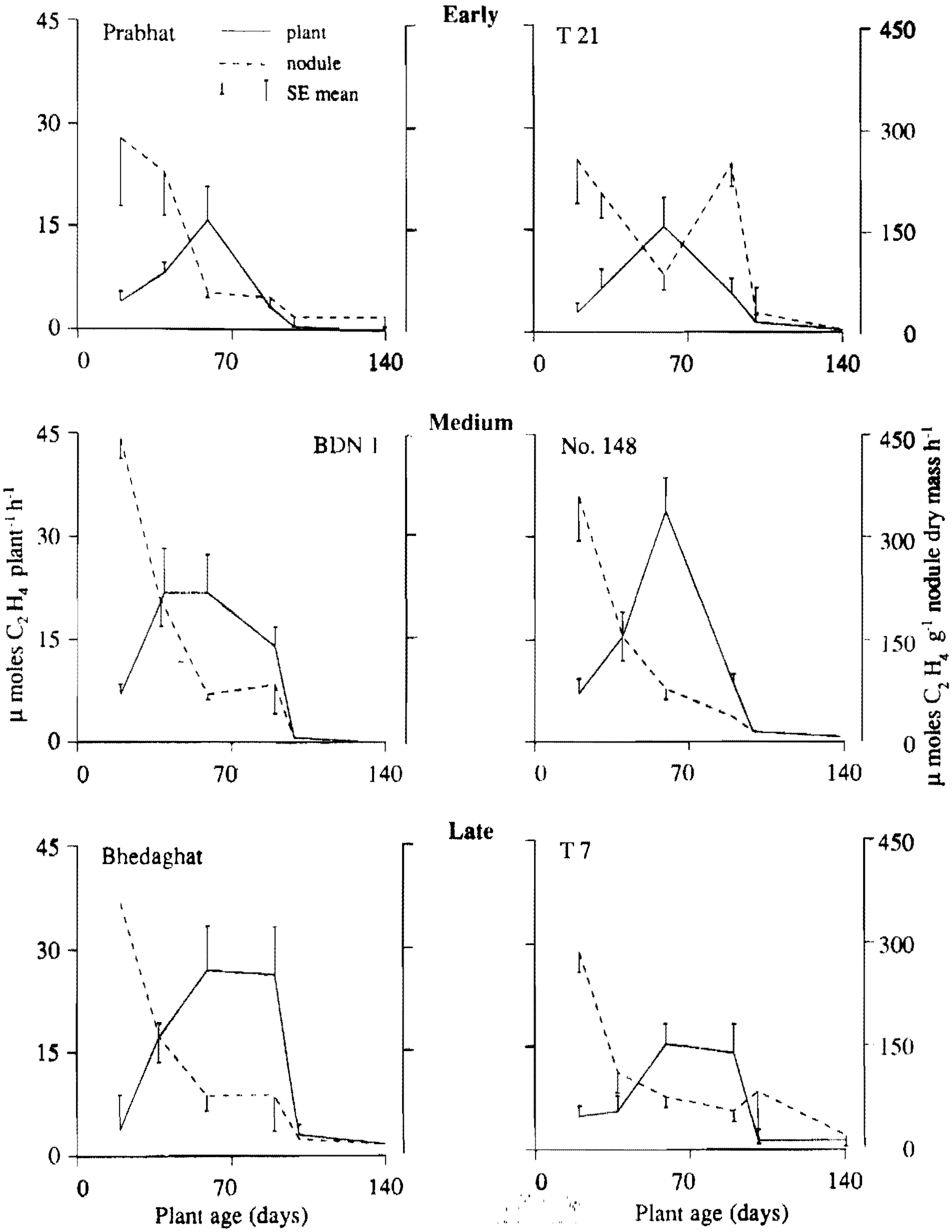


Figure 10.4. Nitrogenase activity plant^{-1}, and g^{-1} nodule dry mass h^{-1} over time of pigeonpea cultivars of different maturities.

Source: Kumar Rao and Dart, 1987.

BIOCHEMISTRY OF NITROGEN FIXATION

Nodule functioning entails intricate biochemical processes about which very little is known in pigeonpea. Nitrogen fixation in legume nodules is carried out by the enzyme nitrogenase which is located within the *Rhizobium* bacteroids. The energy for the reduction of N_2 is supplied by the host plant.

The nitrogenase complex consists of two iron(Fe)-sulphur(S) proteins termed nitrogenase reductase and nitrogenase (Postgate, 1982). Nitrogenase reductase, or Fe protein, contains four iron and four acid-labile sulphur atoms while the nitrogenase, or MoFe protein, contains two molybdenum(Mo), 28-32 iron, and approximately 28 acid-labile sulphur atoms. These two proteins together catalyze the reduction of N_2 to NH_3, C_2H_2 to C_2H_4, H^+ to H_2, N_2O to $N_2 + H_2O$, HN_3 to $NH_3 + N_2$, and a few other reactions. The source of reductant for this electron transfer is believed to be reduced ferredoxin or flavodoxin (Yoch and Valentine, 1972). Although these low-potential proteins may serve as the ultimate source of electrons, the terminal steps of electron transport leading to their reduction particularly in *Rhizobium* bacteroids are not clear (Burns and Hardy, 1975). Electrons flow from ferredoxin to the Fe protein that, when complexed with adenosine tri-phosphate (ATP), will reduce the MoFe protein with the release of inorganic phosphate. The MoFe protein will eventually pass electrons to the reducible substrate. The transfer of electrons from nitrogenase reductase to nitrogenase is associated with ATP hydrolysis. However, the amount of ATP hydrolyzed for each electron pair transferred is uncertain, with estimates varying from two to five (Gordon and Brill, 1974).

The nitrogenase reduces protons to hydrogen (H_2) gas concomitant with ammonia formation in both *in vitro* and *in vivo* nitrogen-fixing organisms. However, the exact relationship between N_2 reduction and H_2 evolution is not clear (Schubert and Evans, 1976). It has been indicated that for every N_2 molecule reduced a minimum of one molecule of H_2 was evolved. The hydrogenase present in bacteroids utilizes part or all of the H_2 produced and yields ATP (Dixon, 1978; Schubert and Evans, 1976). It has been suggested that hydrogenase may help to scavenge oxygen and to protect nitrogenase from inactivation (Emerich *et al.*, 1979); it prevents inhibition of nitrogenase by H_2 (Hwang *et al.*, 1973), and helps recover part of the energy lost to H_2 evolution. Pate *et al.* (1981) estimated a saving of 11-26% of the energy required for nitrogenase functioning in systems with hydrogenase compared to those without hydrogenase. This suggests that there is efficient use of photosynthate in the nodules of those symbioses formed by H_2-uptake-positive (Hup^+) *Rhizobium* strains. Several studies suggested that higher yields of soybean may be obtained by utilizing Hup^+ rather than Hup^- rhizobia (Schubert *et al.*, 1978; Albrecht *et al.*, 1979; Hanus *et al*, 1981; Zablotowicz *et al.*, 1980). However, in pigeonpea no significant difference in the nitrogen-fixing ability of Hup^+ and Hup^- rhizobia was observed (La Favre and Focht, 1985), and the agronomic importance of the Hup^+ trait could not be demonstrated (Hernandez and Focht, 1985). It would be interesting to know the reasons why the Hup^+ character was beneficial in soybean but not in pigeonpea.

GASEOUS EXCHANGE

An efficient gaseous exchange system is clearly necessary in nodules as their function, apart from respiratory considerations, is to fix nitrogen. Nodules are dense organs possessing significant endodermal tissue. This tissue protects the nodules in the relatively dry environment of the soil, but it is likely to impede gaseous diffusion. The intercellular spaces (Bergersen and Goodchild, 1973) and surface lenticels (Dart, 1977; Pate, 1977) found in some nodules are probably adaptations aiding gas exchange (Sprent, 1980). While there is no direct evidence for N_2 fixation being limited by the availability of nitrogen gas to the bacteroids, the supply of oxygen(O_2) to the bacteroids is critical to nodule functioning. The utilization of O_2 in N_2-fixing organisms must be accurately regulated because O_2 is required for ATP synthesis by bacteroids and plant host cells, yet nitrogenase is rapidly inactivated by O_2. Nitrogen fixation and respiration in detached legume nodules can be markedly increased by O_2 partial pressures above atmospheric levels (Bergersen, 1982). Maximum nitrogenase activity occurs at O_2 concentrations of 40-50%; higher concentrations lead to the inactivation of nitrogenase. This suggests that N_2 fixation may be limited by O_2, but this interpretation has recently been questioned (Minchin *et al*, 1985). Oxygen access to the interior of nodules is controlled by a variable diffusion barrier in the nodule periphery. This barrier is sensitive to environmental changes, and may limit the penetration of gases into nodule tissue resulting in an O_2 stress. The increases in nitrogenase activity in detached nodules exposed to high concentrations of O_2 may be due to increased diffusion resistance in response to detachment. Arguments against O_2 limitations have been provided by experiments in which soybean and pea plants were grown at O_2 concentrations ranging from 10 to 30%. Total dry mass and N_2 fixed were not affected by experimental variations of the O_2 content of the atmosphere (Minchin *et al.*, 1985). Understanding of the role of O_2 limitation of N_2 fixation in nodules is limited, and further research is required.

Leghaemoglobin has a vital role in nodule oxygen relations. This protein has a high affinity for O_2 and facilitates the diffusion of bound O_2 to the respiring bacteroids, where the free O_2 tension is maintained at a level that does not inactivate nitrogenase (Appleby, 1984). The synthesis of leghaemoglobin represents a remarkable degree of specialization in the symbiotic association. The protohaem moiety has been reported to be synthesized by the *Rhizobium* symbiont and the apoprotein by the plant host. However, Dilworth and Glenn (1984) state that the evidence that haem synthesis is uniquely a bacteroid property is not unequivocal.

QUANTIFICATION OF NITROGEN FIXATION BY PIGEONPEA

It is difficult to measure nitrogen fixation by pigeonpea grown in the field, because it is difficult to estimate soil nitrogen uptake by such a long-duration and deep-rooted crop. Several different methods; N balance, acetylene reduction assay (ARA), ^{15}N isotope dilution, and ureides in the xylem sap have been used to measure N_2 fixed by pigeonpea. The advantages and limitations of these methods have been discussed by La Rue and Patterson (1981).

Using the N-balance method, Sen (1956) reported that a long-duration pigeonpea grown in northern India could fix up to 200 kg N ha^{-1} over a period of 40 weeks. Using sorghum as the non-fixing control and the N-balance method, estimates of fixed N in pigeonpea genotypes of different maturity ranged from 6 to 69 kg N ha^{-1} (Kumar Rao and Dart, 1987).

The ARA, though sensitive and quick, is difficult to use with pigeonpea mainly because of the excessive labour and time required in quantitative recovery of the nodulated root system, particularly during the later stages of plant growth. However, using this technique Reddi and Prine (1982) reported a fixation of 0.35 kg N ha^{-1} day^{-1} up to 90 DAS, and this was reported to be an underestimate because of the incomplete recovery of the nodules.

Using the ^{15}N isotope dilution method it was estimated that 90% of N in a medium-duration pigeonpea grown as a sole crop in a Vertisol was derived from fixation (Kumar Rao *et al.*, 1987). In intercropped pigeonpea the proportion fixed was 96% and there was no evidence of immediate benefit from N_2 fixed by pigeonpea to the intercropped sorghum (Kumar Rao *et al.*, 1987). The latter observation confirms the report of Kanwar and Rego (1983) that there was not much current nitrogen transfer from pigeonpea to sorghum in Alfisols and Vertisols at ICRISAT Center.

The ureide estimation in the xylem sap has been found unsatisfactory as a measure of N_2 fixation by pigeonpea due to; minimal sap exudation when pigeonpea faces drought stress, varying nitrate reductase activity in the roots, and, again, the instantaneous nature of the measurement (Kumar Rao *et al.*, 1981; J.V.D.K. Kumar Rao *et al.*, unpublished). The measurement of ureides in plant tissues, rather than in xylem sap, was also attempted. However, unlike soybean, there were no apparent correlations between the ureide levels in the tissues, nodulation in pigeonpea, and N_2 fixation (Herridge, 1981; ICRISAT, 1983).

FACTORS AFFECTING NITROGEN FIXATION

The legume-*Rhizobium* symbiosis is a highly integrated and, to a considerable degree, self-regulating process. There are many factors that could limit the symbiosis, but under field conditions; soil moisture, temperature, soil pH, mineral nutrient supply, salinity, and nodule damage by insects are presumably the most important. There have been several reviews on the effect of environment on legume-*Rhizobium* symbioses (Lie, 1981; Eaglesham and Ayanaba, 1984) and only the relevant points with special reference to pigeonpea are discussed here.

Moisture

Pigeonpea experiences both water deficit (drought) and excess (waterlogging) depending on the season (rainy or postrainy), and intensity and distribution of rainfall. The legume symbiosis is sensitive to both drought and waterlogging. It can recover if exposed to short stress periods, but prolonged exposure may lead to permanent damage and shedding of nodules (Wilson, 1931, cited by Lie, 1981). Dry soils inhibit root hair formation and hence infection by *Rhizobium*. With watering, the abnormal root hairs formed during drought may resume growth. On the other hand, nodule development initiated under normal moisture conditions is impaired by later dry conditions (Worrall and Roughley, 1976).

In a closed pot system using a Vertisol as the growth medium the response of pigeonpea to various soil moisture levels was studied (C. Johansen *et al.*, ICRISAT, unpublished). Symbiotic activity (ARA) was affected by water deficit to a greater extent than plant dry matter accumulation in that it continued to increase up to 40% soil moisture, whereas dry matter peaked at 30-35% soil moisture (Figure 10.5). Thus moisture contents in excess of field capacity (26%), and at least up to 40% moisture, enhance N_2 fixation activity in a Vertisol; or conversely, N_2-fixation activity is severely impaired when the soil moisture level falls below field capacity. Similar studies on response of pigeonpea to moisture levels in other major soil types are lacking.

In a field study comparing nodulation and nitrogen fixation of 11 pigeonpea cultivars of different maturity groups grown on an Alfisol, it was reported that soil moisture deficit might be one of the reasons for the cessation of nitrogenase activity by 100 DAS even though the plants were not apparently drought stressed (Kumar Rao and Dart, 1987).

The reduced ARA during drought may be due to reduced photosynthate supply: in soybean for instance, it was observed that the percentage reduction of ARA and of net photosynthesis were similar (Huang *et al.*, 1975). Although the detailed mechanism of water deficit affecting N_2 fixation in pigeonpea is not known, drought stress resulted in decreased water potential of roots, nodules, and leaves. The decreased water potential in nodules resulted in decreased activities of nitrogenase, glutamine synthetase, glutamate dehydrogenase, and uricase. However, the activity of allantoinase increased under mild stress with a slight decrease under severe stress (Sheoran *et al.*, 1981).

Since pigeonpea experiences unpredictable cycles of wetting and drying (Huda and Virmani, 1987), dips and surges in nodule formation and functions during the growing season are not unexpected. It has been observed that pigeonpea plants subjected to waterlogging turn chlorotic and grow poorly. Oxygen deficiency, which accompanies waterlogging of soil, inhibits root nodulation, nodule development, and ARA in peas (Minchin and Pate, 1975). The inhibitory effects of waterlogging on nodule activity in non-aquatic legumes can be attributed to anoxia. In soybean acetylene reduction by nodulated roots was inhibited at oxygen levels below 5% in air. Even a thin film of water on nodules can be a significant barrier to oxygen diffusion (Sprent and Gallacher, 1976). The mechanism by which waterlogging affects pigeonpea growth has not been adequately determined.

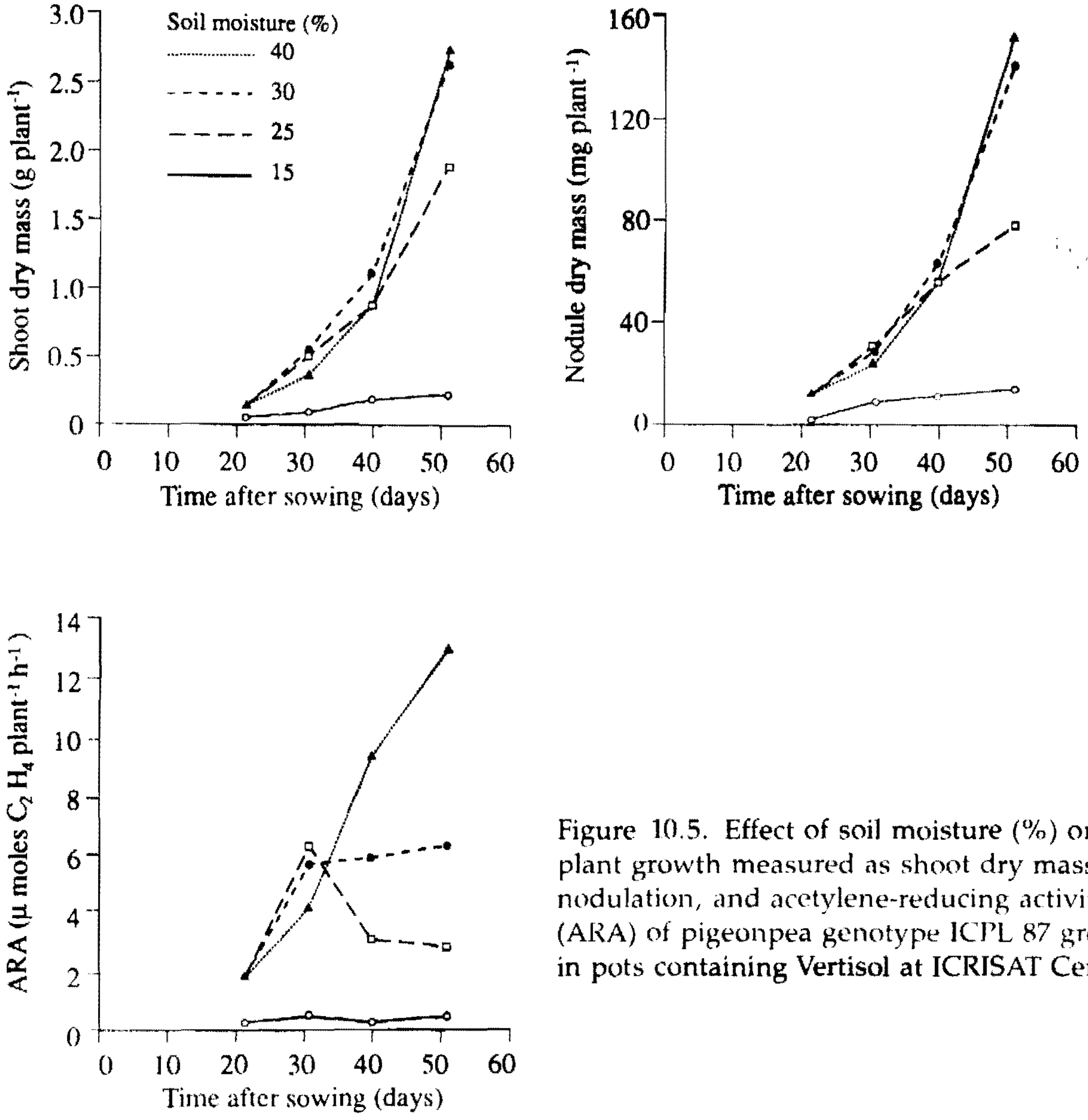


Figure 10.5. Effect of soil moisture (%) on plant growth measured as shoot dry mass, nodulation, and acetylene-reducing activity (ARA) of pigeonpea genotype ICPL 87 grown in pots containing Vertisol at ICRISAT Center.

Temperature

Temperature has a marked influence on the symbiosis, and it affects nearly all the stages of its development and functioning. The optimum temperature range for the symbiotic system is narrower than that of the plant supplied with fertilizer nitrogen (Lie, 1981). At higher temperatures, photosynthesis is drastically reduced (Black, 1973; Black *et al.*, 1978) and hence nitrogen fixation can be indirectly affected by a reduced supply of photosynthates (Luthra *et al.*, 1985). With pigeonpea it was found that nodulated roots incubated at 26°C gave a higher ARA than plant roots incubated at either 20°C or 38°C (Table 10.1).

Table 10.1. Effect of soil temperature on nodulation, acetylene reduction activity (ARA) and plant growth of pigeonpea[1] genotype ICPL 87, at 60 DAS, ICRISAT Center, 1984.

Temperature (°C)	ARA ($\mu M\ C_2H_4$ plant^{-1} h^{-1})	Nodule dry mass (mg plant^{-1})	Plant dry matter (g plant^{-1})
20	5.5	150	5.9
26	10.3	195	6.7
32	8.9	164	6.1
38	6.1	262	6.9
SE	±1.28	±29	±0.3
F test	*[2]	ns[3]	ns

1. Intact plants grown in pots were incubated in water baths maintained at a specific temperature for 10 days before assay, while the shoot was exposed to ambient temperature.
2. Significant at CD 0.5%.
3. ns = not significant

Source: J.V.D.K. Kumar Rao and B.V.S.T. Sai, ICRISAT, unpublished.

In several farmers' fields in northern India pigeonpea sown at the beginning of the season nodulated poorly (Khurana and Dudeja, 1981). Though the reasons for poor nodulation are not clear, high soil temperature (about 40°C) during sowing and early vegetative growth stages might be one of the factors affecting nodule formation and development. The lower and upper limits of temperature within which normal patterns of nodulation may be expected are still poorly understood for pigeonpea.

Nutritional Factors

The legume-*Rhizobium* symbiosis imposes additional nutritional requirements apart from the minerals needed for plant growth as a whole. The elements specifically required for symbiotic functioning are Mo, Cobalt (Co), and Fe. Franco (1977) noted that soil acidity together with toxicity caused by aluminium or manganese (or both) and deficiency of phosphorus (P), sulphur, calcium(Ca), and molybdenum are some of the factors that may limit the grain yield of tropical legumes dependent on symbiotic nitrogen fixation for growth. Pigeonpea can grow and fix N_2 in acid soils, in the pH range 4.5 to 5.5 (Dalal and Quilt, 1977; Edwards, 1981; Abruna *et al.*, 1984). However, its N_2 fixation activity seems more sensitive to acidity than plant growth itself (Edwards, 1981). The addition of P stimulated pigeonpea nodulation in both an Alfisol and a Vertisol, while farmyard manure inhibited pigeonpea nodulation (Kumar Rao and Dart, 1981). Hernandez and Focht (1985) reported that addition of P to an infertile acid Oxisol in the Republic of Panama increased shoot and nodule masses, acetylene reduction activity, and hydrogen evolution of pigeonpea, but Ca addition had no effect on N_2-fixing characteristics. Raj (1987) reported that seed application of Co at a rate of 500 mg cobalt nitrate kg^{-1} seed significantly increased grain yield of pigeonpea, and that this can be interpreted as a primary effect of Co in improving nitrogen fixation. Khurana and Dudeja (1981) reported that soil application of 0.45 kg Mo ha^{-1} as sodium molybdate significantly increased nodulation, plant dry matter, and grain yield of pigeonpea at Hisar in northern India.

Nitrogen fertilization adversely affects the nodulation of many legumes (Franco, 1977). In pigeonpea both nodulation and nitrogenase activity were depressed by soil nitrogen concentrations greater than 25 ppm N as NO_3 (Kumar Rao *et al.*, 1981). Quilt and Dalal (1979) found negligible nodulation in plants up to 10 weeks old in soils with 50 ppm N, whereas normal nodule formation occurred at soil-N concentrations of around 20 ppm. Applications of nitrogen fertilizer at sowing reduced nodule mass per plant by 74% at 20 DAS, but by 60 DAS no differences were apparent (Kumar Rao *et al.*, 1981). The mechanism of inhibition of nodulation by combined nitrogen remains unknown. Pigeonpea cultivars may also vary in their response to nitrogen fertilizer in final seed yield and plant dry matter (Kumar Rao *et al.*, 1981; J.V.D.K. Kumar Rao, unpublished) suggesting that nitrogen fixation is not able to meet the nitrogen requirements of some cultivars.

Salinity

It is generally known that the rhizobia can tolerate a higher level of salinity than the host legume (Wilson, 1970). Pigeonpea rhizobial strains showed significant differences in salt tolerance in yeast extract mannitol agar medium with NaCl contents ranging from 43 mM (0.25%) to 1197 mM (7%). Fast-growing rhizobial strains were more salt-tolerant than slow-growers; there was no major difference between rhizobial strains isolated from saline and non-saline soils in this respect (Subbarao, 1984). Subbarao (1988) observed significant differences among pigeonpea *Rhizobium* strains in their ability to nodulate and fix nitrogen with a given pigeonpea genotype under saline conditions, and further observed that nodule initiation was the most salt-susceptible aspect of pigeonpea growth. He suggested that there is scope for selecting pigeonpea-*Rhizobium* symbioses better adapted to saline conditions. The salinity response of N-fed *vs* *Rhizobium*-inoculated pigeonpea (both cultivated and related wild species) was found to be similar, except that the tolerance limit of wild pigeonpea species was much higher than cultivated pigeonpea (12 dS m^{-1} *vs* 6 dS m^{-1}).

Insect Damage

Two insects; *Sitona* sp, and *Rivellia* sp are known to attack legume nodules (Gibson, 1977). In pigeonpea, extensive damage to root nodules caused by *Rivellia angulata* has been reported by Sithanantham *et al.* (1981). The larva of this insect bores into the core of the nodule, causing a substantial reduction in nodule mass. The extent of nodule damage is greater in pigeonpea grown in Vertisols than in Alfisols. Field studies aimed at assessing the impact of nodule damage on plant growth and yield were not successful as the insecticides, aldrin and hexachlorocyclohexane, could not control *Rivellia* sp in spite of repeated applications of heavy doses. In a pot culture study it was shown that nodule damage by *Rivellia* resulted in significant loss in nodule dry mass (46%), acetylene reduction activity (31%), total leaf area (36%), and shoot dry mass (23%) at 68 DAS. At maturity, *Rivellia* sp infestation caused significant reductions in top (22%), root and nodule (27%), and seed (14%) dry masses, and in total N (29%) and P (19%) uptake. The possible solutions to this problem are to select pigeonpea genotypes that can resist or tolerate attack by *Rivellia* sp, or to develop pigeonpea *Rhizobium* with the toxin-producing gene of *Bacillus thuringensis* var. *israeliensis* through genetic engineering. Another possibility is to construct transgenic plants of pigeonpea with insect resistance, for instance through the introduction of the gene for the *B. thuringiensis* var. *israeliensis* insecticidal protein and its expression in the adult plant (Kumar Rao and Sithanantham, 1989).

Agronomic Practices

In the semi-arid tropics pigeonpea is generally grown as an intercrop or a mixed crop with such cereals as sorghum, millet, or maize; but it is also grown as a sole crop. The number and dry mass of nodules of pigeonpea was significantly increased when it was intercropped with mung bean

(Singh and Faroda, 1986). Using the ^{15}N isotope dilution technique it has been observed that intercropping pigeonpea (ICP 1-6, a medium-maturing genotype) with sorghum on a Vertisol did not affect N_2 fixation by pigeonpea (Kumar Rao *et al.*, 1987). However, it is not known if the same is true for the late-maturing pigeonpeas (about 8 months duration) grown in northern India and parts of Africa.

Cropping systems may also influence the survival and persistence of rhizobia. In many of the rice-growing areas of India it is a common practice to grow a legume after the main crop of rice if irrigation water is insufficient to grow another crop of rice. In the rice fields the population of cowpea group *Rhizobium* was very low, less than 100 g^{-1} of soil as compared to an average of about 1000 rhizobia g^{-1} soil in Vertisols and 10000 rhizobia g^{-1} soil in Alfisols (Kumar Rao *et al.*, 1982). No systematic study has been conducted to examine the effect of the anaerobic conditions that prevail during rice growth on the soil *Rhizobium* populations, or their effect on nodulation of the subsequent pigeonpea crop.

ASSIMILATION OF FIXED NITROGEN

In most legumes ammonia, the first stable product of nitrogen fixation, is the starting material for the incorporation of fixed nitrogen into organic compounds (Dilworth, 1974; Bergersen, 1982). The ammonia that is excreted from bacteroids is assimilated directly into glutamine in the host-cell cytosol via the glutamine synthetase/glutamate synthase pathway (Meeks *et al.*, 1978; Ohyama and Kumazawa, 1980), although it is not certain if any ammonia is assimilated by bacteroids.

Legume species can be broadly grouped into two categories depending on the composition of the nitrogenous compounds which they export from the nodules to the shoot i.e., the ureide-(allantoin and allantoic acid) and the amide-(asparagine and glutamine) producing species (Bergersen, 1982). In many of the tropical legumes, including pigeonpea, most of the nitrogen fixed in nodules is translocated in the form of ureides (Herridge *et al.*, 1978; McClure and Israel, 1979; Pate *et al.*, 1980; Kumar Rao *et al.*, 1981; Luthra *et al.*, 1981; Schubert, 1986) which, with the exception of soybean, have received little research attention. Amide-producing symbioses, on the other hand, are temperate species (e.g., *Pisum, Lupinus, Vicia)* that have been studied in detail.

The metabolic pathways involved in ureide synthesis in tropical legumes have been reviewed by Reynolds and his co-workers (1982). Amarjit and Singh (1984) proposed a pathway for the biogenesis of ureides in pigeonpea nodules. According to this scheme, ammonium is assimilated to the level of glutamine in cytosol. This, along with aspartate and other intermediates, is utilized for the biosynthesis of purines in proplastids. The end-products of purine biosynthesis are oxidised to the level of uric acid in cytosol. Uric acid is oxidised by uricase, and allantoin by allantoinase to the end product, allantoic acid. The last two steps might occur in the peroxisomes and endoplasmic reticulum. The metabolic pathway involved in the further utilization of allantoic acid, with release of nitrogen in a form readily assimilated into amino acids and proteins, has not been defined.

Studies on relating ureides in the xylem sap of pigeonpea (as a proportion of total sap nitrogen) to the nitrogen-fixing ability of the plant indicated a close relationship between the ureide content, particularly of the xylem sap, and the nodulation status and ARA of the plant (Kumar Rao *et al.*, 1981). However, ureide measurements for quantification of N_2 fixation have been found to be unsatisfactory for pigeonpea for reasons stated earlier in this chapter.

RESIDUAL EFFECTS

Pigeonpea, like other legumes, has been found to benefit subsequent cereal crops. A medium-duration pigeonpea grown as a sole crop had a large residual effect on the following maize crop, increasing grain yield by 57% and total biomass by 32% compared to a fallow treatment (Kumar Rao *et al.*, 1983). From this study it was estimated that pigeonpea had a beneficial effect on maize equivalent to about 40 kg N ha^{-1}. Singh and Verma (1985) reported that pigeonpea UPAS 120, an early-maturing genotype, had a negligible effect on following wheat yields compared to fallow. Rathnakumar (1983) (cited by Ahlawat *et al.*, 1986) observed substantial nitrogen economy in maize following sole pigeonpea, or pigeonpea intercropped with short-duration grain legumes compared to a fallow-maize sequence. Similarly, pigeonpea intercropped with maize improved the soil nitrogen status but did not cause any increase in maize yield at any level of fertility. The yield of succeeding sugarcane, however, increased by 43% after a maize + pigeonpea system as compared with sole maize (Yadav, 1981). Recent studies with a short-duration pigeonpea at Gwalior, in the state of Madhya Pradesh in India, indicated a benefit of at least 40 kg N ha^{-1} to the following wheat crop (C.Johansen *et al.*, ICRISAT, unpublished). Recent studies at ICRISAT Center indicate that genotypic differences in nodulation and nitrogen fixation could be reflected in the magnitude of the beneficial effect of pigeonpea on a succeeding cereal crop grown on an Alfisol. The beneficial effect of ICP 1-6, a medium-maturing and high-nodulating pigeonpea genotype, on a succeeding sorghum grain yield was equivalent to about 30 kg N ha^{-1} compared to the fallow treatment. With ICPL 87, a low-nodulating but high-yielding genotype, the beneficial effect was less and equivalent to only about 5 kg N ha^{-1} (J.V.D.K. Kumar Rao *et al.*, unpublished).

Although the beneficial effects of legumes were recognized before the principles of crop rotation were established, the mechanism by which a legume benefits its subsequent crop, is still not very clear (Herridge, 1982). Using the ^{15}N isotope dilution method in a pigeonpea and cereal rotation it was reported that the cereal derived some N_2 fixed by the previous pigeonpea and the residual benefit to cereal was not only an effect of "sparing" of soil N (Kumar Rao *et al.*,1987). This result was in agreement with the observation of Poth *et al.* (1986) who reported that in a low-N soil, the amount of N incorporated into the soil from N_2 fixation by pigeonpea was at least equal to the N incorporated into the above-ground plant mass.

IMPROVEMENT OF NITROGEN FIXATION

Is Improvement Necessary?

Before embarking on ways to improve N_2 fixation in pigeonpea one needs to determine whether existing levels of nitrogen fixation are adequate to meet the nitrogen requirements of the crop or not. Earlier studies at ICRISAT Center showed significant responses of grain yield and shoot biomass in medium-duration pigeonpea to N fertilizer applied at sowing on both Alfisols and Vertisols (Kumar Rao *et al.*, 1981). Kulkarni and Panwar (1981) after reviewing the literature in India reported the beneficial effect of starter dose of 20-25 kg N ha^{-1} on pigeonpea grain yields.

Recent studies with a high-yielding, short-duration pigeonpea indicated that N applied at later growth stages i.e., from flowering onwards, boosted final dry matter and grain yield, particularly on a Vertisol (Table 10.2), thus confirming the inadequacy of the symbiosis on this soil, and suggesting scope for its improvement (ICRISAT, 1987). This finding also tallies with the generally poorer nodule development and greater incidence of nodule damage by insect larvae on this soil type. The lack of response to combined nitrogen in three other soil types, namely, an Alfisol at ICRISAT Center, an Entisol at Hisar in northern India, and an Inceptisol at Gwalior in central India may perhaps be due to high levels of N in the soil pool, or because N_2 fixation was adequate to meet the nitrogen requirements of the crops on these soils.

Rojoa (1980) working in Trinidad reported significant increase in grain yield of pigeonpea to two equal split applications of N; one at sowing, and the second at 40 days after emergence. He found that urea was more effective than sodium nitrate, ammonium chloride, and ammonium nitrate in terms of both growth and grain yield.

Table 10.2. Effect of fertilizer nitrogen (N) and its time of application on grain yield[1] (t ha^{-1}) of pigeonpea genotype ICPL 87 grown on a Vertisol and an Alfisol, ICRISAT Center, 1985/86.

Treatment	Grain yield (t ha^{-1})	
	Vertisol	Alfisol
0 N	2.63	3.21
20 kg N ha^{-1} at sowing	2.83	2.98
20 kg N ha^{-1} at sowing without *Rhizobium*[2]	2.79	3.45
20 kg N ha^{-1} at sowing without irrigation[2]	2.67	2.04
100 kg N ha^{-1} at sowing	2.61	2.37
20 kg N ha^{-1} at sowing + 50 kg N ha^{-1} at 40 DAS[3]	2.70	3.02
20 kg N ha^{-1} at sowing + 75 kg N ha^{-1} at 50% flowering	3.10	3.12
20 kg N ha^{-1} at sowing + 80 kg N ha^{-1} at pod filling	2.92	2.72
20 kg N ha^{-1} at sowing + 80 kg N ha^{-1} at first harvest	2.80	2.89
20 kg N ha^{-1} at sowing + 50 kg N ha^{-1} at 40 DAS + 75 kg N ha^{-1} at 50% flowering + 80 kg N ha^{-1} at pod filling + 80 kg N ha^{-1} at first harvest	3.10	3.11
SE	±0.07	±0.25
CV (%)	5	18

1. Total of three harvests.
2. Treatments omitting either *Rhizobium* inoculation or irrigation were also included for comparison.
3. DAS = Days after sowing.

Source: ICRISAT, 1987.

It thus appears that there is a need to improve nitrogen fixation by pigeonpea. The nitrogen fixation could be improved by; 1. inoculating with effective *Rhizobium* strains, 2. a better understanding of the environmental factors that affect the legume-*Rhizobium* symbiosis and an adoption of suitable management practices to overcome stresses, and 3. breeding and selection of host plants with increased nodulation and nitrogen fixation.

Inoculation with Effective *Rhizobium* Strains

A large variation in the nitrogen-fixing ability of pigeonpea rhizobia in symbiosis with pigeonpea has been reported (Dahiya, 1979; Kumar Rao and Dart, 1979; Ramaswamy and Nair, 1965). Although there were significant increases in early nodulation due to inoculation these were not always well-correlated with grain yield under field conditions. The increase in grain yield of pigeonpea inoculated with effective *Rhizobium* was found to range from 19 to 68% over the non-inoculated control (Rewari *et al.*, 1981; Simhadri and Tilak, 1976; Subba Rao, 1976, 1982; Thompson *et al.*, 1981). Seed inoculation with *Rhizobium* did not always effect increased yields, for the environment in which the legumes were grown, and the legume cultivar largely determined the functioning of the legume-*Rhizobium* symbiosis. For example, Quilt and Dalal (1979) reported from Trinidad that seed inoculation with exotic strains of *Rhizobium* increased pigeonpea grain yield significantly over noninoculated controls, particularly in soils where mineral nitrogen levels were reduced by incorporation of coconut fibre and bagasse. Another reason for lack of consistent response to inoculation over locations across years is the ubiquitous occurrence of the "cowpea" group of rhizobia, that nodulate pigeonpea, in tropical soils. For example, numbers of rhizobia that nodulate pigeonpea in soils at ICRISAT Center are about 10,000 g^{-1} dry soil on Alfisols and about 1000 g^{-1} dry soil on Vertisols (Kumar Rao *et al.*, 1982). There is very little data available to relate soil rhizobial number with extent of nodulation and inoculation response, and to enable conclusions to be drawn.

The method of inoculation may also determine the success of inoculation. The traditional seed inoculation method resulted in minimal increases in nodule number of pigeonpea (J.V.D.K. Kumar Rao, unpublished) and this suggests that development of more effective inoculation methods is warranted. Khurana *et al.* (1981) reported that seed inoculation of *Rhizobium* culture increased grain yield more than side furrow placement.

Another reason for the inconsistent response to *Rhizobium* inoculation is probably that the inoculant strains were less competitive than the native populations. Studies on the competitive ability of inoculant strains in nodulating pigeonpea under field conditions are limited (Nambiar *et al.*, 1988) mainly because there is no sensitive and reliable method by which to differentiate inoculant strains from the native rhizobial population.

Breeding for Increased Nitrogen Fixation

Genotypic variability for symbiotic characterstics has been reported in pigeonpea (Table 10.3). This was based on observations made during early growth stages i.e., around 1 month after sowing, and it is not clear if these early observations on nodulation are related to yields at maturity (Thompson *et al.*, 1981). It is important to establish genotypic differences in biological nitrogen fixation of pigeonpea over the full growing season probably by using either the ^{15}N natural abundance method (Yoneyama *et al.*, 1986) or plots enriched uniformly with ^{15}N. The ultimate aim of such studies should be to provide breeders with genotypes that have significantly superior N_2-fixing capacity, and that can be incorporated into breeding programmes. In a pigeonpea breeding programme care should be taken to ensure that progenies are grown under conditions, i.e., on soils low in nitrogen and with a high population of effective rhizobia, that favour strong symbiotic development.

Table 10.3. Range of symbiotic characteristics in 110 pigeonpea lines, 25 days after sowing in an Alfisol, ICRISAT Center, rainy season 1977.

Character	Range
Nodule number	6.7–37.8
Nodule mass (mg plant^{-1})	9–55
Nitrogenase activity	
(μM C_2H_4 plant^{-1} h^{-1})	1.1–11.3
(μM C_2H_4 g nodule^{-1} h^{-1})	65–565
Shoot dry mass (mg plant^{-1})	383–1408
Root dry mass (mg plant^{-1})	38–185

Source: Thompson *et al.*, 1981.

Recent studies have indicated the possibility of improving nodulation through breeding and identification of progenies with increased yield and N_2-fixation in common bean (Attewell and Bliss, 1985) and red clover, subterranean clover, and alfalfa (Barnes *et al.*, 1985; Phillips and Teuber, 1985; Nutman, 1984). The author is not aware of any such attempt in pigeonpea.

FUTURE

The intensity of nodulation in pigeonpea is low compared to such other tropical legumes as cowpea and groundnut. The reasons for this low nodulation are not known, and they need to be studied. The various steps involved in root infection and nodule formation by rhizobia are little understood in pigeonpea and an insight into the regulatory mechanism of infection would probably explain the reasons for poor nodulation. This information might lead to favourable manipulation of nodulation and nitrogen fixation by pigeonpea. There are many situations, such as at Gwalior (Madhya Pradesh state) and Hisar (Haryana state) in northern India where pigeonpea nodulation has been reported as poor despite vigorous plant growth and detailed investigations are needed to clarify this — is the poor nodulation due to lack of rhizobia, or because of stress factors such as high temperature and high levels of NO_3- N?

In pigeonpea the recently developed, high-yielding, extra-short-duration (about 3 months) genotypes are altogether a new plant type, and they should be examined for the adequacy of their symbiotic nitrogen fixation. There is a need to improve the nitrogen-fixing ability of short-duration pigeonpeas as these genotypes respond to fertilizer nitrogen. This can probably be achieved either by extending the longevity of nodule activity into the pod-filling stage and/or selecting genotypes with resistance to nodule damage by *Rivellia angulata*.

Studies on the ecology of pigeonpea rhizobia deserve more attention. Because of cross-reactivity among cowpea rhizobia it has not been easy to distinguish inoculant strains of pigeonpea from native rhizobia. Unless improved methods of identification of inoculant strains are developed, ecological studies of pigeonpea rhizobia cannot make much progress.

Because of the sensitivity of symbiotic activity to salinity, waterlogging and drought stress, or temperature stress, monitoring the symbiosis and understanding its response to particular stresses will be mandatory before selecting appropriate symbioses for stress conditions.

The nitrogen made available by pigeonpea of different maturity groups; extra-short, medium-, and long-duration in various cropping systems (sole, inter, and mixed cropping), needs to be quantified as this is one of the important assets of legumes that should be catalogued along with their other economically useful characters.

Acknowledgement

The author thanks Dr C. Johansen, ICRISAT for his helpful comments in the preparation of this manuscript.

REFERENCES

Abruna, F., Rivera, E. and Rodriguez Garcia, J.A. (1984) Crop response to soil acidity factors in Ultisols and Oxisols in Puerto Rico. X. Pigeonpeas. *Journal of Agriculture of the University of Puerto Rico* 68, 433-443.

Ahlawat, I.P.S., Ali, M., Pal, M. and Singh, A. (1986) Research needs and directions on pigeonpea based cropping systems. In: Pal, M. (ed), *Proceedings of the National Symposium on Cropping Systems, 3-5 April 1985, Central Soil Salinity Research Institute, Karnal, Haryana.* ICAR and the Indian Society of Agronomy, New Delhi, India, pp. 183-209.

Albrecht, S.L., Maier, R.J., Hanus, F.J., Russel, S.A., Emerich, D.W. and Evans, H.J. (1979) Hydrogenase in *Rhizobium japonicum* increases nitrogen fixation by nodulated soybeans. *Science* 203, 1255-1257.

Alexander, M. (1982) Research to enhance nitrogen fixation: misplaced emphasis? In: *Priorities in Biotechnology for International Development*. National Academy Press, Washington, D.C., USA, pp. 208-229.

Allen, O.N. and Allen, E.K. (1981) *The Leguminosae. A Source Book of Characteristics, Uses, and Nodulation*. The University of Wisconsin Press, Wisconsin, USA, 812 pp.

Amarjit and Singh, R. (1984) Ureide biogenesis and the enzymes of ammonia assimilation and ureide biosynthesis in nitrogen fixing pigeonpea (*Cajanus cajan*) nodules. *Journal of Biosciences* 6, 185-192.

Appleby, C.A. (1984) Leghemoglobin and *Rhizobium* respiration. *Annual Review of Plant Physiology* 35, 443-478.

Attewell, J. and Bliss, F.A. (1985) Host plant characterstics of common bean lines selected using indirect measures of N_2 fixation. In: Evans, H.J., Bottomley, P.J. and Newton, W.E. (eds), *Nitrogen Fixation Research Progress*. Martinus Nijhoff Publishers, Dordrecht, the Netherlands, pp. 3-9.

Bagyaraj, J. and Rangaswami, G. (1966) On the variations in rhizosphere effects of some crop plants. *Current Science* 35, 238-239.

Barnes, D.K., Jessen, D.L., Heichel, G.H. and Vance, C.P. (1985) Selection for multiple traits increases alfalfa N_2-fixation and yield. In: Evans, H.J., Bottomley, P.J. and Newton, W.E. (eds), *Nitrogen Fixation Research Progress*. Martinus Nijhoff Publishers, Dordrecht, the Netherlands, p. 27.

Bauer, W.D. (1981) Infection of legumes by rhizobia. *Annual Review of Plant Physiology* 32, 407-449.

Bergersen, F.J. (1982) *Root Nodules of Legumes: Structure and Functions*. Research Studies Press, John Wiley and Sons, Chichester, 164 pp.

Bergersen, F.J. and Goodchild, D.J. (1973) Cellular location and concentration of leghaemoglobin in soybean root nodules. *Australian Journal of Biological Sciences* 26, 741-756.

Black, C.C. (1973) Photosynthetic carbon fixation in relation to net CO_2 uptake. *Annual Review of Plant Physiology* 24, 253-286.

Black, C.C., Brown, R.H. and Moore, R.C. (1978) Plant photosynthesis. In: Döbereiner, J., Burns, R.H. and Hollaender, A. (eds), *Limitations and Potentials for Biological Nitrogen Fixation in the Tropics*. Plenum Press, New York, USA, pp. 95-110.

Bromfield, E.S.P. and Kumar Rao, J.V.D.K. (1983) Studies on fast and slow growing *Rhizobium* spp. nodulating *Cajanus cajan* and *Cicer arietinum*. *Annals of Applied Biology* 102, 485-493.

Broughton, W.J. (1978) A review: control of specificity in legume-*Rhizobium* associations. *Journal of Applied Bacteriology* 45, 165-194.

Burns, R.C. and Hardy, R.W.F. (1975) Nitrogen fixation in bacteria and higher plants. In: Kleinzer, A., Springer, G.F. and Wittman, H.G. (eds), *Molecular Biology, Biochemistry and Biophysics 21*. Springer-Verlag, Berlin, pp. 1-189.

Dahiya, J.S. (1979) Evaluation of *Cajanus cajan* (L) rhizobia. *Thesis Abstracts* 5, 274.

Dalal, R.C. and Quilt, P. (1977) Effects of N, P, liming and Mo on nutrition and grain yield of pigeonpea. *Agronomy Journal* 69, 854-857.

Dart, P.J. (1977) Infection and development of leguminous nodules. In: Hardy, R.W.F. and Silver, W.S. (eds), *A Treatise on Dinitrogen Fixation–Section III: Biology*. John Wiley and Sons, New York, USA, pp. 367-472.

Dazzo, F.B., Hollingsworth, R.I., Sherwood, J.E., Abe, M., Hrabak, E.M., Gardiol, A.E., Pankratz, H.S., Smith, K.B. and Yang, H. (1985) Recognition and infection of clover root hairs by *Rhizobium trifolii*. In: Evans, H.J., Bottomley, P.J. and Newton, W.E. (eds), *Nitrogen Fixation, Research Progress*. Martinus Nijhoff Publishers, Dodrecht, the Netherlands, pp. 239-245.

Dazzo, F.B. and Hubbell, D.H. (1982) Control of root hair infection. In: Broughton, W.J. (ed), *Nitrogen Fixation, volume II: Rhizobium*. Clarendon Press, Oxford, pp. 274-310.

Dilworth, M.J. (1974) Dinitrogen fixation. *Annual Review of Plant Physiology* 25, 81-114.

Dilworth, M.J. and Glenn, A. (1984) How does a legume nodule work? *Trends in Biochemical Sciences* 9, 519-523.

Dixon, R.O.D. (1978) Nitrogenase-hydrogenase interrelationships in rhizobia. *Biochemie* 60, 233-236.

Dudman, W.F. (1984) The polysaccharides and oligosaccharides of *Rhizobium* and their role in infection process. In: Veeger, C and Newton, W.E. (eds), ***Advances in Nitrogen Fixation Research***. Martinus Nijhoff, The Hague, pp. 397-404.

Eaglesham, A.R.J. and Ayanaba, A. (1984) Tropical stress ecology of Rhizobia, root nodulation and legume fixation. In: Subba Rao, N.S. (ed), *Current Developments in Biological Nitrogen Fixation*. Oxford and IBH, New Delhi, pp. 1-35.

Edwards, D.G. (1981) Development of research on pigeonpea nutrition. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 205-211.

Emerich, D.W., Ruiz-Argueso, T., Ching, T.M. and Evans, H.J. (1979) Hydrogen-dependent nitrogenase and ATP formation in *Rhizobium japonicum* bacteroids. *Journal of Bacteriology* 137, 153-160.

Franco, C.A. (1977) Contribution of the legume-*Rhizobium* symbiosis to the ecosystem and food production. In: Vincent, J.M., Whitney, A.S. and Bose, J. (eds), *Exploiting the Legume-Rhizobium Symbiosis in Tropical Agriculture*. University of Hawaii, Hawaii, USA, pp. 237-252.

Gibson, A.H. (1977) The influence of the environment and managerial practices on the legume-*Rhizobium* symbiosis. In: Hardy, R.W.F. and Gibson, A.H. (eds), *A Treatise on Dinitrogen Fixation–Section IV: Agronomy and Ecology*. John Wiley and Sons, New York, USA, pp. 393-450.

Gordon, J.K. and Brill, W.J. (1974) Depression of nitrogenase synthesis in the presence of excess NH_4^+. *Biochemical and Biophysical Research Communications* 59, 867-871.

Hanus, F.J., Albrecht, S.L., Zablotowicz, R.M., Emerich, D.W., Russel, S.A. and Evans, H.J. (1981) Yield and N content of soybean seed as influenced by *Rhizobium japonicum* inoculants possessing the hydrogenase characteristic. *Agronomy Journal* 73, 368-372.

Hernandez, B.S. and Focht, D.D. (1985) Effects of phosphorus, calcium and Hup and Hup^{+} rhizobia on pigeonpea yields in an infertile tropical soil. *Agronomy Journal* 77, 867-871.

Herridge, D.F. (1981) Estimating N_2 fixation in field grown-soybeans using ureide and nitrate analyses of plant parts and nodulation status of the plant throughout growth. In: Gibson, A.H. and Newton, W.E (eds), *Current Perspectives in Nitrogen Fixation*. Australian Academy of Science, Canberra, p. 484.

Herridge, D.F. (1982) Crop rotations involving legumes. In: Vincent, J.M. (ed), *Nitrogen Fixation in Legumes*. Academic Press, Sydney, pp. 253-262.

Herridge, D.F., Atkins, C.A., Pate, J.S. and Rainbird, R.M. (1978) Allantoin and allantoic acid in the nitrogen economy of the cowpea (*Vigna unguiculata* [L.] Walp.). *Plant Physiology* 62, 495-498.

Huang, C.Y., Boyer, J.S. and Vanderhoef, L.N. (1975) Acetylene reduction (nitrogen fixation) and metabolic activities of soybean having various leaf and nodule water potentials. *Plant Physiology* 56, 222-227.

Huda, A.K.S. and Virmani, S.M. (1987) Agroclimatic environment of chickpea and pigeonpea. In: *Adaptation of Chickpea and Pigeonpea to Abiotic Stresses. Proceedings of the Consultants' Workshop, 19-21 December 1984, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 15-31.

Hwang, J.C., Chen, C.H. and Burris, R.H. (1973) Inhibition of nitrogenase. *Biochimica et Biophysica Acta* 292, 256-270.

ICRISAT (1983) *Annual Report 1982*. Patancheru, A.P., India: ICRISAT, pp. 147-148.

ICRISAT (1987) *Annual Report 1986*. Patancheru, A.P., India: ICRISAT, pp. 191-192.

Jadhav, T.K. and Moniz, L. (1972) Cross inoculation studies with *Rhizobia* of cultivated and wild tur and Sunnhemp. *Research Journal of Mahatma Phule Agricultural University* 3(1-2), 64-66.

Jordon, D.C. (1984) Family III. Rhizobiaceae. In: Kreig, N.R. and Holt, J.G. (eds), *Bergey's Manual of Systematic Bacteriology, volume 1*. Williams and Wilkins, Baltimore, USA, pp. 234-256.

Kanwar, J.S. and Rego, T.J. (1983) Fertilizer use and watershed management in rainfed areas for increasing crop production. *Fertilizer News* 28(9),33-43.

Kapil, R.N. and Kapil, N. (1971) Root nodules of *Cajanus cajan*: origin, structure and ontogeny. *Phytomorphology* 21, 192-202.

Khurana, A.L. and Dudeja, S.S. (1981) Field populations of rhizobia and response to inoculation, molybdenum and nitrogen fertilizer in pigeonpea. In: *Proceedings of the International Workshop on Pigeonpeas, volume 2, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 381-386.

Khurana, A.L., Dudeja, S.S. and Singh, R.C. (1981) Comparison of two methods of inoculation of rhizobia in pigeonpea. *Haryana Agricultural University Journal of Research* 11, 517-520.

Kulkarni, K.R. and Panwar, K.S. (1981) Response of pigeonpea to fertilizers in India: a critical review. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 212-220.

Kumar Rao, J.V.D.K. and Dart, P.J. (1979) Biology of nodulation of pigeonpea *Cajanus cajan* (L.) Millsp. In: *Proceedings of the Sixth Australian Legume Nodulation Conference, 21-24 August 1979, Perth, Australia*. University of Western Australia, Perth, Australia, pp. 80-82.

Kumar Rao, J.V.D.K. and Dart, P.J. (1981) Effect of different plant growth media on nodulation, growth and nutrient uptake of pigeonpea. In: *Proceedings of the International Workshop on Pigeonpeas, volume 2, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 403-408.

Kumar Rao, J.V.D.K. and Dart, P.J. (1987) Nodulation, nitrogen fixation and nitrogen uptake in pigeonpea (*Cajanus cajan* (L.) Millsp.) of different maturity groups. *Plant and Soil* 99, 255-266.

Kumar Rao, J.V.D.K., Dart, P.J., Matsumoto, T. and Day, J.M. (1981) Nitrogen fixation by pigeonpea. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 190-199.

Kumar Rao, J.V.D.K., Dart, P.J. and Sastry, P.V.S.S. (1983) Residual effect of pigeonpea (*Cajanus cajan*) on yield and nitrogen response of maize. *Experimental Agriculture* 19, 131-141.

Kumar Rao, J.V.D.K., Dart, P.J. and Usha Kiran, M. (1982) Cowpea-group *Rhizobium* in soils of the semiarid tropics. In: Graham, P.H. and Harris, S.C. (eds), *Biological Nitrogen Fixation Technology for Tropical Agriculture: Papers presented at a Workshop held at CIAT, March 9-13, 1981*. Cali, Columbia: Centro Internacional de Agricultura Tropical, pp. 291-295.

Kumar Rao, J.V.D.K., Dart, P.J. and Usha Kiran, M. (1984) *Rhizobium* induced leaf-roll in pigeonpea [*Cajanus Cajan* (L.) Millsp.]. *Soil Biology and Biochemistry* 16, 89-91.

Kumar Rao, J.V.D.K. and Sithanantham, S. (1989) Impact of nodule damage by *Rivellia angulata* on N_2-fixation, growth and yield of pigeonpea (*Cajanus cajan* (L.) Millsp.) grown in a Vertisol. *Biology and Fertility of Soils* 7, 95-100.

Kumar Rao, J.V.D.K., Thompson, J.A., Sastry, P.V.S.S., Giller, K.E. and Day, J.M. (1987) Measurement of N_2-fixation in field-grown pigeonpea [*Cajanus cajan* (L.) Millsp.] using ^{15}N-labelled fertilizer. *Plant and Soil* 101, 107-113.

La Favre, J.S. and Focht, D.D. (1985) Nitrogen fixation and hydrogen evolution by the pigeonpea-*Rhizobium* symbiosis. *Tropical Agriculture (Trinidad)* 62, 285-288.

La Rue, T.A. and Patterson, T.G. (1981) How much nitrogen do legumes fix? *Advances in Agronomy* 34, 15-38.

Lie, T.A. (1981) Environmental physiology of the legume-*Rhizobium* symbiosis. In: Broughton, W.J. (ed), *Nitrogen Fixation, volume I: Ecology*. Clarendon Press, Oxford, UK, pp. 104-134.

Luthra, Y.P., Sheoran, I.S. and Singh, R. (1981) Pigeonpea (*Cajanus cajan*)–a ureide producing grain legume. *Current Science* 50, 270-271.

Luthra, Y.P., Sheoran, I.S. and Singh, R. (1985) Influence of source-sink alterations on photosynthesis and nitrogen fixation in pigeonpea. *Field Crops Research* 12, 331-338.

McClure, P.R. and Israel, D.W. (1979) Transport of nitrogen in the xylem of soybean plants. *Plant Physiology* 64, 411-416.

Meeks, J.C., Wolk, C.P., Schilling, N., Shaffer, P.W., Avissar, Y. and Chien, W.S. (1978) Initial organic products of fixation of [^{13}N] dinitrogen by root nodules of soybean (*Glycine max*). *Plant Physiology* 61, 980-983.

Minchin, F.R. and Pate, J.S. (1975) Effects of water, aeration, and salt regime on nitrogen fixation in a nodulated legume–definition of an optimum root environment. *Journal of Experimental Botany* 26, 60-69.

Minchin, F.R., Sheehy, J.E. and Witty, J.F. (1985) Factors limiting N_2 fixation by the legume-*Rhizobium* symbiosis. In: Evans H.J., Bottomley, P.J. and Newton, W.E. (eds), *Nitrogen Fixation Research Progress*. Martinus Nijhoff Publishers, Dordrecht, the Netherlands, pp. 285-291.

Nambiar, P.T.C., Rupela, O.P. and Kumar Rao, J.V.D.K. (1988) Nodulation and nitrogen fixation in groundnut (*Arachis hypogaea* L.), chickpea (*Cicer arietinum* L.) and pigeonpea (*Cajanus cajan* L. Millsp.). In: Subba Rao, N.S. (ed), *Biological Nitrogen Fixation–Recent Developments*. Oxford and IBH, New Delhi, pp. 21- 52.

Nutman, P.S. (1984) Improving nitrogen fixation in legumes by plant breeding; the relevance of host selection experiments in red clover (*Trifolium pratense* L.) and subterranean clover (*T. subterraneum* L.). *Plant and Soil* 82, 285-301.

Ohyama, T. and Kumazawa, K. (1980) Nitrogen assimilation in soybean nodules. II. $^{15}N_2$ assimilation in bacteroid and cytosol fractions of soybean nodules. *Soil Science and Plant Nutrition* 26, 205-213.

Pate, J.S. (1977) Functional biology of dinitrogen fixation by legumes. In: Hardy, R.W.F. and Silver, W.S. (eds), *A Treatise on Dinitrogen Fixation–Section III: Biology*. John Wiley and Sons, New York, pp. 473-517.

Pate, J.S., Atkins, C.A. and Rainbird, R.M. (1981) Theoritical and experimental costing of nitrogen fixation and related processes in nodules of legumes. In: Gibson, A.H. and Newton, W.E. (eds), *Current Perspectives in Nitrogen Fixation*. Australian Academy of Science, Canberra, pp. 105-116.

Pate, J.S., Atkins, C.A., White, S.T., Rainbird, R.M. and Woo, K.C. (1980) Nitrogen nutrition and xylem transport of nitrogen in ureide-producing grain legumes. *Plant Physiology* 65, 961- 965.

Phillips, D.A. and Teuber, L.R. (1985) Genetic improvement of symbiotic nitrogen fixation in legumes. In: Evans, H.J., Bottomley, P.J. and Newton, W.E. (eds), *Nitrogen Fixation Research Progress*. Martinus Nijhoff Publishers, Dordrecht, the Netherlands, pp. 11-17.

Postgate, J.R. (1982) *The Fundamentals of Nitrogen Fixation*.Cambridge University Press, Cambridge, 252 pp.

Poth, M., La Favre, J.S. and Focht, D.D. (1986) Quantification by direct ^{15}N dilution of fixed N_2 incorporation into soil by *Cajanus cajan* (pigeonpea). *Soil Biology and Biochemistry* 18, 125-127.

Quilt, P. and Dalal, R.C. (1979) Effect of soil mineral N levels and inoculation on nodulation, nitrogenase activity, and grain yield of pigeonpea. *Agronomy Journal* 71, 450-452.

Raj, A.S. (1987) Cobalt nutrition of pigeonpea and peanut in relation to growth and yield. *Journal of Plant Nutrition* 10, 2137-2145.

Ramaswamy, P.P. and Nair, K.S. (1965) Symbiotic variation of *Rhizobium* from nodules of redgram (*Cajanus cajan*). *Madras Agricultural Journal* 52, 239-240.

Reddi, K.C.S. and Prine, G.M. (1982) Nitrogenase activity measurements in summer green manure crops. *Florida Scientist* 45, 3.

Rewari R.B., Kumar, V. and Subba Rao, N.S. (1981) Response of pigeonpea to *Rhizobium* inoculation in India. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 238-248.

Reynolds, P.H.S., Boland, M.J., Blevins, D.G., Schubert, K.R. and Randall, D.D. (1982) Enzymes of amide and ureide biogenesis in developing soybean nodules. *Plant Physiology* 69, 1334-1338.

Rojoa, H (1980) Fertilizer response and mineral nutrition of pigeonpea (*Cajanus cajan* (L.) Millsp.). PhD thesis, University of West Indies, Trinidad.

Schubert, K.R. (1986) Products of biological nitrogen fixation in higher plants: synthesis, transport, and metabolism. *Annual Review of Plant Physiology* 37, 539-574.

Schubert, K.R. and Evans, H.J. (1976) Hydrogen evolution, a major factor affecting the efficiency of nitrogen fixation in nodulated symbionts. *Proceedings of the National Academy of Sciences of the United States of America* 73, 1207-1211.

Schubert, K.R., Jennings, N.T. and Evans, H.J. (1978) Hydrogen reactions of nodulated leguminous plants. II. Effects on dry matter accumulation and nitrogen fixation. *Plant Physiology* 61, 398-401.

Sen, A.N. (1956) Nitrogen economy of soil under rahar (*Cajanus cajan*). *Journal of Indian Society of Soil Science* 6, 171-176.

Sethunathan, N. (1970) Foliar sprays of growth regulators and rhizosphere effect in *Cajanus cajan* Millsp. I. Quantitative changes. *Plant and soil* 33, 62-70.

Sheoran, I.S., Luthra, Y.P., Kuhad, M.S. and Singh, R. (1981) Effect of water stress on some enzymes of nitrogen metabolism in pigeonpea. *Phytochemistry* 20, 2675-2677.

Siddapaji, C. and Gowda, T.K.S. (1980) Rhizobial nodules eating insect-*Rivellia* sp.–a new pest of pulse crops in India. *Current Research* 9,122-123.

Simhadri, P. and Tilak, K.V.B.R. (1976) Comparative performance of different strains of *Rhizobium* species on pigeonpea (*Cajanus cajan* (L.) Millsp.). *Pantnagar Journal of Research* 1(1), 26-29.

Singh, C.S. and Subba Rao, N.S. (1981) Nodulation of *Cajanus cajan* (pigeonpea) by *Rhizobium japonicum*. *Current Science* 50, 866-868.

Singh, R.C. and Faroda, A.S. (1986) Effect of cropping systems and phosphorus on nodulation in pigeonpea and soil fertility. *Indian Journal of Agronomy* 31, 203-204.

Singh, S.B. and Verma, B.S. (1985) Effect of *kharif* grain legumes on nitrogen economy in succeeding crop of wheat. *Indian Journal of Agronomy* 30, 397-400.

Sithanantham, S., Kumar Rao, J.V.D.K., Reed, W. and Dart, P.J. (1981) Studies on nodule damage in pigeonpea. In: *Proceedings of the International Workshop on Pigeonpeas, volume 2, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 409-415.

Sprent, J.I. (1980) Root nodule anatomy, type of export product and evolutionary origin in some leguminosae. *Plant, Cell and Environment* 3, 35-43.

Sprent, J.I. and Gallacher, A. (1976) Anaerobiosis in soybean root nodules under water stress. *Soil Biology and Biochemistry* 8, 317-320.

Stewart, W.D.P. (1967) Nitrogen fixing plants. *Science* 158, 1426-1432.

Subbarao, G.V. (1984) Salt tolerance of pigeonpea (*Cajanus cajan*) genotypes, its rhizobia and symbiotic nitrogen fixation. M Tech thesis, Indian Institute of Technology, Kharagpur, West Bengal, India, 74 pp.

Subbarao, G.V. (1988) Salinity tolerance in pigeonpea (*Cajanus cajan* (L.) Millsp.) and its wild relatives. PhD thesis, Indian Institute of Technology, Kharagpur, West Bengal, India, 217 pp.

Subba Rao, N.S. (1976) Field response of legumes in India to inoculation and fertilizer applications. In: P.S. Nutman (ed), *Symbiotic Nitrogen Fixation in Plants*. Cambridge University Press, London, pp. 255-268.

Subba Rao, N.S. (1982) Symbiotic nitrogen fixation by nodulated legumes. In: *Biological Nitrogen Fixation. Proceedings of the National Symposium held at Indian Agricultural Research Institute, New Delhi, February 25-27 1982*. FAO Committee and Department of Atomic Energy, New Delhi, India, pp. 27-48.

Thompson, J.A., Kumar Rao, J.V.D.K. and Dart, P.J. (1981) Measurement of inoculation response in pigeonpea. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 249-253.

Toomsan, B. (1981) Studies on some ecological aspects of *Cicer Rhizobium* and the effect of *Rhizobium* inoculation methods on chickpeas (*Cicer arietinum* L.). PhD thesis, University of Manitoba, Manitoba, Canada.

Upadhayaya, N.M., Tucker, W.T., Kumar Rao, J.V.D.K. and Dart, P.J. (1985) Analysis of a leaf-curl phenomenon in pigeonpea (*Cajanus cajan* (L.) Millsp.) induced by *Rhizobium* nodulation. In: Evans, H.J., Bottomley, P.J. and Newton, W.E. (eds), *Nitrogen Fixation Research Progress*. Martinus Nijhoff Publishers, Dordrecht, the Netherlands, p. 145.

Wilson, J.R. (1970) Response to salinity in *Glycine* VI. Some effects of a range of short-term salt stresses on the growth, nodulation, and nitrogen fixation of *Glycine wightii* (formerly *javanica*). *Australian Journal of Agricultural Research* 21, 571-582.

Worrall, V.S. and Roughley, R.J. (1976) The effect of moisture stress on infection of *Trifolium subterraneum* L. by *Rhizobium trifoli* Dang. *Journal of Experimental Botany* 27, 1233-1241.

Yadav, R.L. (1981) Intercropping pigeonpea to conserve fertilizer nitrogen in maize and produce residual effects on sugarcane. *Experimental Agriculture* 17, 311-315.

Yoch, D.C. and Valentine, R.C. (1972) Ferredoxins and flavodoxins of bacteria. *Annual Review of Microbiology* 26, 139-162.

Yoneyama, T., Nakano, H., Kuwahara, M., Takahashi, T., Kambayashi, I. and Ishizuka, J. (1986) Natural ^{15}N abundance of field grown soybean grains harvested in various locations in Japan and estimate of the fractional contribution of nitrogen fixation. *Soil Science and Plant Nutrition* 32, 443-449.

Zablotowicz, R.M., Russell, S.A. and Evans, H.J. (1980) Effect of the hydrogenase system in *Rhizobium japonicum* on the nitrogen fixation and growth of soybeans at different stages of development. *Agronomy Journal* 72, 555-559.

Chapter 11

PIGEONPEA: OPTIMUM AGRONOMIC MANAGEMENT

Y.S. CHAUHAN

Crop Physiologist, Legumes Program, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Andhra Pradesh 502 324, India.

INTRODUCTION

Pigeonpea has a long history of cultivation as a subsistence crop in the semi-arid areas of the tropics and subtropics. The ability of pigeonpea to produce economic yields in soils characterized by moisture deficits makes it an important crop of dryland agriculture. Farmers grow it in various production systems as a mixed crop, an intercrop, in backyards, and as a perennial crop using long-established traditional practices. Since the primary objective of pigeonpea cultivation has been to meet domestic requirements for food and fuel with limited market surpluses of grain, there has been very little innovation in its cultivation. This has resulted in yields remaining low, at about 600-700 kg ha^{-1}, although the total production of the crop is increasing, mainly due to an increase in the area sown. There has been a growing realization that it is necessary to improve the agronomy of the crop in order to increase its yields. Consequently, research on the agronomy of pigeonpea has been receiving increasing attention both in India, the major producer of this crop, and elsewhere. The earlier agronomic work, which was mainly on the traditional medium- and long-duration genotypes, has been reviewed by Akinola *et al.* (1975). The development of short-duration genotypes has given a new impetus to agronomic research. Several new production systems have been devised in which pigeonpea can be grown as a commercial crop with a greater response to inputs and agronomic management than in traditional production systems.

CROPPING SYSTEMS

Pigeonpea is grown in a wide range of cropping systems which, for convenience, have been broadly divided into three classes; long-, full-, and short-season crops (Byth *et al.*, 1981). Long-season crops are sown around the longest day of the year and flower after the shortest day. Pigeonpea is sown at sparse densities and almost always grown as mixed crop or intercropped with one or more other species (Laxman Singh and Shrivastava, 1976). Pigeonpea in this cropping system, which is traditional in north and central India and eastern Africa, grows vegetatively for nearly 6-7 months and takes about 9-11 months to mature.

Full-season crops mature 3-4 months earlier than long-season crops, when sown around the longest day. These are also grown at low plant densities (<5 plant m^{-2}) either as a mixed crop or intercropped with sorghum, millets, or short-season legumes. This type of production system is common in peninsular India. In both long- and full-season crops, intercropping results in better utilization of resources and higher combined yields of crops are obtained than if the crops were grown separately (Willey *et al.*, 1981). These production systems, though more productive and stable, necessarily restrict the yields of pigeonpea in farmers' fields (Whiteman *et al.*, 1985).

Short-season crops either involve short-duration cultivars which mature in 4-5 months, when sown around the longest day, or depend on sowing several months after the longest day when more rapid flowering under short days enables both photoperiod-sensitive and insensitive cultivars to be used. Both types of crops are usually sown as a sole crop at high plant populations (e.g., 15-50 plants m^{-2}).

By using short-duration cultivars double-cropping is possible. The short-duration pigeonpea-wheat rotation has now become an important production system of pigeonpea cultivation in northern India (Baldev, 1988). Also, where winters are mild, e.g., in peninsular India, one to two additional ratoon harvests with high yields can also be taken (Chauhan *et al.*, 1987b).

Another short-season cropping system involving off-season sowings is feasible only where winters are mild. September/October sowings of pigeonpea and pigeonpea after rice crops in India are typical examples (Narayanan and Sheldrake, 1979; Roy Sharma *et al.*, 1981; Satyanarayana *et al.*, 1988). These short-season cropping systems are relatively new, and can therefore be considered as nontraditional systems — a considerable amount of agronomic work has been carried out in recent years to improve them.

Pigeonpea is also grown as a perennial and in backyards. The perennial characteristic is a useful trait in subsistence cropping and is also being tested for exploitation in agroforestry systems (C.K. Ong, ICRISAT, personal communication).

PRODUCTION PRACTICES

The basic aim of optimizing agronomic practices is to realize the genotypic potential of economic products to maximum extent in a given environment. By and large, the importance of management factors such as improved genotypes, sowing time, plant population, and weed management; and inputs such as fertilizers, irrigation, and insecticides have been overlooked in the context of pigeonpea since it has been treated as relatively a minor crop in traditional production systems. It is now being realized that these factors are not only crucial to the production of good short-season crops, but also to improve the yield potential in more traditional systems (Willey *et al.*, 1981).

Land Requirements and Management

Pigeonpea is grown on a wide range of soils found in the tropics and subtropics including Entisols, Vertisols, Alfisols, Inceptisols, Ultisols, and Oxisols. Depth, pH, nutrient status and moisture-holding capacity vary widely in these soils. Both Entisols and Vertisols are generally deep and hold more than 200 mm plant-available water to a 1.5-m depth at the end of the rainy season, whereas Alfisols are usually less than 1m deep and hold less than 90 mm plant-available water to a 1.0-m depth (Reddy and Virmani, 1981). Production of pigeonpea varies greatly depending on the depth and moisture holding capacity of the soil. The crop generally thrives well on Entisols, but suffers from excess water on Vertisols and moisture deficits on Alfisols and Inceptisols (Reddy and Virmani, 1981).

Pigeonpea grows well in the soil pH range of 5-8. In acidic soils crop growth is adversely affected due to aluminium (Al) toxicity (Abruna *et al.*, 1984) or calcium (Ca) deficiency. Such soils can be amended by the application of lime (Dalal and Quilt, 1977). Soils with electrical conductivity greater than 1.5 dS m^{-1} (measured in 1:2 soil water extracts) affect the plant by stunting its growth (Chauhan, 1987; Johansen *et al.*, in press). Since cultivated pigeonpea is relatively susceptible to salinity compared to other crop plants, it is better to avoid saline soils. Similarly, fields where pigeonpea has been cultivated in the previous one or two seasons should be avoided, as these sometimes produce a poor crop due to a build up of nematodes and increased incidence of soilborne diseases (ICRISAT, 1977), besides possible allelopathic effects.

The pigeonpea crop does not require special land preparation. Deep ploughing to a depth of 15 cm is sufficient to obtain a good crop (Khan and Mathur, 1962; Lugo-Mercado *et al.*, 1987). However, where a hard pan exists in the rooting zone, subsoiling has been found beneficial in improving root development and infiltration rate (Reddy *et al.*, 1978). A well-tilled field may promote better root and nodule development in seedlings. Once established, pigeonpea roots are capable of penetrating hard-pan layers (Chauhan, in press).

Pigeonpea is very sensitive to waterlogging, particularly during the seedling stages. While a moderate excess of moisture may cause general yellowing of the crop, perhaps due to inhibition of nitrogen fixation, standing water for 2-3 days may result in partial or complete loss of stands depending on the growth stage of the crop (Chauhan, 1987). Adequate provision of surface drainage is therefore a very important consideration in land preparation. A crop sown on ridges gives 26-31% higher yield than one sown on flat beds (Choudhury and Bhatia, 1971; Tayo, 1985b), because ridges provide better soil aeration even on lighter soils such as Alfisols (K. Okada, ICRISAT, personal communication). Where ridging is not practical, a gentle slope is desirable. The broadbed and furrow system has been found very useful in improving drainage on Vertisols (Kampen, 1982). This system consists of relatively flat beds or ridges approximately 90-cm wide and shallow furrows 60-cm wide prepared using a multipurpose tool carrier, e.g., a "Tropicultor". Land-preparation operations with this machine begin in the dry season and are completed before the onset of the rainy season. Dry sowing is usually preferred as it is difficult to work on Vertisols when they are wet.

Such soils as Entisols and Alfisols that characteristically form a crust when the upper surface dries, can affect pigeonpea emergence (Sivaprasad and Sarma, 1987). Sowing on these soils should therefore be done when the soil has sufficient moisture content. If soils become crusted, a light irrigation or breaking the crust by mechanical means helps seedling emergence.

Seed and Seeding

Genotypes

One of the reasons often cited for the low yields of pigeonpea is the lack of improved genotypes available to the farmers (Singh, 1982). Farmers generally grow landraces of medium- and late-maturing types that are suitable for a single cropping sequence only. These genotypes incur greater risks of being exposed to abiotic stresses such as frosts and droughts. Moreover, they do not fit into intensive cultivation systems, e.g., in rotation with wheat in northern India. In keeping with the changing requirements of pigeonpea cultivation, a number of short-duration genotypes have been developed in India (AICPIP, 1986) and elsewhere (e.g., Hunt, Quantum, and Quest from the University of Queensland, Australia). Table 11.1 gives a list of short-duration genotypes that are currently recommended for different parts of India. A number of genotypes with tolerance of, or resistance to important diseases of pigeonpea are available in medium- and long-duration backgrounds. These can be sown in both the rainy and postrainy seasons.

Table 11.1. Short-duration genotypes of pigeonpea recommended for different zones in India, and their time to maturity in those zones.

	Maturity in different zones[1] (days)			
Genotypes	North-west plains	North-east plains	Central	Peninsular
Prabhat	120	-	-	-
Pusa Ageti	150	-	140	-
Pusa 74	160	-	150	-
Pusa 33	160	-	114	-
Pusa 84	140	-	-	-
UPAS 120	140	-	130	-
Pant A3	120	-	-	-
Sagar (H 77-208)	145	-	-	-
Manak (H 77-216)	140	-	-	-
ICPL 87	-	-	-	120
TT 5	160	-	-	-
TT 6	-	-	-	120
T 21	160	140	140	135
ICPL 151	140	-	120	-

1. According to their zone of adaptability.
Source: AICPIP, 1986.

Seed Quality

The capacity to form a good crop stand depends to a large extent on the quality of seed. Pigeonpea genotypes often cross-pollinate with genotypes growing in the surrounding area; the extent of such outcrossing depending on the genotypes and their location (Bhatia *et al.*, 1981). To obtain a uniform crop, farmers should use seed produced in isolation and subjected to roguing during the reproductive stage. Although precise estimates are not available, roguing of off-type plants from crops obtained from outcrossed seed can result in 10-20% loss of yield (K.B. Saxena, ICRISAT, personal communication).

Seeds stored at ambient temperatures and humidity for more than two seasons tend to lose their viability, sometimes by almost 50% (ICRISAT, 1981). Since no dormancy has been reported in pigeonpea (Khan and Ashley, 1975), it is preferable to use seed produced in the immediately previous season.

The importance of grading seed to obtain higher yields is well established in many crops. Limited work done on pigeonpea suggests that bolder seeds give better germination and seedling vigour than smaller seeds from the same lot (Khan and Ashley, 1975; Karivaratharaju *et al.*, 1982). Large seeds obtained by grading seed produce larger and heavier seedlings than small seeds; differences can persist for up to 6 weeks (Saxena *et al.*, 1981). Saxena *et al.* (1981) did not find this difference in seed size affected final seed yield, probably because the genotypes they used were of medium-duration; but seed size may have a greater effect on shorter-duration crops.

It is advantageous to discard off-coloured seeds that could be due to a mixture of genotypes, or to infection by *Rhizoctonia solani* and *Alternaria* sp (Karivaratharaju *et al.*, 1982).

Seeding Depth

Farmers following traditional practices broadcast seed on the soil surface and then use a blade harrow to bury the seed. This usually results in uneven sowing depth and poor emergence. The optimum depth for seeding pigeonpea is 4-5 cm (Khan and Ashley, 1975; Tayo, 1983). Tayo (1983) found that emergence declined from 84 to 42% when sowing depth increased from 4 to 8 cm. Seed yield was significantly reduced by sowing 8 cm deep. This is mainly because seedlings exhaust the reserves in their cotyledons before they emerge. For intensively managed pigeonpea sowing depth thus has very important implications for satisfactory stands, seedling vigour, and yield. A 4-5 cm depth is also suitable for sowing under dry conditions on Vertisols (Kampen, 1982). Seeds sown at shallower depths may be exposed to water deficits if dry weather persists soon after sowing. A uniform seeding depth is easily obtained when mechanical planters or drills are used, and since pigeonpea seeds are spherical, they are very suitable for machine sowing.

Time of Sowing

Long- and Full-season Crops

In traditional Indian systems, medium- and long-duration genotypes are sown around the longest day, at the onset of rains (15 Jun to approximately 15 Jul), when temperatures and soil moisture conditions are relatively favourable for their growth and yield. Sowing when days are long ensures that plants develop sufficient vegetative growth before they begin to flower. In rainfed areas there is little possibility of advancing sowing time to the summer because there is insufficient soil moisture. Even when irrigation is available there is no yield advantage in sowing earlier in the dry season (Bahar, 1982) though overall vegetative growth is considerably enhanced. Because pigeonpeas are photoperiod-sensitive, when they are sown later in the season they produce less vegetative growth since they flower early. In Australian conditions, this has facilitated mechanized cultivation (Wallis *et al.*, 1981). Late sowing, however, increases proneness to terminal drought in areas where winter rains are scarce, because the crop matures under receding moisture conditions (Singh and Das, 1987). In eastern Africa, pigeonpeas are sown in October/November, at the onset of the short rains. Being closer to the Equator, daylength changes in this region are relatively small and therefore do not induce early flowering or a reduced period of vegetative growth as they do in India and other pigeonpea-growing regions.

Short-season Crops

Short-duration Pigeonpea-Wheat Rotation

For short-duration pigeonpea genotypes maturing in 140-160 days, sowing at the onset of rainy season, which is in the first or second week of July in northwest India, is not the best way to obtain high yields (Rathi *et al.*, 1974; Ahlawat *et al.*, 1975; Kaul *et al.*, 1980; Saxena and Yadav, 1975; Rathi and Tripathi, 1978; Singh and Kalra, 1980; Sandhu *et al.*, 1981). Sowing in the first fortnight of June with irrigation or pre-monsoon rains generally results in higher yields while delayed sowings cause progressive reductions in yield. The reason for this is the decline in biomass production due to early flowering and slow growth (Dahiya *et al.*, 1974; Singh and Saxena, 1981). The other reason for the low yields of crops sown in the first week of July or later is that they come into the pod-filling stage some time in November when the cold period sets in so that pod formation and grain development are retarded (Ahlawat *et al.*, 1975). Further, if pigeonpea is sown late it delays the sowing of the sequential wheat crop (Kaul *et al.*, 1980; Sandhu *et al.*, 1981). The data given in Table 11.2 clearly show significant reductions in yields of both pigeonpea and wheat when pigeonpea was sown after 15 June. The yield reduction in wheat sown after pigeonpea is sometimes attributed to the harmful effects of pigeonpea on wheat, but it appears to be primarily due to delay in sowing the wheat. Whatever the reasons, the notion that yields of wheat sown after short-duration pigeonpea decline seems to be limiting the further expansion of the pigeonpea-wheat rotation in northern India.

Table 11.2. Effect of sowing date of pigeonpea on its grain yield (t ha^{-1}), and yield (t ha^{-1}) of subsequently sown wheat at Ludhiana, Punjab, India.

Pigeonpea sowing date	Time to maturity (days)	Yield (t ha^{-1}) Pigeonpea	Yield (t ha^{-1}) Wheat	Wheat sowing date
1 Jun	160	2.05	3.84	20 Nov
15 Jun	150	1.90	3.92	20 Nov
30 Jun	143	1.72	3.30	1 Dec
15 Jul	142	1.51	2.87	10 Dec
CD at 5%		0.250	0.240	

Source: Sandhu *et al.*, 1981.

The recently developed extra-short-duration genotypes can be sown as late as July in India with only a slight reduction in yield (Y.S. Chauhan and C. Johansen, ICRISAT, unpublished). Since these mature 15-20 days earlier than short-duration genotypes, they allow timely sowing of wheat. The height attained by these genotypes is about 1.5 m, about 25% less than the short-duration genotypes, but their yield potential is similar. Such genotypes may therefore be more suitable for rotation with wheat. If these genotypes, sown at the beginning of June, are affected by rains during the reproductive stage this reduces pod-set and delays maturity, indicating that agronomic conditions found suitable for short-duration pigeonpeas may not necessarily work well for extra-short-duration types.

In recent years, advancing sowing short-duration pigeonpea to April has been encouraged, mainly to allow timely sowings of wheat (Singh *et al.*, 1985). April-sown crops mature about 15-20 days earlier than those sown in June and produce more stalk (up to 15-17 t ha^{-1} as compared to 5-6 t ha^{-1} from June sowings), total dry matter, and up to 50% more seed yield. In addition, the following wheat crop produces 25% more yield than that following June-sown crops (Panwar and

Yadav, 1981). While there are substantial advantages in April sowing, the potential of this cropping pattern is limited by its requirement for several irrigations. Further, April-sown crops grow more than 3-m tall and therefore pose problems for insect control. Also, due to possible overlap with long-duration pigeonpea growing in the surrounding areas, susceptible cultivars risk being infected with sterility mosaic disease.

Short-duration Pigeonpea Multiple Harvest System

In tropical environments, such as peninsular India, winter temperatures are mild (e.g., >10°C) and therefore do not restrict pod-set in short-duration genotypes (Chauhan *et al.*, 1987b). For this reason, it is possible to obtain multiple harvests by allowing the crop to continue growing after harvesting the first flush of pods. In this situation sowing as early as possible in June ensures not only high yields from the first flush, but also from subsequent flushes under both rainfed and irrigated conditions (Figure 11.1). The main reason for the decline in the yield in July/August sowings is the reduced vegetative growth under the influence of declining temperature and solar radiation.

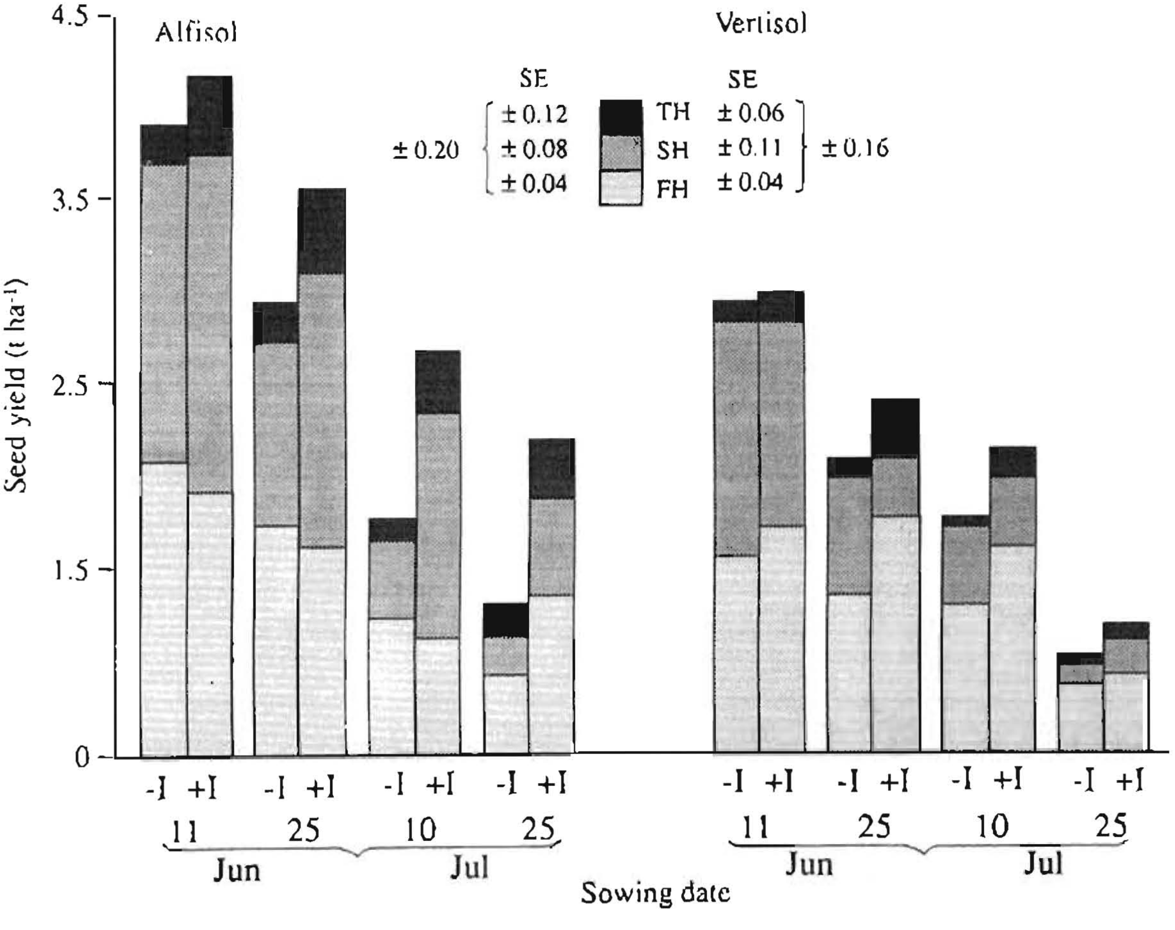


Figure 11.1. Effect of sowing date on the first (FH), second (SH), and third harvest (TH) and total seed yield (t ha^{-1}) of pigeonpea, ICPL 87 grown without (-I) and with (+I) irrigation on an Alfisol and a Vertisol, ICRISAT Center, 1984/85.

Source: ICRISAT, 1986.

Postrainy-season Pigeonpea

Pigeonpea can be sown as a postrainy-season crop in areas where winters are mild, such as parts of eastern and peninsular India. Under the influence of short photoperiods the crop takes less time to flower than in its normal growing seasons, and matures before the environmental conditions become too harsh. This has opened up the possibility of extending pigeonpea cultivation to areas where excessively wet conditions make it difficult to grow in the rainy season. Such areas include parts of eastern Uttar Pradesh, Bihar, and West Bengal in India. Long-duration genotypes sown when the major monsoon rains have stopped have been found to yield 2-3 t ha^{-1} seed which compares well with yields obtained in the main cropping season (Roy Sharma *et al.*, 1981; Sengupta, 1981; Bhowmik *et al.*, 1983). The yield potential is somewhat lower in peninsular India, between 1-2 t ha^{-1} (Narayanan and Sheldrake, 1979) due to increasing soil drought during the reproductive stage. Nevertheless, in all regions, September is the optimum time for post-monsoon sowing. In sowings later than 15 October, yields decline drastically (Narayanan and Sheldrake, 1979; Roy Sharma *et al.*, 1981). Figure 11.2 shows the response of short-, medium-, and long-duration genotypes to sowing date in the postrainy season in the peninsular Indian environment. The November-sown crop is constrained by extremely slow growth in the vegetative stage, and high

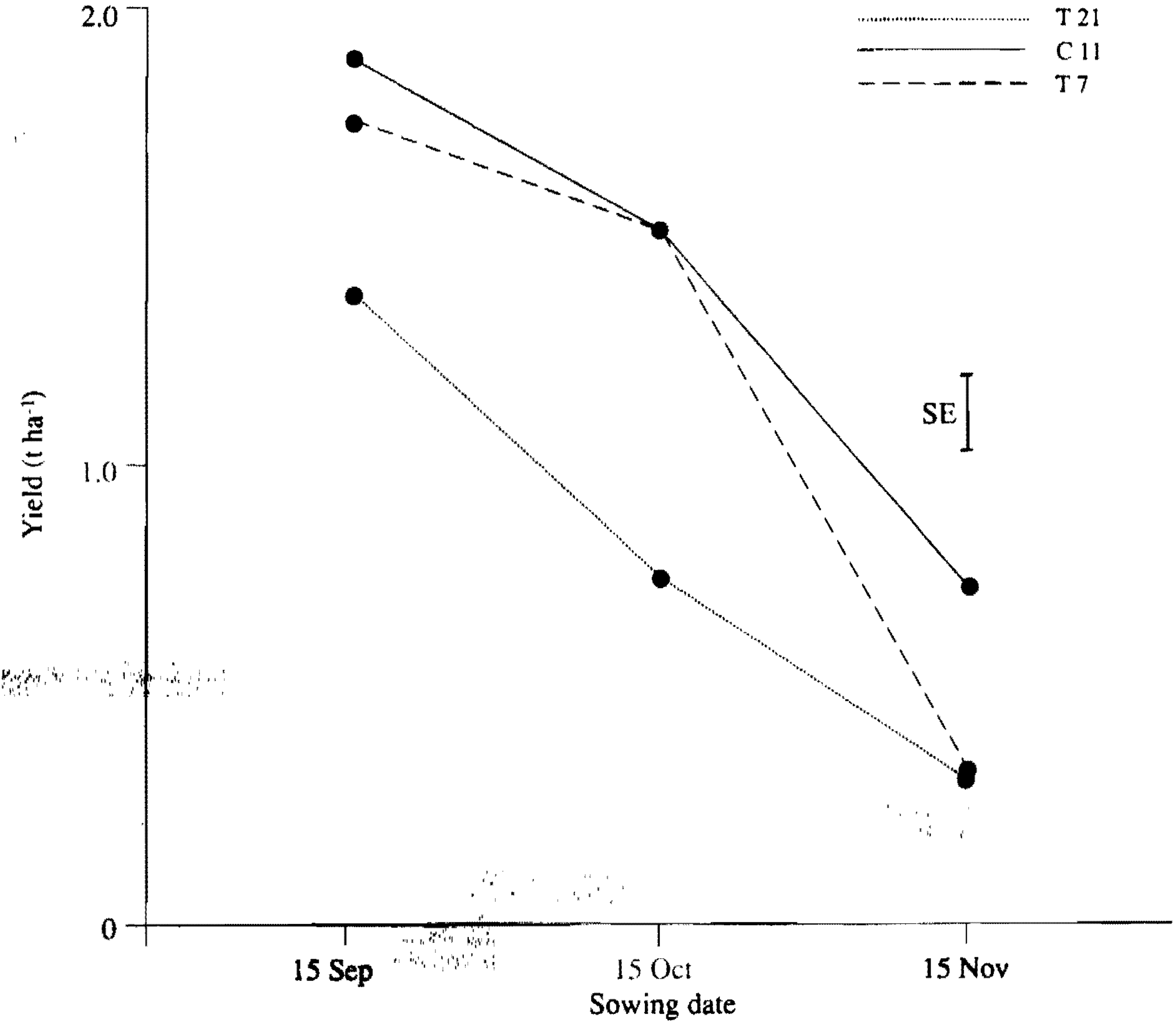


Figure 11.2. Effect of sowing date on yield of T21 (short-), C11 (medium-) and T7 (long-duration) pigeonpea genotypes grown at 25 plants m^{-2} under rainfed conditions ICRISAT Center, postrainy season 1977.

temperatures during the reproductive stage. Attempts are being made to develop agronomy suitable for late-sown crops, because those sown in rice fallows are unavoidably late. In such situations short-duration genotypes have performed well since they can escape terminal atmospheric and soil droughts better than long-duration types (Satyanarayana *et al.*, 1988). In environments where high temperature stress is not serious, e.g., in Trinidad, West Indies, crops sown as late as January are able to produce up to 4 t ha^{-1} under dry conditions, and up to 3 t ha^{-1} in irrigated conditions (Keatinge and Hughes, 1981).

Plant Population

Long- and Full-season Crops

In traditional production systems, pigeonpea generally has a low optimum plant population, less than 5 plants m^{-2} (Mukherjee, 1960; Pathak, 1970). In these systems the crop matures using moisture stored in the soil profile, and increasing plant population may enhance inter-plant competition for limited water. Thus, in these situations although the pigeonpea stand may appear sparser, and the light interception pattern may suggest scope for increasing plant population, such as increase may not result in significant increases in seed yield. In fact there could be a decline in yield at higher than optimum plant populations (Hammerton, 1971; Akinola and Whiteman, 1975; Singh and Kush, 1981). Natarajan and Willey (1980) found that 10 plants m^{-2} gave marginally higher yields in intercrops than 5 plants m^{-2}, but the net effect as seen in the land equivalent ratios (LERs) was not significant, because the yield of the sorghum intercrop was adveresly affected. A similar observation was made by Rao and Willey (1983).

In traditional production systems higher gains in yield can be obtained by sowing in lines rather than broadcasting (Mukherjee, 1960), and by adopting certain improved row proportions. For example, Natarajan and Willey (1985) found that on a Vertisol a 1:1 row proportion of sorghum and pigeonpea (with about 15 plants m^{-2} of sorghum and 5 plants m^{-2} of pigeonpea) produced good yields; whereas on an Alfisol a 2:1 row proportion of sorghum and pigeonpea with the same plant populations was found optimum.

Short-season Crops

Short-duration Pigeonpea

Plant population is one of the important factors affecting yield of short-duration pigeonpea genotypes that are more responsive to close sowing since they are small plants that have a shortened growth duration. Moreover, unlike long-duration genotypes, these crops grow under relatively assured soil moisture conditions. They mature at the end of the rainy season and, in the event of long dry spells, are irrigated. Plant population requirements for short-duration genotypes vary with location, time of sowing, and genotype, depending mainly on the extent of vegetative growth. The interactions between plant population and sowing date, and plant population and genotype are often significant (Singh *et al.*, 1981; Ahlawat *et al.*, 1985; Chauhan *et al.*, 1987b).

In Australian conditions, a population density of 40-50 plants m^{-2} is required to obtain high yields from photoperiod-insensitive cultivars within the optimum range of sowing dates (Wallis *et al.*, 1981). Table 11.3 shows the response of a photoperiod-insensitive cultivar (selected from ICP 7179) to increasing plant population in the range of 10-50 plants m^{-2}, and the required row arrangement. The basis for a higher yield from close-spaced plants is the attainment of higher leaf area index, e.g., 4.5, although the leaf area of individual plants declines as the population density increases (Rowden *et al.*, 1981). Since high plant population also results in fewer branches per plant, a greater synchrony in time to flowering and maturity is observed (Wallis *et al.*, 1981); this facilitates better pest control and mechanized harvesting.

Table 11.3. Mean seed yield (t ha^{-1}) of different flushes of photoperiod-insensitive pigeonpea sown on 19 Jan 1978, Redland Bay, Australia.

Density (plants m^{-2})	Arrangement (cm)	Seed yield (t ha^{-1}) First harvest (Jun '78)	Second harvest (Jan '79)	Third harvest (Apr '79)	Total
10	25x40	1.61	0.42	0.93	2.96
20	25x20	2.18	0.67	1.16	4.01
30	25x13	2.67	0.76	0.88	4.31
40	25x10	2.40	0.84	1.35	4.59
50	25x 8	2.89	0.88	1.24	5.01

Source: Wallis *et al.*, 1981.

In peninsular India, the optimum plant population for short-duration genotypes is about 30 plants m^{-2}; this is obtained by maintaining a row-to-row spacing of 30 cm and plant-to-plant spacing of 10 cm (Chauhan *et al.*, 1987b). The precise plant population required varies with genotype because genotype × plant population interactions are significant. For example, genotype ICPL 87 has an optimum plant population requirement of about 25 plants m^{-2} as it grows relatively more vigorously than ICPL 4 and ICPL 81 whose optimum plant population is somewhat higher (Figure 11.3). Similar interactions have been observed for extra-short-duration genotypes in this environment. Some genotypes show an increase in yield up to 66 plants m^{-2}, whereas others show negative response to very high plant populations. Such interactions have implications for yield tests of genotypes in a breeding programme. All genotypes are usually tested at the same plant population, but in view of such interactions it is desirable that promising genotypes are tested over a range of populations in order to accurately determine their yield potential before they are finally selected or discarded.

In the subtropical environment of northern India, the growth of short-duration pigeonpea genotypes is greater than in peninsular India due to their increased growth rates, and the longer crop growth duration (Chauhan *et al.*, 1987b; Table 11.1). The plant population required by these genotypes in this environment is therefore lower, in the range of 4.4-16 plants m^{-2} (Table 11.4). There are strong sowing date × plant population interactions with the April-sown crop requiring about 5 plants m^{-2}, and the June-sown crop about 15 plants m^{-2} (Ahlawat *et al.*, 1985). Spreading plant types have lower plant population requirements. For example, for UPAS 120 and BS 1, that are spreading types, 10 plants m^{-2} was optimum, whereas for Prabhat, a less spreading type, it was about 20 plants m^{-2} (Singh *et al.*, 1981). The use of higher than optimum plant population does not necessarily result in decline in yield. For example, Chauhan *et al.* (1987b) found neither positive or negative response in yield to plant population in the range of 16 to 66 plants m^{-2} at Hisar in northern India. This indicates considerable plasticity of these genotypes in this environment. Since high plant population hastens canopy development (Chauhan *et al.*, 1987b) and increases the production of stalk and fallen leaves (Rao *et al.*, 1981), higher populations than those previously found optimum could be used. Pigeonpea stalks are useful as a source of fuel wood, and fallen leaves, that contain about 1.5% N, can enrich the soil with nitrogen. Also, crops grown at higher density seem to suffer less from waterlogging because of their greater consumptive use of moisture from the soil profile (Singh *et al.*, 1983). However, under rainfed conditions, increasing inter-plant competition for the limited moisture does not permit sowing more than 10 plants m^{-2} (Ahlawat and Saraf, 1981).

There is no clear-cut evidence to suggest that planting geometry can influence yields of short-duration pigeonpea. Baldev (1988) and Ahlawat *et al.* (1982) have found that pigeonpea crops

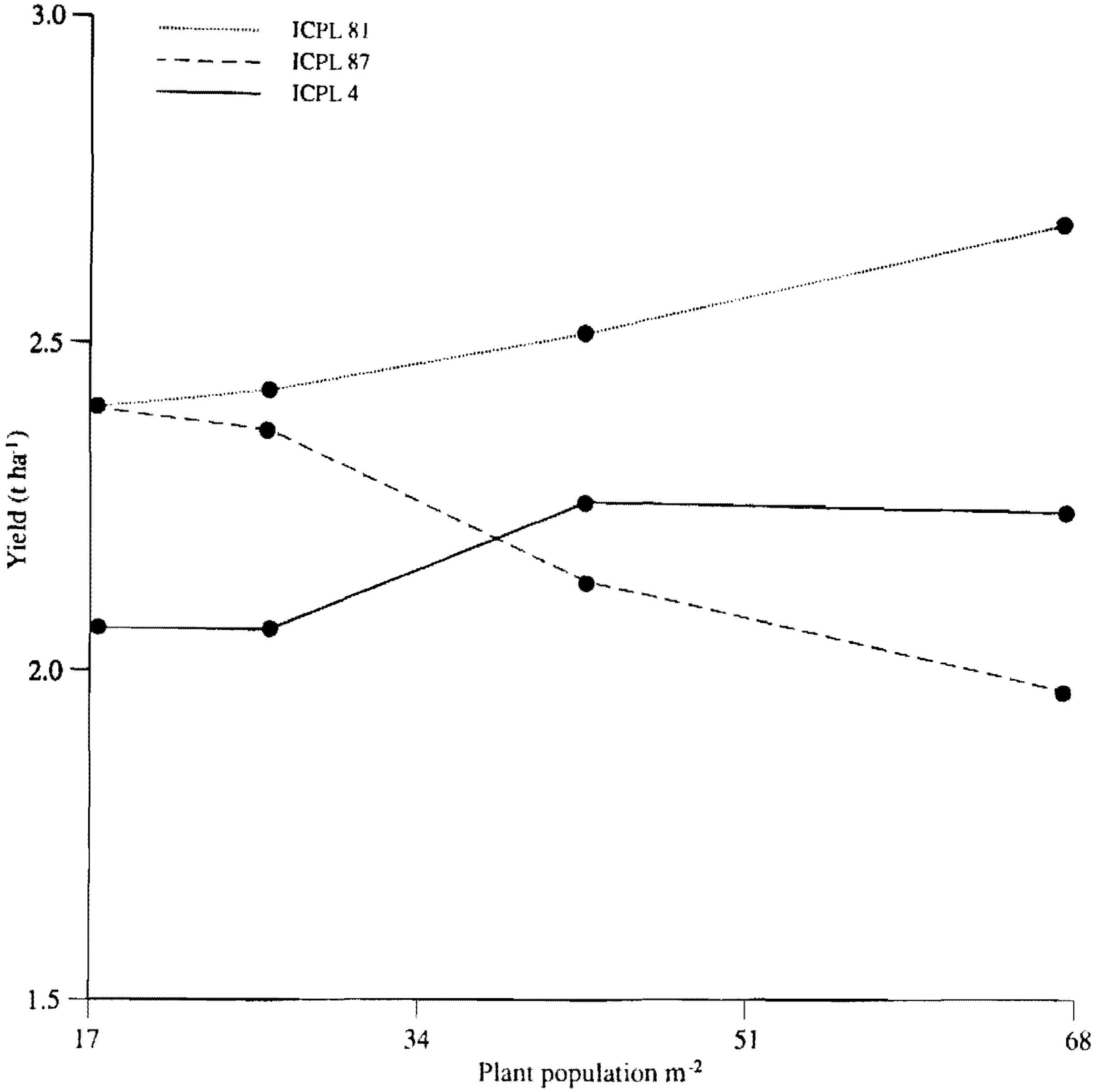


Figure 11.3. Effect of plant population on the first-harvest yield (t ha^{-1}) of three short-duration pigeonpea genotypes grown on an Alfisol, ICRISAT Center, rainy season 1982/83.
Source: Chauhan *et al.*, 1987b.

grown in paired rows yield more than those grown in equally spaced rows. The paired-row sowing enlarges the pod-bearing zone, not only by broadening the apical pod-bearing zone, but also by increasing pod-bearing on lower branches because light can reach the lower parts of the canopy. In uniformly spaced rows, lower branches do not produce many pods because they are shaded by apical branches. Paired rows are useful when pigeonpea is grown as an intercrop with short-season legumes, but for sole-crop situations their advantage has yet to be verified.

Postrainy-season Pigeonpea

When pigeonpea is grown in the cool postrainy season in India, it matures sooner and grows much less tall than when it is sown at the beginning of the rainy season. Consequently, to obtain satisfactory yields in the postrainy season the crop requires 12-30 plants m^{-2}, 3-6 times more than required by the same genotypes in the rainy season (Narayanan and Sheldrake, 1979; Roy Sharma

Table 11.4. Response to plant population of short-duration pigeonpea in a northern India environment.

Density (plants m^{-2})	Spacing (cm)		Optimum			Yield at optimum (t ha^{-1})	Reference
	Inter-row	Intra-row	Plants m^{-2}	Inter-row spacing	Intra-row spacing		
4, 5, 6	50, 70	-	6	ns[1]	-	1.21 (31)[2]	Laxman Singh *et al.*, 1971
5, 6, 10	50	20, 30, 40	10	-	20	2.87 (43)	Choudhury and Bhatia, 1971
5, 7.5	50, 75	-	7.5	50	-	2.18 (4)	Manjhi *et al.*, 1973
5, 8, 16	60	10, 20, 30	16	-	10	2.01 (43)	Singh and Kalra, 1980
6.6, 10	50, 75	-	10	50	-	1.59 (23)	Ahlawat *et al.*, 1975
5.3, 8, 16	25, 50, 75	-	16	25	-	1.45 (30)	Kaul *et al.*, 1980
5, 7.5	50, 75	-	7.5	ns	-	1.93 (16)	Sandhu *et al.*, 1981
3.3, 4.4, 6.6	50, 75, 100	-	4.4	75	-	1.76 (18)	Rathi and Tripathi, 1978
10, 13.3, 20	25, 37.5, 50	-	10	50	-	1.86 (97)	Singh *et al.*, 1983

1. ns = not significant
2. Figures in parentheses indicate percentage advantage over lowest-yielding treatment.

et al., 1981; Reddy *et al.*, 1984; Venkataratnam *et al.*, 1984). Since soil moisture often becomes limiting in the postrainy season, yields tend to decline beyond a certain population. For example, Narayanan and Sheldrake (1979) obtained maximum yields at 12 plants m^{-2}, and thereafter as plant population increased yields declined. Keatinge and Hughes (1981) observed significant plant population × moisture interactions in the January-sown crop in Trinidad. They did not, however, notice any adverse effect of increasing plant population from 20 to 60 plants m^{-2} under dry conditions. Increase in yield in this range was, of course, much larger with irrigation.

Intercropping Possibilities

The practice of advancing the sowing date of short-duration pigeonpea to April or May not only allows timely sowing of wheat in northern India, but also prolongs the favourable period for pigeonpea growth and can result in yields up to 50% higher than those from the June-sown crop (Panwar and Yadav, 1981). Since the crop grows more luxuriently in early sowings, wider row spacings of 90-100 cm and a population density of 5 plants m^{-2} have been found optimal for April sowings compared to 15 plants m^{-2} for June sowings (Ahlawat *et al.*, 1985). Due to slow initial growth rates, the crop at these wide spacings is inefficient in using light and moisture resources, and in competing with weeds. The inclusion of additional intercrop species can overcome this limitation. Unlike medium- and long-duration pigeonpea, where cereal-based intercropping systems have been found quite productive (Willey *et al.*, 1981), intercropping short-duration pigeonpea with short-season legumes, such as green gram, black gram, or cowpea has been found to be more remunerative than intercropping with cereals (Saraf *et al.*, 1975; Saxena and Yadav, 1979). The advantage of including short-season legumes, particularly in April sowings is that the yield of pigeonpea is maintained more or less at a sole-crop level, and an additional legume crop yield of 0.3-0.4t ha^{-1} is obtained (Ahlawat *et al.*, 1985). Such legume/legume intercropping is feasible even in June sowings, but the relative advantage declines in that season (Panwar and Yadav, 1981; Ahlawat *et al.*, 1985). Legume/legume intercropping is becoming increasingly popular in the irrigated belt of northern India for the same reasons (Baldev, 1988).

One or two rows of intercrop legume between two rows of pigeonpea have generally been found to be more productive than other intercropping combinations (Saxena and Yadav, 1979). Pigeonpea/groundnut intercropping is also possible, and both crops can be simultaneously harvested if short-duration pigeonpea genotypes are used. Since groundnut offers very little competition to pigeonpea growth it causes relatively small reductions in pigeonpea yields. In fact, Baldev (1988) claimed if pigeonpea and groundnut were intercropped using a "solid row" technique, marginally higher yields of pigeonpea, and additional groundnut yields could be realized than when pigeonpea was sown as a sole crop in rows 50 cm apart. The technique involves sowing paired rows of pigeonpea spaced 20 cm apart, with each pair sown at a distance of 80 cm, thus accommodating two rows of pigeonpea in 1 m. Two rows of groundnut are then sown 10 cm apart in between the two paired rows of pigeonpea. During the reproductive stage, the two paired rows of pigeonpea merge giving the appearance of a solid row. Pigeonpea grown in these solid rows with groundnut has been found more productive than when it is grown with such other crops as soybean and urd bean (Table 11.5). These studies thus indicate the considerable benefit of including additional legume populations within a crop of short-duration pigeonpea. The possible reasons for such an advantage have been referred to earlier in this chapter, but these results need to be confirmed on an operational scale.

Table 11.5. Yields (t ha^{-1}) of pigeonpea and its companion crops in various cropping systems, Indian Agricultural Research Institute, New Delhi, India.

Cropping systems	Yield (t ha^{-1}) Pigeonpea	Yield (t ha^{-1}) Intercrop
Pigeonpea BS 15, sole crop, 50-cm rows	1.38	-
Pigeonpea sole crop, solid row (SR)	1.50	-
Pigeonpea (SR) + groundnut SM 5	1.60	0.70
Pigeonpea (SR) + mung bean PS 16	1.46	0.20
Pigeonpea (SR) + urd bean T 9	1.24	0.25

Source: Baldev, 1988.

It is also possible to intercrop pigeonpea with short-season legumes in the postrainy season, particularly in rice fallows. In one such intercropping experiment with black gram in rice fallows in coastal Andhra Pradesh, India, up to 1 t ha^{-1} of pigeonpea, comparable to its sole-crop yield, and about 1.3 t ha^{-1} of black gram was harvested from crops sown on 17 November (Satyanarayana *et al.*, 1988). This indicates the compatibility of the two crops, probably due to their differing growth patterns (Satyanarayana *et al.*, 1988).

Nutrition

Pigeonpea in traditional systems is not ordinarily given fertilizer, perhaps due to the general belief that it does not respond to fertilizers. To produce 1 t of pigeonpea grain about 56 kg N, 5 kg P, and 22 kg K are required (Kanwar and Rego, 1983). Since yields of pigeonpea in traditional production systems are low, its nutrient requirements in such systems are also low, and are easily met from nitrogen fixation or from existing soil nutrients. For intensively managed pigeonpea, yield and biomass production are higher, and more nutrients are removed by the crop. For example, Rao (1974, as quoted by Kulkarni and Panwar, 1981) estimated that to produce 2 t grain ha^{-1} and 6 t stalks ha^{-1}, short-duration genotype Pusa Ageti removed 132 kg N, 20 kg P, and 53 kg K ha^{-1}. Several studies summarized by Kulkarni and Panwar (1981) and Sadaphal (1988) indicate that P is the most frequently limiting nutrient for pigeonpea. These studies indicate that maximum yields of pigeonpea were obtained with the application of 17-26 kg P ha^{-1}. Response to a "starter dose" of 15-20 kg N ha^{-1} has also been found by several researchers. The dependence of the seedling on soil N in its early stages has been suggested as the reason for such responses to starter doses of N, which result in quick, early crop growth. A considerable proportion of the N required by plants is derived from fixation in nodules under normal growth conditions To promote maximum nodulation, inoculation with an efficient strain of *Rhizobium* is often recommended as a precautionary measure (see Chapter 10 for more details on nitrogen nutrition). Deficiencies of K, Zn, and other elements have also been recorded on some soils. The procedure for diagnosing nutrient deficiencies, estimating their requirements, the application of appropriate fertilizers, and their time and methods of placement are discussed in Chapter 9.

Water Requirements

Pigeonpea uses about 20-25 cm water to produce about 1 t ha^{-1} of grain under traditional production systems (Saxena and Yadav, 1975; Sardar Singh and Russell, 1981). Most pigeonpea-growing regions in India receive 60-140 cm annual rainfall (Reddy and Virmani, 1981). The moisture available in soils is generally sufficient to meet pigeonpea's requirements in northern and central India. There is often a need to remove excess water rather than to irrigate. Moisture availability in peninsular India is relatively poor, and the length of the growing season in many areas is only 90-120 days (Reddy and Virmani, 1981). Since medium-duration pigeonpea genotypes are generally grown in this region, they suffer from terminal drought stress. The application of three irrigations doubled yields on Alfisols, but only increased yields by about 20% on Vertisols (Y.S. Chauhan, unpublished). As moisture is only available for 90-120 days on Alfisols, genotypes with relatively shorter duration may do well under such conditions. Genotypes maturing in 150 days have yielded over 1.5 t grain ha^{-1} in the same environment where 180-day genotypes gave less than 1 t ha^{-1} (Y.S. Chauhan, unpublished).

The intensively managed pigeonpea systems that involve short-duration pigeonpea have a higher water requirement because they are grown at high densities (Mehrotra *et al.*, 1977; Singh *et al.*, 1983). Mehrotra *et al.* (1977) estimated water use by T 21 to be in the range of 55-60 cm. In years of low rainfall, or when the crop is grown on soil of low water-holding capacity, the amount of water available to the crop may fall short of its requirement. Bhan and Khan (1979) recorded significant responses to one or two supplemental irrigations on sandy loam soils at Kanpur, India (Table 11.6). In this study a single irrigation applied at the pod-filling stage gave a better response than application on the basis of a cumulative pan evaporation demand of 80 or 120 mm. In Rajasthan, India, water applied at the early vegetative stage reduced yield by 14%, whereas when it was applied at the branching stage, it increased yield by up to 34% (Makhan Lal and Gupta, 1984). Saxena and Yadav (1975), on the other hand, reported no response to applied irrigation. Chauhan *et al.* (1987b) did not observe any response to applied irrigation on an Alfisol in a normal (about 700 mm) rainfall year. However, three or four irrigations, each of 5 cm significantly improved the yield in the second and third harvests (Figure 11.1). These studies indicate that injudicious use of water may not help the pigeonpea crop sown in the rainy season, rather it may harm the crop. The crop should be irrigated when it shows stress, indicated by the leaves pointing towards the sun at noon. Irrigation of the crop before plants show drought stress, as well as being wasteful of water, can cause waterlogging and make the crop more prone to infection by such diseases as fusarium wilt (*Fusarium udum*) (Sharma *et al.*, 1987) and phytophthora blight (*Phytophthora drechsleri* f.sp. *cajani*). Such irrigations may also delay maturity, thus affecting the prospects of subsequent crops.

Table 11.6. Effect of irrigation on yield (t ha^{-1}) of pigeonpea, rainy season 1976/77, Kanpur, India.

Stages of irrigation	Yield (t ha^{-1})
Control	1.28
Flower initiation	1.30
Peak flowering	1.22
Pod filling	2.14
Flower initiation and pod filling	2.43
Irrigation after 80 mm cumulative pan evaporation (CPE)	2.27
Irrigation at 120 mm CPE	2.36
CD at 5%	0.49

Source: Bhan and Khan, 1979.

Responses to irrigation are generally more consistent in pigeonpea sown in the postrainy season, as the crop then has to rely on moisture stored in the soil profile. At ICRISAT Center, application of two or three irrigations about one month after sowing increased seed yield by about 150-160% over a nonirrigated control (Rao *et al.*, 1983). In a similar environment on clayey soil where the soil moisture-holding capacity was high, the increase in yield due to irrigation was relatively small, i.e., 14-19% (Reddy *et al.*, 1984). Bhowmik *et al.* (1983), on an alluvial soil in West Bengal, recorded a significant increase in seed yield of postrainy-season pigeonpea with two irrigations; but found three irrigations had a negative effect, again indicating the need to apply irrigations only according to crop requirement.

Weed Control

Among the pulses, pigeonpea is the only crop that has a characteristically slow initial growth rate. This makes pigeonpea less competitive with weeds. Weeds grow profusely in the rainy season due to the favourable moisture conditions and, if not timely controlled, can cause up to 90% reduction in seed yield (Saxena and Yadav, 1975). Some of the common weeds associated with pigeonpea are *Cyperus rotundus*, *Echinochloa* sp, *Digitaria* sp, *Dactyloctenium aegyptium*, *Setaria glauca*, *Amaranthus* sp, *Celosia argentea*, *Commelina benghalensis*, *Phyllanthus niruri*, *Digera arvensis*, and *Euphorbia* sp (Shetty, 1981). Their relative importance, however, varies with location.

Weed control improves the productivity of pigeonpea in both traditional and nontraditional production systems (Singh and Faroda, 1977; Ahlawat *et al.*, 1982). Shetty (1981), summarizing work on weed management in pigeonpea, concluded that in traditional production systems, intercropping is able to reduce weed infestation by 50-70%. Intercrops with maize and sorghum are capable of suppressing weeds for longer periods. With short-season crops of pigeonpea, fast-growing cereals are unsuitable intercrops, but there is a possibility of using some low-statured crops such as; cowpea, green gram, black gram, groundnut, and soybean as smother crops (Shetty, 1981). The advantage of using these in intercrops is the elimination of at least one hand-weeding and some additional yield from the smother crop itself. Further, for legume/legume intercropping, a range of herbicides are available, unlike for cereal/legume systems where the choice is limited due to crop specificity.

Short-season crops can also take advantage of high plant density even when grown alone. It has been found that the ability of pigeonpea to suppress weeds markedly improved when plant population was increased from 1 to 10 plants m^{-2} (Rao and Shetty, 1976).

Timing weed control is also important. For short-season crops, the first 30 days appear critical, although this period may vary with genotype and time of sowing (Diaz-Rivera *et al.*, 1985). One hand weeding given 45 days after sowing (DAS) resulted in lower yields than weeding twice at 25 and 45 DAS (Singh *et al.*, 1980). However, incessant rains may not permit hand weeding in time since the crop is normally sown in the rainy season. Pre-emergence herbicides can control weeds for the first 30-40 days. A number of herbicides have been found useful for pigeonpea systems (Singh and Faroda, 1977; Faroda and Singh, 1981; Shetty, 1981). Singh *et al.* (1980) found that alachlor at 1 kg ai ha^{-1} gave better control, and controlled a wider range of weeds than nitrofen applied at the same rate. Metolachlor and pendimethalin also gave 85-95% weed control at 1.0 kg ai ha^{-1} when used alone or in combination at ICRISAT Center (A. Ramakrishna, ICRISAT, personal communication). A hand weeding at 40-45 days after pre-emergence herbicide application kept fields generally weed free. Singh and Singh (1985) found oxadiazone and pendimethalin at 0.75 kg ai ha^{-1} controlled weeds satisfactorily, and resulted in similar yields to those in the weed-free treatment.

At ICRISAT Center excellent control of weeds in pigeonpea experimental plots is achieved by using a mixture of prometryn, fluchloralin, and paraquat at 1.0 kg ai of each in 350 L water ha^{-1} on Vertisols and with 0.75 kg ai ha^{-1} of each on Alfisols. Prometryn was quite effective in controlling broadleaved weeds and fluchloralin in controlling grass weeds. Both these herbicides when used in combination significantly increased pigeonpea yield in treated plots over an unweeded control, and over that from plots where either herbicide was used alone. A hand weeding at 30-40 DAS was still required, even after the use of herbicides to keep fields entirely weed-free. The use of paraquat on all fields was found necessary to control weeds that had already started germinating at the time of sowing pigeonpea, even on freshly prepared land. There was no toxicity apparent to the crop even when paraquat was applied 5 DAS. An irrigation or rain after sowing enhanced the effect of these herbicides under the cropping systems used at ICRISAT Center. Moreover, these chemicals did not affect subsequent crops since prometryn loses its effectiveness after about 10 weeks, and fluchloralin after about 16 weeks.

Paraquat can also be used with care in the standing pigeonpea crop. Semidey *et al.* (1987) applied paraquat in combination with pre-emergence herbicides using a shielded hand pump 5 and 9 weeks after sowing. The pigeonpea crop suffered less than 2% damage.

Most researchers have found herbicides to be slightly inferior to mechanical weed control because the efficacy of herbicides seems to diminish with time. Researchers therefore suggest a hand weeding at 40-45 DAS in herbicide-treated plots (Singh and Faroda, 1977; Singh *et al.*, 1980). The marginal superiority of oxadiazone and pendimethalin herbicides has been indicated, since with these chemicals weed control is effected from the beginning of the crop season (Singh and Singh, 1985). At ICRISAT, hand weedings have always been found to be superior to herbicides, but the latter is more economical and hence preferable.

Pest and Disease Management

The incidence of insect pests and diseases is a major cause of unstable yields of pigeonpea, particularly in intensively managed systems. For details see Chapters 13 and 14.

Harvesting

Unlike other crops, the leaves of pigeonpea remain green when the pods are ready for harvest; this may confuse decisions on optimum harvest time. The crop is considered mature and ready to harvest when 80-90% of the pods have turned brown. For single harvests, cutting plants at ground level is a common practice, but where ratoon harvests are intended, the method of harvesting greatly influences subsequent flush yields (Tayo, 1985a; Chauhan *et al.*, 1987a). In the lowland humid tropics, cutting stems at about 0.3 m above soil level results in better ratoon growth and yield than where pods are picked by hand, or plants are ratooned at 0.6 m above soil level (Tayo, 1985a). However, in the semi-arid tropics where the second flush formation is faster pod picking gives higher yields than ratooning (Chauhan *et al.*, 1987a). Since pod picking is more labour-intensive, to maximize yields light ratooning of pod-bearing branches is a practical option.

FUTURE

The development of short-duration genotypes has greatly increased the possibility of including pigeonpea in multiple cropping systems. Use of these genotypes is likely to increase, not only in pigeonpea-wheat rotations and multiple-harvest systems, but also in other systems that have been discussed earlier. In subtropical environments, short-duration genotypes grow very tall and sometimes mature very late, thereby affecting the prospects of sequential crops. To overcome these limitations, extra-short-duration pigeonpea (ESDP) genotypes have been developed. As ESDP genotypes represent a relatively new plant type, their agronomic requirements need to be established, but preliminary work at ICRISAT Center has indicated that they have good yield potential.

For environments where the crop matures fast and where presently short-season legumes such as cowpea, green gram, and black gram are grown as catch crops, ESDP genotypes provide an additional choice to the farmers since some of these genotypes can mature in as few as 90 days. Such genotypes can also escape terminal drought stress. Again, agronomic information for adapting these genotypes to rainfed conditions is lacking and further work needs to be done.

Further expansion of pigeonpea sowing to areas vacated by a rice crop is possible. For rice-fallow conditions, the agronomic requirements for pigeonpea as sole crops and intercropped with other short-season crops are yet to be determined. One of the constraints faced by pigeonpea in rice-fallow conditions is that of crop establishment. Since pigeonpea has slow initial growth rates, the penetrability of the roots into soil is reduced. Identification of genotypes with greater seedling vigour could be useful for rice fallows. Its slow initial growth is of little advantage when pigeonpea is to be grown as a sole crop. There is also a need to develop genotypes that can grow well at mean temperatures below 20°C, because pigeonpea growth in the postrainy season is limited by low temperatures.

The medium- and long-duration genotypes will continue to be used in cropping systems for the forseeable future. Efforts to improve their agronomy do not seem to be making much headway. For the present, it appears that better productivity of these genotypes could be achieved by improving their stability against biotic and abiotic stresses. The possibility of using pigeonpea in agroforestry systems, as a perennial crop, and as a plantation crop needs to be investigated.

Evidence to date suggests that pigeonpea growth is greatly influenced by environmental factors. There is need to model crop growth so that it can be predicted in particular environments, and to facilitate the determination of optimum sowing dates and plant populations to maximize yields.

REFERENCES

Abruna, F., Rivera, E. and Rodriguez Garcia, J.A. (1984) Crop response to soil acidity factors in Ultisols and Oxisols in Puerto Rico. X . Pigeonpeas. *Journal of Agriculture of the University of Puerto Rico* 68, 433-443.

Ahlawat, I.P.S. and Saraf, C.S. (1981) Response of pigeonpea (*Cajanus cajan* (L.) Millsp.) to plant density and phosphorus fertilizer under dryland conditons. *Journal of Agricultural Science, Cambridge* 97, 119-124.

Ahlawat, I.P.S., Saraf, C.S. and Singh, A. (1975) Studies on the performance of pigeonpea varieties to dates of planting and row spacing. *Indian Journal of Agronomy* 20, 245-247.

Ahlawat, I.P.S., Saraf, C.S. and Singh, A. (1985) Production potential of summer and rainy-season pigeonpea intercropped with cowpea and greengram. *Indian Journal of Agricultural Sciences* 55, 565-569.

Ahlawat, I.P.S., Singh, A. and Mohta, N.K. (1982) Studies on weed control in solid and mixed stands in pigeonpea and soybean. *Indian Journal of Agronomy* 27, 191-193.

AICPIP (1986) *Improved Varieties of Pulse Crops in India*. All India Coordinated Pulses Improvement Project (AICPIP), Directorate of Pulses Research, Kanpur, 68 pp.

Akinola, J.O. and Whiteman, P.C. (1975) Agronomic studies on pigeonpea (*Cajanus cajan* (L.) Millsp.). II. Response to sowing density. *Australian Journal of Agricultural Research* 26, 57-66.

Akinola, J.O., Whiteman, P.C. and Wallis, E.S. (1975) *The Agronomy of Pigeonpea (Cajanus cajan). Review Series no.1/1975*. CAB, UK, 57 pp.

Bahar, F.A. (1982) Cultural practices for pigeonpea (*Cajanus cajan* (L.) Millsp.) as forage, green manure, and grain crop. *Dissertation Abstract International, Section B* 43, 10.

Baldev, B. (1988) Cropping patterns. In: Baldev, B., Ramanujam, S. and Jain, H.K. (eds), *Pulse Crops (Grain Legumes)*. Oxford and IBH Publishing Co., New Delhi, pp. 513-557.

Bhan, S. and Khan, S.A. (1979) Response of Kharif crops to irrigation in light textured alluvium of Uttar Pradesh. *Indian Journal of Agronomy* 24, 410-416.

Bhatia, G.K., Gupta, S.C., Green, J.M. and Sharma, D. (1981) Estimates of natural cross-pollination in *Cajanus cajan* (L.) Millsp.: several experimental approaches. In: *Proceedings of the International Workshop on Pigeonpeas, volume 2, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 129-136.

Bhowmik, N.N., Ghosh, N. and Chowdhury, P.B. (1983) Effect of irrigation and phosphorus on growth and yield of pigeonpea (*Cajanus cajan* L.). *Indian Agriculturist* 27, 343-347.

Byth, D.E., Wallis, E.S. and Saxena, K.B. (1981) Adaptation and breeding strategies for pigeonpea. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 450-465.

Chauhan, Y.S. (1987) Screening for tolerance to salinity and waterlogging: case studies with pigeonpea and chickpea. In: *Adaptation of Chickpea and Pigeonpea to Abiotic Stresses.Proceedings of the Consultants' Workshop, 19-21 December 1984, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 93-103.

Chauhan, Y.S. (in press) The root system of pigeonpea. In: Abdul Salam, M. and Wahid, P.A. (eds), *Rooting Pattern of Tropical Crops*. Tata McGraw Hill Publishing Co., Ltd., New Delhi.

Chauhan, Y.S., Sheldrake, A.R. and Venkataratnam, N. (1987a) Effect of harvest methods on the second flush yield of short-duration pigeonpea *(Cajanus cajan)*. *Journal of Agricultural Science, Cambridge* 109, 591-593.

Chauhan, Y.S., Venkataratnam, N. and Sheldrake, A.R. (1987b) Factors affecting growth and yield of short-duration pigeonpea and its potential for multiple harvests. *Journal of Agricultural Science, Cambridge* 109, 519-529.

Choudhury, S.L. and Bhatia, P.C. (1971) Ridge-planted kharif pulses yield high despite waterlogging. *Indian Farming* 21(3), 8-9.

Dahiya, B.S., Brar, J.S. and Kaul, J.N. (1974) Changes in growth habit of pigeon-peas (*Cajanus cajan* (L.) Millsp.) due to late sowing. *Journal of Agricultural Science, Cambridge* 83, 379-380.

Dalal, R.C. and Quilt, P. (1977) Effects of N, P, liming, and Mo on nutrition and grain yield of pigeonpea. *Agronomy Journal* 69, 854-857.

Diaz-Rivera, M., Hepperly, P.R., Riveros, G. and Almedovar-Vega, L. (1985) Weed-crop competition in pigeonpeas in Puerto Rico. *Journal of Agriculture of the University of Puerto Rico* 69, 201-213.

Faroda, A.S. and Singh, R.L. (1981) Weed control in pulses. *Pulse Crops Newsletter* 1(2), 50-51.

Hammerton, J.L. (1971) A spacing/planting date trial with *Cajanus cajan* (L.) Millsp. *Tropical Agriculture (Trinidad)* 48, 341-350.

ICRISAT (1977) *Annual Report 1976-77.* Patancheru, A.P., India: ICRISAT, p. 87.

ICRISAT (1981) *Annual Report 1979/80.* Patancheru, A.P., India: ICRISAT, p. 257.

ICRISAT (1986) *Annual Report 1985.* Patancheru, A.P., India: ICRISAT, p. 180.

Johansen, C., Saxena, N.P., Chauhan, Y.S., Subbarao, G.V., Pundir, R.P.S., Kumar Rao, J.V.D.K. and Jana, M.K. (in press) In: *Proceedings of the International Congress of Plant Physiology, 15-20 February 1988, New Delhi.* Society for Plant Physiology and Biochemistry, New Delhi, India.

Kampen, J. (1982) *An Approach to Improved Productivity on Deep Vertisols. Information Bulletin no. 11.* Patancheru, A.P., India: ICRISAT, 14 pp.

Kanwar, J.S. and Rego, T.J. (1983) Fertilizer use and watershed management in rainfed areas for increasing crop production. *Fertilizer News* 28 (9), 33-43.

Karivaratharaju, T.V., Ramakrishnan, V., Vadivelu, K.K. and Ramaswamy, K.R. (1982) Effect of seed size and seed coat colour on seed quality and productivity of red gram (*Cajanus cajan* L.). *Madras Agricultural Journal* 69, 421-430.

Kaul, J.N., Sekhon, H.S., Dhingra, K.K. and Tripathi, H.P. (1980) Date of planting and row-spacing studies with early maturing pigeonpea (arhar) varieties under irrigated conditions for double cropping. *Tropical Grain Legume Bulletin* 19, 20-23.

Keatinge, J.D.H. and Hughes, G. (1981) Planting density effects on the dry-season productivity of short pigeonpeas in the West Indies: II. Yield and moisture supply. In: *Proceedings of the International Workshop on Pigeonpeas, volume 2, 15-19 December 1980, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 241-248.

Khan, A.R. and Mathur, B.P. (1962) Studies on tillage XIII. Effect of variation in the depth of cultivation with different methods of phosphate application on the yield of pigeonpea (*Cajanus cajan*). *Indian Journal of Agricultural Sciences* 32, 35-38.

Khan, T.N. and Ashley, J.M. (1975) Factors affecting plant stand in pigeonpea. *Experimental Agriculture* 11, 315-322.

Kulkarni, K.R. and Panwar, K.S. (1981) Response of pigeonpea to fertilizers in India: a critical review. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 212-220.

Laxman Singh, Maheshwari, S.K. and Sharma, D. (1971) Effect of date of planting and plant population on growth, yield, yield components and protein content of pigeonpea (*Cajanus cajan* (L.) Millsp.). *Indian Journal of Agricultural Sciences* 41, 535-538.

Laxman Singh and Shrivastava, M.P. (1976) Cultivation systems and varietal adaptations of pigeonpea in Madhya Pradesh. *Indian Journal of Genetics and Plant Breeding* 36, 293-300.

Lugo-Mercado, H.M., Badillo-Feliciano, J. and Ortiz-Alvarado, F.H. (1987) Yield response of watermelon, tomato and pigeonpea to land preparation techniques in southern Puerto Rico. *Journal of Agriculture of the University of Puerto Rico* 71, 203-208.

Makhan Lal and Gupta, O.P. (1984) Effect of irrigation schedules on pigeonpea in Rajasthan, India. *International Pigeonpea Newsletter* 3, 25-26.

Manjhi, S., Choudhury, S.L. and Kavitkar, A.G. (1973) Influence of varieties, planting rates, row spacings and fertilizer nutrients on yield and yield components of pigeonpea (*Cajanus cajan* (L.) Millsp.). *Indian Journal of Agricultural Sciences* 43, 998-1001.

Mehrotra, O.N., Pal, M. and Singh, G.S. (1977) A note on comparative yields and water use efficiency by Kharif crops under rainfed conditions. *Indian Journal of Agricultural Research* 11, 247-248.

Mukherjee, D. (1960) Studies on spacing of *Cajanus cajan* (L.) Millsp. *Indian Journal of Agricultural Sciences* 30, 177-184.

Narayanan, A. and Sheldrake, A.R. (1979) Pigeonpea (*Cajanus cajan*) as a winter crop in peninsular India. *Experimental Agriculture* 15, 91-95.

Natarajan, M. and Willey, R.W. (1980) Sorghum-pigeonpea intercropping and the effects of plant population density. 1. Growth and yield. *Journal of Agricultural Science, Cambridge* 95, 51-58.

Natarajan, M. and Willey, R.W. (1985) Effect of row arrangement on light interception and yield in sorghum-pigeonpea intercropping. *Journal of Agricultural Science, Cambridge* 104, 263-270.

Panwar, K.S. and Yadav, H.L. (1981) Response of short-duration pigeonpea to early planting and phosphorus levels in different cropping systems. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 37-44.

Pathak, G.N. (1970) Red gram. In: *Pulse Crops of India.* Indian Council of Agricultural Research, New Delhi, India, pp. 14-53.

Rao, I.M., Venkataratnam, N., Faris, D.G. and Sheldrake, A.R. (1983) Response to irrigation in postrainy-season pigeonpea. *International Pigeonpea Newsletter* 2, 35-36.

Rao, I.M., Venkataratnam, N. and Sheldrake, A.R. (1981) Response to row-to-row and plant-to-plant spacing in pigeonpea. In: *Proceedings of the International Workshop on Pigeonpeas, volume 2, 15-19 December 1980, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 249-255.

Rao, J.V. (1974) Studies on fertilizer management of wheat in maize-wheat and arhar-wheat cropping systems. PhD thesis, Indian Agricultural Research Institute, New Delhi, India.

Rao, M.R. and Shetty, S.V.R. (1976) Some biological aspects of intercropping systems on crop-weed balance. *Indian Journal of Weed Science* 8, 32-43.

Rao, M.R. and Willey, R.W. (1983) Effects of pigeonpea plant population and row arrangements in sorghum/pigeonpea intercropping. *Field Crops Research* 7, 203-212.

Rathi, K.S. and Tripathi, H.N. (1978) Studies on time of sowing, row spacing and phosphate fertilization of early maturing *arhar* variety T-21 in central U.P. *Indian Journal of Agronomy* 23, 233-237.

Rathi, S.S., Singh, D. and Malik, R.S. (1974) Response of short-duration arhar to dates of sowing, row spacing and phosphate application. *Fertilizer News* 19(2), 27 and 31.

Reddy, D.S., Reddy, D.R. and Acharya, G.V.N. (1978) Studies on water intake and hydraulic conductivity in shallow and deep ploughing operating under rainfed agriculture at Anantapur. *Annals of Arid Zone* 17, 291-297.

Reddy, G.R.S., Ramaseshaiah, K., Jain, T.C. and Yogeswara Rao, Y. (1984) Irrigation and plant density requirements for optimum yields of red gram. *Madras Agricultural Journal* 71, 281-284.

Reddy, S.J. and Virmani, S.M. (1981) Pigeonpea and its climatic environment. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 259-270.

Rowden, R., Gardiner, D., Whiteman, P.C. and Wallis, E.S. (1981) Effects of planting density on growth, light interception and yield of a photoperiod insensitive pigeonpea *(Cajanus cajan). Field Crops Research* 4, 201-213.

Roy Sharma, R.P., Thakur, H.C. and Sharma, H.M. (1981) Pigeonpea as a rabi crop in India. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 26-36.

Sadaphal, M.N. (1988) Agronomy of pulses. In: Baldev, B., Ramanujam, S. and Jain, H.K. (eds), *Pulse Crops (Grain Legumes).* Oxford and IBH Publishing Co., New Delhi, pp. 456-512.

Sandhu, H.S., Brar, S.S., Dhillon, M.S., Gill, G.S. and Singh, G. (1981) Effect of sowing time, row spacing and plant population on the performance of *arhar* and succeeding wheat in *arhar*-wheat rotation. *Indian Journal of Agronomy* 26, 154-157.

Saraf, C.S., Singh, A. and Ahlawat, I.P.S. (1975) Intercropping of compatible crops with pigeonpea. *Indian Journal of Genetics and Plant Breeding* 35, 248-252.

Sardar Singh and Russell, M.B. (1981) Water use by maize/pigeonpea intercrop on a deep Vertisol. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 271-282.

Satyanarayana, A., Sreemannarayana Murthy, S., Johansen, C., Laxman Singh, Chauhan, Y.S. and Kumar Rao, J.V.D.K. (1988) Introducing pigeonpea into rice fallows of coastal Andhra Pradesh, India. *International Pigeonpea Newsletter* 7, 11-12.

Saxena, M.C. and Yadav, D.S. (1975) Some agronomic considerations of pigeonpeas and chickpeas. In: *International Workshop on Grain Legumes, 13-16 January 1975, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 31-61.

Saxena, M.C. and Yadav, D.S. (1979) Parallel cropping with short-duration pigeonpea under the humid subtropical conditions at Pantnagar. *Indian Journal of Agricultural Sciences* 49, 95-99.

Saxena, N.P., Narayanan, A. and Sheldrake, A.R. (1981) Effect of seed-grading on the yields of chickpea and pigeonpea. *Indian Journal of Agricultural Sciences* 51, 699-702.

Semidey, N., Almodóvar, L. and Orengo-Santiago, E. (1987) Postemergence weed control in pigeonpeas with glyphosate shielded treatments. *Journal of Agriculture of the University of Puerto Rico* 71, 359-364.

Sengupta, K. (1981) Prospects of arhar cultivation as rabi crop in West Bengal. *Pulse Crops Newsletter* 1(1), 88-89.

Sharma, H.C., Dixit, J.P. and Saran, R.N. (1987) Effect of intercrops and irrigation levels on the incidence of pigeonpea wilt caused by *Fusarium udum* Butler. *Indian Journal of Agricultural Sciences* 57, 650-653.

Shetty, S.V.R. (1981) Some aspects of weed management in pigeonpeas. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 137-146.

Singh, A., Prasad, R. and Saraf, C.S. (1981) Effects of plant type, plant population density and application of phosphate fertilizer on growth and yield of pigeonpea. *Journal of Agricultural Science, Cambridge* 97, 103-106.

Singh, A., Prasad, R. and Saraf, C.S. (1983) Effect of variety, row spacing and phosphate fertilization on yield and moisture extraction pattern in pigeonpea. *Indian Journal of Agronomy* 28, 33-36.

Singh, B. and Kalra, G.S. (1980) Effect of seeding dates and plant spacings in relation to phosphorus levels on yield and quality of pigeonpea. *Legume Research* 3, 102-103.

Singh, D.N. and Kush, A.K. (1981) Effect of population density on growth pattern and yielding ability in pigeonpea. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 165-174.

Singh, H.P. (1982) Recent advances in arhar production. *Seeds and Farms* 8(4), 7-9.

Singh, H.P. and Saxena, M.C. (1981) Effect of date of planting on the time of flowering in greengram, blackgram, cowpea and pigeonpea. *Indian Journal of Agricultural Sciences* 51, 33-37.

Singh, H.P., Saxena, M.C., Yadav, D.S. and Sharma, R.P. (1980) Chemical and mechanical weed control in pigeonpea under humid-subtropical conditions of Pantnagar. *Legume Research* 3, 22-26.

Singh, O.N. and Singh, R.S. (1985) Chemical weed control in pigeonpea. *International Pigeonpea Newsletter* 4, 26.

Singh, R.C., Dahiya, D.R. and Singh, V.P. (1985) April-planted arhar gives higher yields. *Indian Farming* 34(12), 36 and 39.

Singh, R.C. and Faroda, A.S. (1977) Weed control in pigeonpea. *Indian Journal of Weed Science* 9, 38-42.

Singh, R.P. and Das, S.K. (1987) Management of chickpea and pigeonpea under stress conditions, with particular reference to drought. In: *Adaptation of Chickpea and Pigeonpea to Abiotic Stresses. Proceedings of the Consultants' Workshop, 19-21 December 1984, ICRRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 51-61.

Sivaprasad, B. and Sarma, K.S.S. (1987) Seedling emergence of chickpea (*Cicer arietinum* L.), pigeonpea (*Cajanus cajan* L.) and pearl millet (*Pennisetum typhoides* L.). Effect of differential soil crusting, as induced by raindrop size, and depth of sowing. *Plant and Soil* 104, 263-268.

Tayo, T.O. (1983) Growth, development and yield of pigeonpea (*Cajanus cajan* (L.) Millsp.) in the lowland tropics 4. Effect of sowing depth. *Journal of Agricultural Science, Cambridge* 101, 435-440.

Tayo, T.O. (1985a) Assessment of the effect of ratooning pigeonpea (*Cajanus cajan* (L.) Millsp.) in the lowland tropics. *Journal of Agricultural Science, Cambridge* 104, 589-593.

Tayo, T.O. (1985b) The effect of ridging on the performance of pigeonpea (*Cajanus cajan* (L.) Millsp.) in the lowland tropics. *Journal of Agricultural Science, Cambridge* 104, 243-245.

Venkataratnam, N., Rao, I.M. and Sheldrake, A.R. (1984) Effects of plant population on postrainy-season pigeonpea yields. *International Pigeonpea Newsletter* 3, 20-22.

Wallis, E.S., Byth, D.E. and Whiteman, P.C. (1981) Mechanized dry seed production of pigeonpea. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 51-60.

Whiteman, P.C., Byth, D.E. and Wallis, E.S. (1985) Pigeonpea. In: Summerfield, R.J. and Roberts, E.H. (eds), *Grain Legume Crops*. Collins Professional and Technical Books, London, pp. 658-698.

Willey, R.W., Rao, M.R. and Natarajan, M. (1981) Traditional cropping systems with pigeonpea and their improvement. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 11-25.

Chapter 12

PIGEONPEA: CROPPING SYSTEMS

M. ALI

Principal Investigator and Head (Agronomy), Directorate of Pulses Research, Indian Council of Agricultural Research (ICAR), Kanpur 208 024, India.

INTRODUCTION

In traditional cropping systems, pigeonpea is often intercropped or mixed with other crops (Aiyer, 1949; Acland, 1971; Osiru and Kibira, 1981). This is primarily because long-duration, tall varieties with slow initial growth rates are grown at wide row spacings. As a sole crop, long-duration pigeonpea has limited scope in low rainfall, nonirrigated areas. In recent years, however, the advent of short-duration genotypes, that have a high harvest index and can be grown at high population densities, has led to the introduction of pigeonpea as a sole crop in irrigated/assured rainfall areas. Short-duration pigeonpea is becoming popular as a sequential crop (Sheldrake, 1979; Willey *et al.*, 1981). Some of the short-duration genotypes have also shown promise in multiple-harvest ratoon systems especially in areas where the winter is mild (Chauhan *et al.*, 1987b; Rao and Sachan, 1988). Pigeonpea is also grown by small farmers as a single plant or hedge in their home backyards, and around field boundaries (van der Maesen, 1983).

CONSIDERATIONS THAT DETERMINE CROPPING SYSTEMS

A cropping system refers to a combination of crops in space and time. Traditional cropping systems in the arid and semi-arid tropics are based on resource-poor farmers' subsistence requirements, and are therefore not necessarily the most efficient ones. An ideal cropping system should make the most efficient use of the natural resources, and provide stable and high returns. Such production systems should also be ecologically sustainable.

The efficient use of the basic resources in a cropping system depends partly on the inherent efficiency of the individual crops that make up the system, and partly on complementary effects between the crops (Willey *et al.*, 1981). The choice of crops and cropping systems in the semi-arid tropics is mainly determined by rainfall pattern, the moisture storage capacity of the soil, and water availability during crop growth periods. For example, in the Alfisols, shallow Vertisols, deep Vertisols, and Entisols of India receiving 350-600 mm annual rainfall, and with an effective growing season of 20 weeks, only single cropping is possible. Intercropping is possible in regions where the effective growing season is 20-30 weeks long. In areas with more than 750 mm rainfall and an effective growing season of 30 weeks or more double-cropping is a distinct possibility (Singh and Subba Reddy, 1988).

Stability is achieved by using crops and varieties that have a wide range of adaptability, and by improved management practices. In an intercropping system, one particular crop component is often more stable than the other components over seasons and years. For example, in cereal/pigeonpea intercropping systems, it is pigeonpea that is more stable over environments and seasons than the cereal. Similarly, in sequential cropping systems, the crop grown during the rainy season usually has more stable productivity under dryland conditions than the crop grown on receding soil moisture. Rao and Willey (1980) examined the stability of a sorghum/pigeonpea intercropping system in 51 experiments. Based on the coefficient of variation (cv) for grain yield, sole pigeonpea (cv 44%) was more stable than sole sorghum (cv 49%), but intercropping was more stable than either (cv 39%). When regressions of yield were computed against an environmental index sole pigeonpea would fail 1 year in 5, sole sorghum 1 year in 8, but intercropping only 1 year in 36.

In ratoon cropping, the regeneration ability of crops and cultivars and their amenability to high population density and photoperiod-insensitivity largely decide the success of the system. In double-cropped regions, the ratoon yield should be reasonably high to compensate for the loss of the second crop in the system.

CROPPING SYSTEMS IN SOUTH ASIA

In South Asia, India and Myanmar are major pigeonpea-producing countries. India has the world's largest hectarage of pigeonpea, and contributes about 90% of the global production. In 1986/87 Indian production of pigeonpea was 2.31 million tonnes from 3.23 million hectares. The major pigeonpea-growing states in India are Maharashtra, Uttar Pradesh, Madhya Pradesh, Karnataka, and Gujarat. These states together contribute 86.1% of the total growing area, and 84.5% of the total production.

In India, pigeonpea has an unique place in traditional cropping systems. Comprehensive reviews on this topic have been made by Willey *et al.* (1981) and Ahlawat *et al.* (1986). About 90% of pigeonpea crops, mainly long- and medium-duration cultivars, are grown in dryland areas as intercrops or in mixed cropping systems (Aiyer, 1949). In irrigated areas of northern and central India, short-duration cultivars are proving quite popular in double-cropping systems (Panwar and Yadav, 1981; Sandhu *et al.*, 1981). In a double-cropping system, pigeonpea is either grown as a sole crop or intercropped with shortseason legumes, like urd bean, mung bean, cowpea, etc. In the northeast plains, postrainy-season pigeonpea has shown promise as a sole crop. It fits well into sequential cropping systems, and offers stability (Roy Sharma *et al.*, 1981b). In the low-lying rice belt of eastern and peninsular India pigeonpea is also grown in close-planted rows on field bunds.

Farmers in Myanmar grow pigeonpea on about 83,000 ha and annually produce 51,000 tonnes. The dry zones of Mandalay, Sagaing, and Magway Divisions are the main production area (Kyaw Moe, 1989). Generally, the long-duration (250-270 days), tall varieties are grown, either mixed or as an intercrop with sesame, groundnut, and short-staple cotton. Pigeonpea/sesame and pigeonpea/groundnut are the most popular intercrops. In this system, three rows of sesame or groundnut sown at 40-cm row spacing are alternated with single rows of pigeonpea, thus maintaining 1.6-m spacing between pigeonpea rows. In the pigeonpea/cotton intercropping system, five rows of cotton are alternated with single pigeonpea rows.

In recent years, short-duration genotypes such as ICPL 87, ICPL 151, and ICPL 83024 have been introduced, and are likely to change the existing cropping system from intercropping to double cropping in dryland areas (Kyaw Moe, 1989). Short-duration pigeonpea could be adopted as a sole crop in the postrainy season after sesame, or mung bean. Early pigeonpea that can be grown in rice fallows has interesting potential.

In Bangladesh, long-duration pigeonpea genotypes are generally mixed with May-sown rice on uplands in the districts of Kustia and Jessor, in the southwest. The medium-duration genotypes being introduced in recent years may also encourage rice-pigeonpea sequential cropping. Pigeonpea is also grown on rice bunds in some areas. In Pakistan, pigeonpea is only a minor crop confined to the province of Sindh, where long-duration cultivars are grown either mixed with cereals or as a sole crop.

In Nepal, pigeonpea is grown in the Terai region (the foot-hill plains). In eastern Terai, late-maturing tall genotypes are grown on rice bunds. In western Terai, pigeonpea is grown on the uplands either mixed with maize, urd bean, and sesame, or as a sole crop. The medium- and short-duration genotypes show good promise as postrainy-season crops for sequential cropping systems.

In this chapter various aspects of the cropping systems involving pigeonpea with special reference to India are discussed. Please refer to the map (Figure 1.1) in Chapter 1.

Intercropping

Traditional intercropping consists of either mixing and broadcasting seeds of the component crops, or sowing a few rows of the intercrop between the rows of the base crop. An ideal intercropping system should aim to: 1. produce higher yields per unit area through better use of natural resources, minimizing the incidence of insect pests, diseases, and weeds, and improving the nitrogen economy in legume associations; 2. offer greater stability in production under aberrant weather conditions; 3. meet the domestic needs of the farmer; and 4. provide an equitable distribution of farm resources.

In a traditional intercropping system, pigeonpea is grown in association with cereals, oilseeds, short-season pulses, or cotton. Of these, the pigeonpea/cereal intercrop is the most common, and, depending on the region can involve sorghum, pearl millet, maize, finger millet, and rice as the cereal component. In this system, the cereal is generally regarded as the main crop, and management practices are centred around it. Efforts are made to obtain a "full" yield of cereal, and the pigeonpea component is regarded as a "bonus" crop, and an insurance against total crop loss due to aberrant weather. Generally, the cereal is sown at the sole-crop rate. The pigeonpea genotypes used are tall, and medium- to long-duration.

Pigeonpea/oilseed intercrops are gaining considerable importance because of the growing demand for vegetable oils and protein. In this system, both the component crops are considered important by the farmers. Commonly intercropped oilseeds include groundnut, soybean, and sesame. Pigeonpea/groundnut is widely sown in Maharashtra, Andhra Pradesh, Karnataka, and Gujarat, pigeonpea/soybean is popular in Madhya Pradesh and part of Uttar Pradesh, and pigeonpea/sesame in north-central Madhya Pradesh.

Pigeonpea is intercropped with a short-season pulse both with early- and late-maturing pigeonpea cultivars. In this system, pigeonpea is grown as the main crop, and the short-duration pulses (urd bean, mung bean, cowpea, etc.) are grown as a bonus. The system has been widely adopted in northern and central India under both irrigated and rainfed conditions. In Maharashtra and Gujarat, pigeonpea/cotton intercropping is popular on deep Vertisols.

In order to achieve high productivity from intercrops, it is very important to; select compatible crops with reference to the rainfall characteristics and edaphic conditions of the region, identify genotypes with varying duration and growth rhythms, use suitable sowing geometry, optimal populations of the component crops, fertilizers at the optimum rate, and efficiently manage pests, diseases, and weeds.

Compatible Crops

When two or more crops are grown together, it is imperative that the peak periods of growth of the components do not coincide. Crops of varying maturity duration should be chosen so that a rapidly maturing crop completes its life cycle before the major growth period of the other crop starts.

At ICRISAT Center, Willey *et al.* (1981) studied the dry matter accumulation pattern of a medium-maturing pigeonpea (ICP 1) grown with sorghum (CSH 6) and groundnut on deep Vertisols. They found that the initially slow growth rate of pigeonpea offers good scope for intercropping with fast-growing, early-maturing sorghum or groundnut.

Several functions/parameters, e.g., monetary advantage (Willey, 1981), relative crowding coefficient (de Wit, 1960 in de Wit and Goudriaan, 1974), agressiveness (McGilchrist and Trenbath, 1971), expected cash return (Chowdhury, 1981), land equivalent ratio (LER) (Willey and Rao, 1980), and equivalent yield have all been used to assess the efficiency of intercrops. However, LER is considered the most appropriate in combination with the absolute yields of the component crops.

Studies to identify compatible crops for intercropping with medium- or late-maturing pigeonpea in different agroecological zones of India were conducted under the auspices of the All India Coordinated Research Project for Dryland Agriculture (AICRPDA) from 1972 to 1980. Results showed that pigeonpea/sorghum was most productive and efficient on Vertisols in central and southern India, whereas pigeonpea/pearl millet proved ideal on the Alfisols and Entisols in Karnataka and Gujarat (Ali, 1985b). Maize was the most compatible component on the light-textured soils of Rajasthan and eastern regions of India. On the plateau of Bihar, pigeonpea/rice was quite efficient under upland conditions. The LER in cereal-based intercrops varied from 1.14 (with sorghum) to 1.81 (with pearl millet). High productivity and profitability from pigeonpea/cereal intercropping with; sorghum (Gupta and Sharma, 1984; Umrani *et al.*, 1984), maize (Yadahalli, 1973; Rajaram, 1984), and pearl millet (Giri and Gayke, 1983) have been reported from different parts of India. In this system, the yield of pigeonpea is depressed, but the system as a whole proves more profitable than either sole cereal or sole pigeonpea.

Rao and Willey (1981) analysed results from 80 experiments on sorghum/pigeonpea intercrops and found that, on an average, the intercropping system provides 90% of the equivalent yield of sole sorghum, and 52% of the sole pigeonpea. In the rice/pigeonpea system, sowing pigeonpea 2 weeks after direct-seeded upland rice proved quite beneficial and efficient (LER 1.5 to 1.75) in the northeast plains (Chatterjee and Bhattacharya, 1987). In the Gangetic plains, however, the rice/pigeonpea combination has been reported to be inefficient (Moinbasha and Singh, 1988).

Studies on intercropping involving early pigeonpea were extensively conducted from 1973 to 1985 by the All India Coordinated Pulses Improvement Project (AICPIP). Results showed that short-season pulses like urd bean, mung bean, and cowpea, are quite compatible. These intercrops did not depress pigeonpea yield, and provided 400-500 kg bonus yield ha^{-1} of the pulse crop (Ali, 1985a). In this system, the sole-crop population of pigeonpea was maintained, and the intercrops were alternated with one or two rows of pigeonpea. Other workers have also reported that intercrops of; mung bean (Giri and De, 1978), urd bean (Saraf *et al.*, 1975; Singh *et al.*, 1978), and mung bean, urd bean, and cowpea (Singh *et al.*, 1978; Saxena and Yadav, 1976, 1979; Singh, 1981; Ali, 1988) did not depress pigeonpea yield under good management conditions.

Ramadoss and Thirumurugan (1983) and Venkateswarlu (1986) reported that under rainfed conditions, short-season pulses depressed pigeonpea yield, but the additional yield they provided made the system more profitable.

Among oilseeds; groundnut (Appadurai and Selva Raj, 1974; Giri *et al.*, 1981; Patel and Bhardwaj, 1985; Rafey and Verma, 1988), sesame (Kharwara and Singh, 1986; Kumar and Ahlawat, 1986; Venkateswarlu and Ahlawat, 1986), and soybean (Thirumurugan and Ramadoss, 1984; Prasad *et al.*, 1985; Tomar *et al.*, 1984; Patra and Chatterjee, 1986; Rafey and Verma, 1988) have been found quite compatible with pigeonpea. In this system, the yields of both crops are reduced as compared to their sole crop yields, but the total productivity and LER of the system are usually higher.

Pigeonpea/groundnut is the most popular combination, especially in central and southern India. Willey *et al.* (1981) reported that in a pigeonpea/groundnut system grown on Alfisols, groundnut produced 82%, and pigeonpea 85% equivalent yields of their sole stand. In this system, groundnut utilizes early season resources efficiently owing to its rapid growth and large crop canopy. Even at later stages, when the pigeonpea develops sufficient canopy, groundnut has the ability to make efficient use of the lowered light intensity under the pigeonpea canopy.

Intercropping of pigeonpea with such long-duration crops as cotton and castor has not given encouraging results, probably due to their similar growth patterns. Ramanujam (1973) in Ramanujam, 1981 reported that it is possible to intercrop early-maturing pigeonpea varieties with sugarcane under conditions that exist at Coimbatore, but the authors did not examine the economic viability of the system or its acceptability to farmers.

Genotypic Compatibility

The identification of compatible genotypes for component crops is imperative for the complementarity of an intercropping system. A genotype's duration, growth rhythm, canopy structure, and rooting pattern are the major selection criteria. In the past intercropping research has mainly focussed on selection of compatible crops for various agroecological zones, and relatively little attention has been paid to developing genotypes especially suited to intercropping situations. There is experimental evidence to show that the genotypes which give high yields in sole-cropping systems are not necessarily high yielders in intercropping systems (Rao *et al.*, 1981). Green *et al.* (1981) reported that only 41% of the genotypes identified in a sole-cropping system at 20% selection pressure, and 55% of those identified at 33% selection pressure matched those identified in intercropping systems.

The duration of genotypes plays a key role in determining yield advantage. High yield advantages can be expected only when the maturity period of the genotypes differ widely. In a cereal/pigeonpea intercropping system, the longer the duration of the cereal, the lower is the yield of pigeonpea. Intercropping cereals with early-maturing pigeonpea often leads to drastic reduction in pigeonpea yield. Willey and Rao (1981) suggested the use of pigeonpea genotypes that can withstand early sorghum competition, and early dwarf sorghum genotypes to minimize competition. Early-maturing dwarf sorghum hybrids such as CSH 5 and CSH 6, and determinate (150-day duration) pigeonpea cultivars such as Hy 2 and Hy 4, proved most promising in intercropping systems at ICRISAT Center (Venkateswarlu *et al.*, 1981). Tarhalkar and Rao (1981) found that in Vertisols, Hy 3A an erect, long-duration pigeonpea genotype proved better than Hy 2 when intercropped with sorghum, the base sorghum having lost 8% yield with Hy 3A, amd 12% yield with Hy 2. At Indore however, the medium-maturing pigeonpea genotypes (C 11 and No.148) behaved almost identically when intercropped with sorghum hybrids (Rathore *et al.*, 1987). In relay intercropped pigeonpea/groundnut, the early-maturing pigeonpeas UPAS 120 and T 15-15 did not have detrimental effects on groundnut, but other genotypes did (Yadavendra *et al.*, 1987).

The canopy structure of the component crop genotypes also determines species compatibility. Ideal pigeonpea genotypes are those that grow compactly in their early stages thus avoiding competition from the intercrop, and that later develop a spreading habit so that they can utilize available resources. On Inceptisols at Kanpur, Bahar, a compact, medium- to long-duration (240-250 days) pigeonpea genotype proved an ideal intercrop for pearl millet hybrid BJ 104 (Singh and Ali, 1985), it was superior to such spreading types as T 17 Gonda local, and NP(WR) 15. In a pigeonpea/sorghum intercrop PDA 10 a compact but long-duration (270-280 days) pigeonpea proved better than Bahar (Kushwaha, 1987).

In multilocational trials to evaluate pigeonpea genotypes for intercropping with sorghum, the genotypes exhibited differential responses in sole and intercropping situations (Table 12.1). At Sehore (Madhya Pradesh), an early genotype (T 21) suffered more loss in the intercropping system than late-maturing ones. It was interesting to note that at Parbhani (Maharashtra), some of the intercropped genotypes produced identical or higher yields than when they were sole cropped. Such genotypes need to be further studied to confirm their behaviour. Evaluation of long-duration pigeonpea genotypes under sole and intercropping systems at ICRISAT Cooperative Research Center, Gwalior, Madhya Pradesh showed that ICPL 366 which gave high yields as a sole crop also yielded well when intercropped (Table 12.2). Detailed studies are needed to examine the behaviour of genotypes at different sowing geometries and population densities.

Table 12.1. Genotypic compatibility of pigeonpea intercropped with sorghum at three Indian locations.

		Pigeonpea yield ($t\ ha^{-1}$)		Reduction in intercrop over sole crop (%)
Location	Genotypes	Sole	Intercrop	
Sehore	Gwalior 3	1.22	0.88	28
	No.148	0.75	0.27	64
	T 21	0.42	0.14	67
	NP(WR) 15	1.35	0.73	46
Gwalior	NP(WR) 15	0.85	0.57	33
	K 28	0.88	0.43	51
	AS 29	0.98	0.90	8
	K 23	1.11	1.07	4
Parbhani	No.56-30	1.12	1.11	1
	BDN 1	0.87	0.88	−2[1]
	No.56-45	1.09	1.21	−11
	No.38	0.63	0.84	−33

1. Negative sign indicates higher yield under intercropping.

Source: Ramanujam, 1981.

In pigeonpea/short-season pulse systems, mung bean genotypes, ML 227 and MH 309 and urd bean genotypes, UG 218 and Pant U 19 were found to be most compatible with short-duration pigeonpea in northern India (Lal and Ali, 1988). In coastal Andhra Pradesh, mung bean genotypes Pusa 105 and ML 267 proved superior to LCG 127 when intercropped with medium-duration pigeonpea LRG 30. The highest monetary return was obtained from ML 267 at a density of 22 plants m^{-2} (equivalent to 222,000 plants ha^{-1}).

Table 12.2. Grain yield (t ha^{-1}) of long-duration pigeonpea genotypes under sole and intercropping, ICRISAT Cooperative Research Center, Gwalior, 1986/87.

	Grain yield (t ha^{-1})	
Genotypes	Sole crop	Intercrop[1]
Gwalior 3	2.13	1.80
ICPL 360	2.13	1.92
T 7	2.13	1.78
ICPL 366	2.44	2.41
Bahar	1.75	1.50
PDA 10	1.53	1.51
SE	±0.145[2]	
Mean	2.02	1.82
SE	±0.042	

1. Intercropped with pearl millet BJ 104.
2. Except when comparing means within a cropping treatment, ±0.152.

Source: ICRISAT, 1988.

Sowing Pattern

The sowing pattern and spatial arrangement considerably influence competition among component crops (Choudhary and Bhargava, 1986). It is, therefore, imperative to adopt an appropriate plant geometry which minimizes competition, and at the same time enhances total productivity.

Sowing systems vary from place to place depending upon crop combination, soil type, rainfall pattern, farm resources, and farmers' needs. Traditionally, seeds of component crops are either mixed in a certain ratio and broadcast, or sown in separate rows. In the seed-mixed broadcast system, the full seeding rate of the cereal is maintained, and pigeonpea along with any other associated crops added at 25 to 40% of its recommended sole-crop seeding rate. However, in fodder sorghum or pearl millet/pigeonpea intercrops, the full seeding rate of both crops is used, as the cereal competition is removed early in the pigeonpea growing season. In the seed-mixed broadcast system, the pigeonpea plant population is often sub-optimal and its distribution uneven. This system is also difficult to manage.

When the component crops are sown in rows, different row ratios are used depending on the importance and growth rhythms of the components. In the traditional system, after a few rows of the base crop, one or two rows are skipped at sowing, and then sown with the intercrop. Thus, the population of the base crop is proportionally reduced, and this is often reflected by its final yield.

An improvement over this system is paired-row sowing. Here the rows of the tall component (base crop) are paired at 50% of their normal spacing thus leaving a wide space (about 50% more) between pairs, where one or two rows of the intercrop can be accomodated. This system allows more radiation to reach dwarf component crops grown between the base-crop rows, and minimizes competition. Shelke and Krishnamoorthy (1980) observed that in a sorghum (CSH 6)/pigeonpea

(Hy 2) intercropping system, the yield of the component crops increased as their proportion was increased from 1:4 to 4:1. The yield of sorghum in the 1:4 row ratio was 1.02 t ha^{-1} as against 3.63 t ha^{-1} in the 4:1 row ratio. Similarly, pigeonpea yield was increased from 0.65 t ha^{-1} to 2.20 t ha^{-1} as its population increased in the system. On the whole, this system provides only a marginal advantage. Working on a pigeonpea/groundnut intercropping system at Badnapur (Maharashtra), Giri *et al.* (1981) found that by pairing rows of pigeonpea at 30-70 cm, the yield of groundnut increased from 0.81 t ha^{-1} (uniform row at 50 cm) to 1.29 t ha^{-1} without any adverse effect on pigeonpea yield. Higher yields from crops associated with pigeonpea in paired-row sowings were also obtained by: Srinivasan and Ahlawat, 1984; Gupta and Sharma, 1984; Subramanian *et al.*, 1984; Venkateswarlu, 1984; Kumar, 1985; and Umrani *et al.*, 1987. In pigeonpea/soybean (Prasad *et al.*, 1985) and pigeonpea/sesame (Ahlawat and Venkateswarlu, 1987) intercrops, however, both uniform and paired-row sowings systems were found identical.

In pigeonpea/short-season pulse systems, sowing pigeonpea in rows 50-60 cm apart and accommodating one or two rows of mung bean, urd bean, or cowpea in between the pigeonpea rows proved quite efficient and profitable (Giri and De, 1978; Saxena and Yadav, 1979; Tomar *et al.*, 1984; Tripathi, 1987).

In a pigeonpea/sorghum system, Ali and Raut (1985) found that a 2:1 row ratio with a 67% sorghum population and 33% pigeonpea population equivalent to their sole-crop populations proved most productive and efficient on the Alfisols of Bundelkhand. In a pigeonpea/maize system, a 1:1 row ratio, with maize sown at 75-cm row spacing recorded a high yield in southern Bihar (Roy Sharma *et al.*, 1981a). Summarizing results of 80 experiments on sorghum/pigeonpea intercrops, Rao and Willey (1981) found that a 2 sorghum:1 pigeonpea row ratio was better than a 1:1 ratio. In further studies at ICRISAT Center, it was observed that with a good moisture supply alternate rows (1:1) could be as effective as a 2 sorghum:1 pigeonpea (2:1) arrangement, but with a poorer moisture supply, alternate rows are not a worthwhile option because of the risk of reducing sorghum yield to such an extent that can not be offset by the small increase in pigeonpea yield (Natarajan and Willey, 1985).

Method of sowing and bed configurations also affect the yields of intercropping systems. On deep Vertisols at ICRISAT Center, the broadbed-and-furrow (BBF) system proved better than the flat system. It was observed that in a standard row arrangement on a graded BBF that had two rows of sorghum on either side of the bed with one row of pigeonpea in the centre, the light interception was poor after the harvest of the sorghum. When two rows of pigeonpea were grown in the centre, with two rows of sorghum on either side, or vice versa, the light interception was improved and yields were higher, (Rao and Willey, 1983).

Efforts have been made to increase cropping intensity and total productivity by relay sowing a third crop after harvesting the cereal component of a pigeonpea/cereal intercrop (Willey, 1981; Reddy and Willey, 1982).

At ICRISAT Center, the addition of chickpea in gaps left by harvesting maize from a maize/pigeonpea intercrop gave an additional yield of 528 kg ha^{-1} of chickpea (equivalent to 36% of a sole crop) without causing any yield reduction in the pigeonpea (Willey *et al.*, 1981). The financial returns were higher than those from the best double-cropping system of maize followed by chickpea. Such systems may prove more useful when short-season pulses are intercropped with late-maturing pigeonpea. However, the success of this system will depend on the availability of moisture required for germination of the third crop, and this is generally uncertain in dryland areas. On deep Vertisols in the Saurashtra region of Gujarat, Yadavendra *et al.* (1987) reported that relay intercropping pigeonpea with groundnut did not have a detrimental effect on the yield of groundnut, and under favourable conditions, the yield of pigeonpea was similar to normal sowing situations. In this system, the pigeonpea was sown 2 weeks after groundnut. De and Singh (1981) also suggested staggered sowing of component crops so that their peak periods of growth do not coincide, especially when crops of the same phenological group are intercropped.

Plant Density

Low plant populations have been generally recognized as one of the factors limiting productivity in intercropping systems. Recent studies by AICRPDA have clearly shown that high productivity from sorghum/pigeonpea intercrops was obtained when the optimal population of both crops (18 plants m^{-2} for sorghum and 4 plants m^{-2} for pigeonpea) were maintained in a 2:1 row arrangement (Venkateswarlu *et al.*, 1981). Tarhalkar and Rao (1981) suggested a normal population of sorghum (18 plants m^{-2}) and a relatively low population (2.7 plants m^{-2}) of pigeonpea. Natarajan and Willey (1980b) observed that in sorghum/pigeonpea intercropping pigeonpea yields were limited by poor light interception after the sorghum harvest. An increase in pigeonpea population improved light interception and productivity.

In intercropping studies at ICRISAT Center, when normal populations of sorghum (18 plants m^{-2}) and pigeonpea (4 - 5 plants m^{-2}) was maintained, the sorghum produced 4.2 t ha^{-1} as against 4.5 t ha^{-1}, its sole crop yield. The pigeonpea, however, suffered considerable competition during the period of sorghum growth and at sorghum harvest it had accumulated only 16% of the dry matter yield of its sole crop. After the sorghum harvest, however, the pigeonpea was able to compensate to quite a large extent and finally produced 53% of its sole-crop dry matter Willey *et al.* (1981). Natarajan and Willey (1980a) also obtained almost the full yield of sorghum from an intercrop by maintaining the sole-crop population of sorghum. In pearl millet/pigeonpea intercropping the highest returns were obtained when the recommended populations of both the crops (15 plants m^{-2} of pearl millet and 5.5 plants m^{-2} of pigeonpea) were maintained (Patel *et al.*, 1985).

Fertilizer Management

Despite the fact that pigeonpea is generally grown under inter- or mixed cropping systems, studies on fertilizer use have mainly been conducted on sole-cropping systems. Only in recent years has there been a shift in fertilizer use research focussing on other cropping systems. For pigeonpea-based intercropping systems that involve crops of different duration, growth rhythms, and nutrient needs, specific information on the optimal nutrient requirements and their mode of their application is imperative.

Due to the high plant population per unit area in intercrops nutrient requirements are generally higher. Soundarajan (1978) observed that in a pigeonpea/sorghum intercrop the uptake of N was 185 kg ha^{-1}, 8 kg P ha^{-1}, and 250 K kg ha^{-1} compared with 116 kg N ha^{-1}, 8 kg P ha^{-1}, and 75 kg K ha^{-1} in sole-cropped pigeonpea. Higher nutrient uptakes in pigeonpea/maize (Dalal, 1974), and pigeonpea/mung bean or urd bean (Hegde and Saraf, 1982; Srinivasan and Ahlawat, 1984) intercrops as compared to sole pigeonpea have also been reported.

In multilocational AICPIP trials it was observed that the application of a full (N 60-P 40-K 0) dose of fertilizer to the cereal component was adequate to meet the nutrient requirement of the pigeonpea component. There was only marginal increase in pigeonpea yield with the application of the full (N 18-P 46-K 0) recommended dose of nutrients. Application of half the recommended dose to each of the component crops was equally good. Venkateswarlu (1984) reported that under dryland conditions, application of nitrogen and phosphorus only to the cereal component in a pigeonpea/sorghum intercropping system was beneficial. In this system, pigeonpea yield was marginally decreased, but there was a substantial increase in sorghum yield. In a pigeonpea/pearl millet intercropping system the application of a full dose of fertilizer to pearl millet was most productive on Alfisols (Giri and Gayke, 1983).

The nitrogen requirement in a cereal/pigeonpea intercropping system is largely governed by the nature of the cereal component and the growing conditions. Venkateswarlu *et al.* (1981) and Reddi *et al.* (1980), reported that in a sorghum/pigeonpea intercrop, 80 kg N ha^{-1} was optimal. Narain *et al.* (1980), however, recommended a moderate dose of N (25-30 kg ha^{-1}) for sorghum/

pigeonpea. They found that the application of higher doses of N accelerated sorghum growth, and that this consequently suppressed pigeonpea growth, and ultimately the total productivity of the system was low. In a pigeonpea/sesame intercrop, increasing the dose of N from 0 to 50 kg ha^{-1} did not adversely effect the pigeonpea, and increased the overall yield of the system (Kumar and Ahlawat, 1986).

Studies on phosphorus requirements at ICRISAT Center showed that in a pearl millet/pigeonpea intercrop, 10 kg P ha^{-1} was optimal (ICRISAT 1980). For a pigeonpea/urd bean intercrop, the phosphate requirement has been reported to be 40-60 kg P_2O_5 ha^{-1} (Yadav, 1984; Singh *et al.*, 1986).

In irrigated areas, the nutrient requirement is generally higher. In an AICRPDA trial during 1981/82 at Indore (Madhya Pradesh) in a sorghum/pigeonpea intercrop, application of the full recommended dose of fertilizer to both the component crops was productive and profitable. Hiremath (1980) recommended that for a sorghum/pigeonpea intercrop under irrigated conditions 35-40 kg N, 60 kg P_2O_5, and 40 kg K_2O ha^{-1} should be given as a basal dose at sowing, and 35-40 kg N ha^{-1} should be top dressed. Ahlawat *et al.* (1986) suggested that in cereal/pigeonpea intercropping systems, nitrogen should be applied in two splits; i.e., half as a basal dose, and the remaining half as a top dressing. They postulated that application of the full dose of N at sowing will promote the initial vegetative growth of the cereal, which may suppress pigeonpea growth, and also adversely affect nodulation.

Weed Management

The nature and magnitude of crop-weed competition differs considerably between sole and intercropping systems. The crop species, population density, sowing geometry, duration, and growth rhythm of the component crops; the moisture and fertility status of soil, and tillage practices all influence weed flora in intercropping systems (Moody and Shetty, 1981). See Chapter 11 for more details.

Insect Pest and Disease Occurrence

Little work has been done on understanding the nature and magnitude of pest complex and its effect on crop losses, pesticide use, and pest management practices in intercropped compared with sole-cropped pigeonpea. It is generally believed that one component crop in an intercropping system may act as a buffer or barrier against the spread of pests and pathogens.

Raheja (1973) reported that the damage by sorghum ear fly *(Calocoris angustatus)* in a sorghum/pigeonpea intercrop was considerably less than that in sole sorghum. However, such interactions are not always beneficial. Bhatnagar and Davies (1981) found that in a sorghum/pigeonpea intercrop, pod damage to the pigeonpea component by pod borer *(Helicoverpa armigera)* was more than in sole-cropped pigeonpea.

A low incidence of wilt disease in pigeonpea intercropped with sorghum has been reported. It is believed that some root exudates of sorghum could be responsible for minimizing the incidence of soilborne *Fusarium udum* (Natarajan *et al.*, 1985). However, the incidence of pigeonpea sterility mosaic disease increased in this system.

Sequential Cropping

Sequential cropping refers to growing crops in sequence within a crop year, one crop being sown after the harvest of the other. When two or more crops are grown in a year, they are said to be double-cropped or multiple-cropped.

The traditional long-duration cultivars of pigeonpea continue to be grown as intercrops. In the recent past, the advent of short-duration (140-160 days), high-yielding genotypes has paved the way for double-cropping and the introduction of pigeonpea to non-traditional areas. Pigeonpea-wheat sequential cropping has spread widely in irrigated areas of northern and central India (Faroda and Singh, 1983; Chandra and Ali, 1986). In eastern and peninsular India, postrainy-season pigeonpea has shown great promise in double-cropping systems (Narayanan and Sheldrake, 1979; Roy Sharma *et al.*, 1981b). In the rice fallows of eastern coastal regions, rice-pigeonpea sequential cropping appears to be a distinct possibility (Lenka and Satpathy, 1976). Thus, in the near future double-cropped, short-duration pigeonpea will play an important role in boosting Indian pulses production.

Pigeonpea-Cereal System

This system is popular in the states of Punjab, Haryana, part of Rajasthan, Gujarat, Uttar Pradesh, and Madhya Pradesh, where irrigation facilities exist. Generally, wheat follows early pigeonpea in the sequence. Pigeonpea is often grown as a sole crop at high population densities (10 to 15 plants m^{-2}), but in some areas short-season pulses like urd bean, mung bean and cowpea are also intercropped with the pigeonpea.

The first shorter-duration cultivar of pigeonpea, T 21 was released for cultivation in 1974. It matures in 150-170 days and yields about 2 t ha^{-1}. This variety quickly spread in northern India as it could be double-cropped with wheat and also escape from the frost, which causes substantial damage to long-duration cultivars. It was however, observed that T 21 delayed wheat sowing since it has a tendency to spill over into the wheat-growing season whenever late monsoon showers occur. Later on, short-duration varieties (140-150 days) such as UPAS 120, Pusa Ageti, Pusa 74, Pusa 84, Manak, AL 15, ICPL 151, and TT 6, were developed; these allow timely sowing of wheat (DPR, 1988). Results of multilocational AICPIP trials showed that pigeonpea-wheat sequential cropping was highly profitable in northern India (Table 12.3). The yields of pigeonpea ranged between 1.70 and 2.11 t ha^{-1}, and wheat between 2.86 and 4.10 t ha^{-1}. Intercropping mung bean or urd bean with the pigeonpea further increased the monetary return. At Akola (Maharashtra), a pigeonpea-wheat rotation gave a net return of Rs.8970 ha^{-1} which increased to Rs.9560 ha^{-1} when urd bean was intercropped with pigeonpea.

Table 12.3. Yield and monetary return from pigeonpea-wheat sequential cropping at three locations in northern India.

Location	Yield (t ha^{-1}) Pigeonpea	Wheat	Net return (Rs ha^{-1})
Hisar	1.74	4.10	8 223
Dholi	1.75	2.86	7 550
Kanpur	2.11	5.34	15 811

Source: Chandra and Ali, 1986.

Sowing time and the choice of an appropriate genotype play key roles in deciding the success of a pigeonpea-wheat system. The ideal time to sow early pigeonpea is mid-June. Late sowing not only threatens the timely sowing of the wheat crop, but also lowers yields because plant stands are poor, and less biomass is produced. At Ludhiana, Punjab, sowing pigeonea in the first fortnight of June was found to be ideal for pigeonpea-wheat rotation (Kaul *et al.*, 1980; Sandhu *et al.*, 1981). For genotypes of the T 21 cultivar group maturity, April sowing has been found quite promising, especially in areas where summer mung bean is cultivated. In this system, pigeonpea is sown at 1-m row intervals and three rows of mung bean are sown between pigeonpea rows, 25 cm apart. April sowing ensures good plant stands, increases grain and dry stick yields, and facilitates timely sowing of wheat. Panwar and Yadav (1981) reported that T 21 sown on 15 April produced 2.60 t grain ha^{-1} as against 1.74 t ha^{-1} from a crop sown on 30 June. Further, the yield of wheat succeeding April-sown pigeonpea was 6.72 t ha^{-1}, whereas it was only 5.34 t ha^{-1} after June-sown pigeonpea. Similar observations were made by Ahlawat *et al.* (1986).

Information on the effect of pigeonpea genotypes on the total productivity of pigeonpea-wheat rotations is meagre. Available short-duration varieties, although they allow timely sowing of wheat, do not yield well and also add less biomass to the soil than early ones. Shrivastava *et al.* (1988) evaluating four genotypes ICPL 87, ICPL 151, ICPL 161, and UPAS 120 in pigeonpea-wheat rotations at Gwalior, Madhya Pradesh reported that ICPL 87 and ICPL 151 were more suitable than the other genotypes. However, because of the slightly longer duration of ICPL 87, they recommended ICPL 151 for double-cropping systems. Ahuja (1984) reported that Pant A 3 was more suited to sequential cropping than Pant A 1 and Prabhat. In Uttar Pradesh, Punjab and Haryana, UPAS 120, AL 15, and Manak are considered ideal for double cropping.

Cereal-Postrainy-Season Pigeonpea System

The cultivation of pigeonpea during the postrainy season is a recent development. It is of paramount importance in eastern India where rainy-season pigeonpea often suffers heavy losses from the frequent floods and waterlogging. Postrainy-season pigeonpea has also shown promise in peninsular India, particularly in rice fallows as it makes better use of the residual moisture, and thrives under mild winters. Because of favourable growing conditions (low incidence of weeds, insect pests, and diseases, more sunshine hours, and avoidance of excess moisture), and its high harvest index, the productivity of the postrainy-season pigeonpea crop is often high. Since it fits well in double-cropping systems, the farmers are readily accepting it. During the postrainy season, pigeonpea is grown as a sole crop at high population densities (3.3 plants m^{-2}). In double-cropping systems, it can follow maize, pearl millet, or rice (Khatua *et al.*, 1977; Willey *et al.*, 1981.

At Dholi (Bihar), pigeonpea grown in sequence with maize yielded 3.43 t seed ha^{-1} (Roy Sharma *et al.*, 1981b). Among various crop rotations, maize-pigeonpea with a net return of Rs 7552 ha^{-1} was found to be most remunerative, followed by maize-peas (Rs 5272), and maize-mustard (Rs 4803). In peninsular India and in the rice fallows of coastal regions where postrainy-season pigeonpea grows on residual moisture, its productivity is generally low (0.5 to 1.0 t ha^{-1}).

One of the prerequisites for achieving high productitivity from postrainy-season pigeonpea crops is that they should be sown early. The first fortnight of September appears to be the ideal time to sow. Results of AICPIP experiments during the 1982/83 season revealed that at Dholi (Bihar) variety MA 128-2 yielded 2.0 t ha^{-1} when sown on 1 September, but if sown on 21 September its yield was only 0.27 t ha^{-1}. Similarly, at Akola (Maharashtra), variety C 11 which produced 1.8 t ha^{-1} when sown on 25 September gave only 0.68 t ha^{-1} when sown on 30 October.

After rainy-season cereals, sowing pigeonpea is often delayed, and consequently its desired productivity is not achieved. In order to overcome this problem, relay sowing 2 to 3 weeks before the harvest of the previous crop has been suggested (Khatua *et al.*, 1977). At ICRISAT Center, a 20-day overlap with maize or sorghum increased pigeonpea yield from 0.73 to 1.0 t ha^{-1}. However, relay sowing poses practical difficulties, and a more realistic solution would therefore be to develop cultivars that can be successfully sown a bit late. In rice fallows at Hyderabad, relay sowing of pigeonpea (by broadcasting seeds) 2 weeks before the rice harvest proved better than sowing after the rice harvest (Narayanan *et al.*, 1981). This system allows early sowing, and also eliminates the tillage operations required for land preparation after the rice harvest.

Selection of an appropriate variety is an important consideration in cereal-postrainy-season pigeonpea. Since crop growth is restricted by low temperature, indeterminate long-duration genotypes perform better than determinate, early-maturing ones. At Kanpur, two determinate and two indeterminate genotypes were evaluated for their yield performance when sown on 10 September. Determinate genotypes yielded 1.2 to 1.5 t ha^{-1} as against 0.3 to 0.9 t ha^{-1} by determinate ones. At Dholi (Bihar), long-duration genotypes MA 128-2 and ICPL 87-2 yielded about 2 t ha^{-1} as against 0.7 t ha^{-1} by early-maturing TT 6 sown on 1 September. Similarly, at Akola (Maharashtra), medium-maturing C 11 yielded 1.8 t ha^{-1}, whereas T 21 yielded only 0.7 t ha^{-1}. In Orissa, latematuring Nayagarh local out-yielded early-maturing UPAS 120 and T 21 (Misra *et al.*, 1980).

Alternaria blight (*Alternaria tenuissima*) poses a serious threat to postrainy-season pigeonpea, particularly in northern India, and it is therefore imperative to develop varieties resistant to this disease. Presently, DA 11 - a long-duration indeterminate genotype is by far the most promising against this disease.

Ratoon Cropping

Ratoon cropping refers to a multiple-harvest system in which regenerating stubbles of the first-sown crop are managed for subsequent production. This system minimizes the cost of cultivation, avoids the risks associated with sowing a second crop in rainfed conditions, and provides high returns.

The development of short-duration genotypes of pigeonpea has regenerated a lot of interest in ratoon cropping. Intensive studies have been done at ICRISAT Center and by AICPIP in the last 6-7 years, to identify suitable genotypes and develop an appropriate management system. At ICRISAT Center, a short-season genotype ICPL 87 (released as "Pragati" in 1986) produced 4.1 to 5.2 t ha^{-1} under good management conditions in three harvests during a growing period of 220 days (Chauhan *et al.*, 1987b). Rao and Sachan (1988) observed that even under rainfed conditions, ratoon cropping of ICPL 87 was quite successful. On Alfisols, the yield of ICPL 87 in three harvests (by picking pods) was 2.5 t ha^{-1} compared to 1.33 t ha^{-1} from medium-maturing genotypes ICP 1-6 under rainfed conditions (Table 12.4).

Multilocational studies by AICPIP revealed that in peninsular India where winters are mild, ratoon management of pigeonpea was promising under irrigated conditions. Among early genotypes, ICPL 87 at a high population density (32 plants m^{-2}) produced more than other genotypes, including the medium-maturing control. But under rainfed conditions at Badnapur (Maharashtra) and Bangalore (Karnataka), the ratooned medium-duration genotypes gave higher ratoon yields than ICPL 87. In northern India where the pigeonpea-wheat rotation is becoming popular, ratoon cropping of pigeonpea is not encouraging. The yield from the second flush ranges from 0.50 - 0.70 t ha^{-1} and can not compensate for the loss of a wheat crop in sequential cropping.

Studies on management of ratoon crops have shown that harvesting by picking pods is superior to cutting the pod-bearing branches, because the former system favours better regeneration. At ICRISAT Center, harvesting by picking pods gave 20 to 25% more yield than cutting the pod-bearing branches at 2/3 crop height (Chauhan *et al.*, 1987a; Rao and Sachan, 1988). Irrigation generally enhances the productivity of the ratoon crop. On Alfisols at ICRISAT Center, two irrigations to the first ratoon crop resulted in 0.32 - 0.44 t ha^{-1} more yield than that produced by non-irrigated crops.

The possibilities of managing rainy-season pigeonpea for fodder and seed have also been explored. At ICRISAT Center, ratooning pigeonpea C 11 at the 60-day stage for fodder did not reduce seed yield, but when ratooning was done at the 80-day stage, the yield declined by 10%. In another genotype, BDN 1 ratooning even at the 60-day stage decreased yield by 13%. Apparently, the system of producing both fodder and seed does not seem to be viable, because during the rainy season good quality fodders are available in plenty. Further, drought stress after ratooning may impair pod production and seriously impair seed yield.

The disadvantage of the ratoon system, however, is that the ratoon crop usually produces a

Table 12.4. Grain yield (t ha^{-1}) of short - (ICPL 87) and medium - (ICP 1-6) duration pigeonpea genotypes grown on Alfisols, ICRISAT Center, 1986.

	Harvested by cutting branches				Harvested by picking pods		
Treatments	Main crop	First ratoon	Second ratoon	Total	First ratoon	Second ratoon	Total
ICP 1-6 (Rainfed)				1.33			1.33
ICPL 87 (Rainfed)	1.46	0.46	0.27	2.18	0.51	0.57	2.54
ICPL 87 (Two irrigations, 1 before first ratoon, 1 between first and second ratoon)	1.43	0.47	0.16	2.06	0.52	0.45	2.40
ICPL 87 (Two irrigations, both between first and second ratoon)	1.46	0.79	0.25	2.50	0.63	0.75	2.84
ICPL 87 (Two irrigations, 1 between first and second ratoon, 1 after second ratoon)	1.46	0.63	0.26	2.34	0.52	0.58	2.56
SE	±0.12	±0.08	±0.03	±0.16	±0.07	±0.08	±0.22
CV %	19	32	27	16	33	32	22

Source: Rao and Sachan, 1988.

lower yield, i.e., only 50 - 65% of the sown-crop yield. Thus on yield consideration alone, the ratoon system is unlikely to compete where sequential cropping is a viable alternative. In rainfed areas where moisture conditions are limiting to doublecropping, the ratoon system may prove beneficial provided adequate care is taken to control the insect pests which often cause serious problems. Since a ratoon crop also serves as a potential source for the inoculum of sterility mosaic disease it is imperative that the genotypes chosen should be resistant to this disease.

CROPPING SYSTEMS IN SOUTHEAST ASIA AND THE PACIFIC

Pigeonpea is only a minor crop in Southeast Asia and the Pacific. In some parts of Thailand, pigeonpea has been traditionally grown as a green manure crop at high plant populations prior to a crop of sugarcane. In this system, pigeonpea is sown in May and ploughed back into the soil by September. In northeast Thailand, early-maturing pigeonpea cultivars have shown good yield potential (Sukarin *et al*, 1987), but in the absence of suitable markets and acceptability by farmers, pigeonpea has yet to find a place in established cropping systems. Late-maturing, tall cultivars are also used to rear lac insects.

In the Philippines, long-duration, tall cultivars are grown in home backyards for vegetables, and sometimes as mixed crops with rice. In rice-pigeonpea mixed cropping, the full population of rice is maintained, and the pigeonpea population is sub-optimal. In Indonesia, pigeonpea is grown in Java, Sumatra, and Sulawasi, usually on rice bunds. However, in some areas it is grown intercropped with maize or other legumes (Karsono and Sumarno, 1987). It is seldom grown as a sole crop.

In Fiji, pigeonpea is an important pulse crop usually grown on fallow or sloping lands. Late-maturing genotypes are either mixed or intercropped with other upland crops, or grown as guard rows around sugarcane fields. Short- and medium-duration varieties, introduced recently, have shown good potential for intercropping in sugarcane (Sivan *et al.*, 1987). Studies on ratoon-cropping short-duration genotyes showed that the yields are generally low because of the prevailing drought.

CROPPING SYSTEMS IN AFRICA

Pigeonpea is widely distributed in Africa. It is cultivated in 37 countries at altitudes ranging from sea level to 2050 m. Kenya, Malawi, Uganda, Tanzania, Zaire, Nigeria, Zambia, and Ghana are the major pigeonpea-producing countries (van der Maesen, 1983). Published reports on cropping systems involving pigeonpea are, however, scanty.

In Africa, pigeonpea is commonly intercropped with maize, sorghum, cowpea, and cassava in the first year, but thereafter it is allowed to perennate as a sole crop in subsequent years (Acland, 1971). This ensures that the crop is handled as a sole crop only when it is fully established and can produce a rapid cover at the beginning of the rains. In many African countries pigeonpea is alley-cropped.

In eastern Africa, pigeonpea is grown both as a sole crop and as an inter- or mixed crop. In Kenya, it is an important food legume cultivated commercially for dry seeds as well as green vegetables. In Zambia, pigeonpea is generally grown by small farmers in their home backyards and around the fields of annual crops. However, near urban areas, it is also grown commercially as a sole crop for vegetables and dry seeds. Studies on the genotypic compatibility of pigeonpea in pigeonpea/maize intercropping (2 maize:1 pigeonpea) revealed that LRG 30, C 11, and ICP 7035 were ideal genotypes (Kannaiyan *et al.*, 1988). The yield of intercropped maize was same as that of sole-crop maize (Table 12.5).

In Uganda, pigeonpea/millet intercropping is a striking feature of the cropping systems. However, information on the scientific management of intercrops is lacking. Recent studies at Kabanyolo showed that replacing sole sorghum with a sorghum/pigeonpea intercrop gave 28% more overall

Table 12.5. Performance of pigeonpea genotypes in sole-, and maize intercropping systems in Zambia.

	Yield (t ha^{-1})						
	Sole		Intercrop		Land equivalent ratio (LER)		
Genotypes	Maize	Pigeonpea	Maize	Pigeonpea	Maize	Pigeonpea	Total
Sole pigeonpea							
ICPL 7035	-	2.41	3.86	1.22	0.96	0.51	1.47
BDN 1	-	2.21	3.23	1.15	0.81	0.52	1.33
LRG 30	-	1.56	4.03	0.93	1.01	0.60	1.61
C 11	-	1.24	3.96	0.71	0.99	0.57	1.56
Sole maize	3.99						

Source: Kannaiyan *et al.*, 1988.

yield than the sole-cropped sorghum (Osiru and Kibira, 1981). In northern Ghana, a 3:1 row ratio proved ideal for maize/pigeonpea intercropping (Sharma and Sowley, 1984).

CROPPING SYSTEMS IN THE CARIBBEAN AND CENTRAL AMERICA

Pigeonpea is an important food legume in the Caribbean islands and some South American countries. The Dominician Republic, Haiti, Jamaica, Panama, Puerto Rico, and Venezuela are the major pigeonpea producers in the region. Pigeonpea is used mainly as a vegetable, eaten either fresh or canned. February to April is the main harvest season for the vegetable crop.

Ariyanayagam (1981) reported that three pigeonpea production systems exist in the Caribbean regions; the full-season crop production followed by small farmers, mechanized large-scale production, and dry grain production. In the first system, tall, indeterminate, long-duration genotypes are grown at low plant populations whereas in the later systems, early-maturing grain types are grown at high plant populations. The usual intercrop with tall, indeterminate pigeonpea is maize (Ariyanayagam, 1975).

CROPPING SYSTEMS IN AUSTRALIA

Pigeonpea was introduced into Australia about a century ago as a fodder crop, but in recent years, the development of short-duration, high-yielding cultivars has brightened its potential as a grain crop for export. All pigeonpea in Australia is grown as sole crops, mainly in a dryland cropping system in rotation with such crops as wheat, barley, sorghum, sunflower, and mung bean (R.J. Troedson, University of Queensland, personal communication). The crop is still in its evaluation phase in eastern Australia, while the first large-scale commercial sowings in New South Wales were made in 1985/86 under dryland conditions (Holland, 1987).

The first cultivar, Royes, a long-duration, photoperiod-sensitive, determinate type was released in 1979, but it had limited scope in Australian farming systems especially in frost-prone areas. Subsequently two more cultivars, Hunt and Quantum, that are early-flowering (68-70 days), and photoperiod-insensitive were released. These showed better adaptability and productivity. Quantum has 34% higher yield potential than Hunt (Meekin *et al.*, 1988).

Field trials at the University of Queensland have shown encouraging results from ratooning early cultivars. When sown in the spring season, the early genotypes mature in 110 to 120 days and if harvested high, leaving the leaf canopy intact, the second crop will be ready in 8 to 10 weeks. Unless temperature and water are limiting, the second-crop seed yield can be comparable with the first harvest (Meekin *et al.*, 1987). Under good management conditions, a spring-sown crop may provide three harvests. Wallis *et al.* (1981) reported that at Redland Bay Farm (27°S), Queensland, the September sown crop yielded 5.5 t seed ha^{-1} in three harvests when sown at 40 plants m^{-2}. The first harvest yielded 2.5 t ha^{-1}, the second 2.7 t ha^{-1}, and the third 0.2 t ha^{-1}. The January-sown crop gave a lower yield (4.59 t ha^{-1}) than the September-sown because of a poor harvest from the ratoon crop.

In sub-tropical and tropical regions of Australia pigeonpea has potential as a dual purpose crop for seed production and grazing. In situations where environmental stress reduce the probability of economic seed yield, the crop may provide valuable grazing from both sown and ratoon crops (Wallis *et al.*, 1981).

FUTURE

In the traditional cropping systems of the semi-arid tropics, pigeonpea will continue to be an important crop especially in sole-cropping situations. The indeterminate, tall, and long- duration genotypes are well-adapted to limitations of moisture and nutrients, and thus impart greater stability into production systems when intercropped with short-season cereals, oilseeds, or other upland crops. This conventional intercropping is, however, oriented towards subsistence and multiple crop production rather than to high productivity.

The refinement of management practices and selection of component crops and genotypes matched to rainfall patterns, soil conditions, and length of growing season could considerably improve productivity in intercropping systems. More stability in production is expected from the new genotypes that have resistance to sterility mosaic, wilt, and the pod-borer complex. This may also encourage alley cropping and multiple harvesting.

A better understanding of the complementarity of associated crops, moisture use, nutrient needs, soil health, and pest management in intercropping systems is needed to achieve higher productivity and stability. Pigeonpea/sorghum, pigeonpea/maize, and pigeonpea/groundnut are by far the most popular intercrops in South Asia and Africa. Special attention should be paid to analyse production constraints in these intercrops, and overcome them.

In the Caribbean, South America, and some of the African countries, pigeonpea is largely grown in home backyards and on field boundaries for green vegetables. It is imperative to develop an appropriate cropping system for vegetable pigeonpea that can use some of the recently evolved ICRISAT varieties such as ICPL 87 (Pragati) so that they can be grown on a commercial scale.

The recent advent of short-duration (140-160 days), high-yielding, determinate genotypes is a landmark in pigeonpea improvement. A breakthrough in pigeonpea production is expected from commercial cultivation of these genotypes under good management conditions. Early pigeonpea has already spread to non-traditional areas and in new cropping systems. Pigeonpea following wheat in northern India is a good example of a significant shift in cropping systems that is a result of the short-duration genotypes. Pigeonpea-wheat sequential cropping could also be followed in Pakistan, Nepal, and Australia, where similar agroecological situations exist. Efforts to identify extra-early and high-yielding genotypes with a high harvest index should be continued. The productivity, stability, and sustainability of such cropping systems as a replacement for cereal-cereal sequential cropping should be studied.

Postrainy season sowing has offered good potential for pigeonpea production in areas where heavy monsoon showers and floods often lead to failure of the rainy-season crop. In northeast, central, and southern India, postrainy-season pigeonpea in sequence with early rice, maize, or millets has proved quite promising. In Southeast Asian countries postrainy-season pigeonpea may offer a good option to farmers, but appropriate agronomic management practices need to be developed. The new cropping system may also invite new diseases and pests that will need to be carefully watched.

The development of extra-short duration, photoperiod-insensitive, high-yielding genotypes that tolerate excess moisture may help in bringing considerable areas of rice fallows into pigeonpea production, and may also allow relay cropping. In-depth studies on management aspects of these systems should be conducted.

Information on ratoon cropping is meagre. Detailed studies are needed to explore the feasibility and economic viability of this system in different agroecological regions. Long-season perennial pigeonpea could be introduced into the dryland agroforestry system if appropriate genotypes and management practices are developed.

REFERENCES

Acland, J.D. (1971) *East African Crops: An Introduction to the Production of Field and Plantation Crops in Kenya, Tanzania and Uganda*. Longmans, London, pp. 140-141 (reprinted).

Ahlawat, I.P.S., Ali, M., Pal, M. and Singh, A. (1986) Research needs and directions on pigeonpea based cropping systems. In: *Proceedings of the National Symposium on Cropping Systems, 3-5 April 1985, Central Soil Salinity Research Institute, Karnal, Haryana*. ICAR and Indian Society of Agronomy, New Delhi, India, pp. 183-209.

Ahlawat, I.P.S. and Venkateswarlu, U. (1987) Weed management in pigeonpea-based intercropping systems. *International Pigeonpea Newsletter* 6, 37-39.

Ahuja, K.N. (1984) II. Economics of pigeonpea-wheat rotation. *Indian Journal of Agronomy* 29, 335-340.

Aiyer, A.K.Y.N. (1949) Mixed cropping in India. *Indian Journal of Agricultural Sciences* 19, 439-543.

Ali, M. (1985a) Pigeonpea. In: Balasubramanian, V. and Venkateswarlu, J. (eds), *Efficient Management of Dryland Crops*. Central Research Institute for Dryland Agriculture, Hyderabad, India, pp. 143-168.

Ali, M. (1985b) For higher returns grow arhar in intercropping system. *Indian Farming* 35(1), 7-9.

Ali, M. (1988) Weed suppressing ability and productivity of short duration legumes intercropped with pigeonpea under rainfed conditions. *Tropical Pest Management* 34, 384-387.

Ali, M. and Raut, M.S. (1985) Dry matter accumulation pattern and productivity of sorghum and pigeonpea under different systems of intercropping. *Indian Journal of Agronomy* 30, 271-273.

Appadurai, R. and Selva Raj, K.V. (1974) A note on groundnut-redgram mixture in lower Bhawani Project area. *Madras Agricultural Journal* 61, 803-804.

Ariyanayagam, R.P. (1975) Status of research on pigeonpeas in Trinidad. In: *International Workshop on Grain Legumes, 13-16 January 1975, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 131-139.

Ariyanayagam, R.P. (1981) Pigeonpea breeding in the Caribbean Regional Programme. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 415-426.

Bhatnagar, V.S. and Davies, J.C. (1981) Entomological studies in intercropped pigeonpea systems at ICRISAT Center: Future developments and collaborative research needs. In: *Proceedings of the International Workshop on Pigeonpeas, volume 2, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 341-347.

Chandra, S. and Ali, M. (1986) *Recent Achievements in Pulses Production. Technical Bulletin no. 1.* Directorate of Pulses Research, Kanpur, India, pp. 17-18.

Chatterjee, B.N. and Bhattacharya, K.K. (1987) Food legumes under intensive cropping systems in India. In: Wallis, E.S. and Byth, D.E. (eds), *Food Legume Improvement for Asian Farming Systems: Proceedings of an International Workshop held in Khon Kaen, Thailand, 1-5 September 1986. ACIAR Proceedings no. 18.* ACIAR, Canberra, pp. 232-233.

Chauhan, Y.S., Venkataratnam, N. and Johansen, C. (1987a) The agronomy of multiple harvest pigeonpea. In: Wallis, E.S. and Byth, D.E. (eds), *Food Legume Improvement for Asian Farming Systems: Proceedings of an International Workshop held in Khon Kaen, Thailand, 1-5 September 1986. ACIAR Proceedings no. 18.* ACIAR, Canberra, p. 234.

Chauhan, Y.S. Venkataratnam, N. and Sheldrake, A.R. (1987b) Factors affecting growth and yield of short duration pigeonpea and its potential for multiple harvests. *Journal of Agricultural Science, Cambridge* 109, 519-529.

Choudhary, B.L. and Bhargava, P.N. (1986) Statistical assessment of effect of sowing and fertilizer application on the yields of sorghum and pigeonpea intercrops. *Indian Journal of Agricultural Sciences* 56, 629-634.

Chowdhury, S.L. (1981) Recent studies in intercropping systems on the drylands of India–some thoughts, some results. In: *Proceedings of the International Workshop on Intercropping, 10-13 January 1979, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 299-305.

Dalal, R.C. (1974) Effect of intercropping maize with pigeonpeas on grain yield and nutrient uptake. *Experimental Agriculture* 10, 219-224.

De, R. and Singh, S.P. (1981) Management practices for intercropping systems. In: *Proceedings of the International Workshop on Intercropping, 10-13 January 1979, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 17-21.

de Wit, C.T. and Goudriaan, J. (1974) *Simulation of Ecological Processes*. Centre for Agricultural Publishing and Documentation, Wageningen, the Netherlands, p. 39.

DPR (1988) *Technology for Increasing Pulses Production in India*. Diectorate of Pulses Research, Kanpur, India, 12 pp.

Faroda, A.S. and Singh, R.C. (1983) Effect of preceding crops on the nitrogen need of succeeding wheat crop. *Indian Journal of Agricultural Sciences* 53, 123-128.

Giri, A.N. and Gayke, T.S. (1983) Fertilizer management and intercropping studies with pearl millet and pigeonpea. *Pulse Crops Newsletter* 3, 27-28.

Giri, A.N., Yadav, M.V., Bainade, S.S. and Jondhale, S.G. (1981) Intercropping studies with pigeonpea. In: *Proceedings of the International Workshop on Pigeonpeas, volume 2, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 257-261.

Giri, G. and De, R. (1978) Intercropping of pigeonpea with other grain legumes under semi-arid rainfed conditions. *Indian Journal of Agricultural Sciences* 48, 659-665.

Green, J.M., Sharma, D., Reddy, L.J., Saxena, K.B., Gupta, S.C., Jain, K.C., Reddy, B.V.S. and Rao, M.R. (1981) Methodologies and progress in the ICRISAT breeding programme. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 437-449.

Gupta, M.L. and Sharma, O.L. (1984) Studies on sorghum/pigeonpea intercropping under rainfed conditions. *Indian Journal of Agronomy* 29, 213-217.

Hegde, D.M. and Saraf, C.S. (1982) Effect of intercropping and phosphorus fertilization on nitrogen, phosphorus and potassium concentration and uptake and productivity of pigeonpea. *Journal of Agronomy and Crop Sciences* 151, 302-314.

Hiremath, S.M. (1980) Effect of row proportion and nitrogen application on the growth and yield of sorghum and pigeonpea in intercropping system. *Mysore Journal of Agricultural Sciences* 14, 637-638 (abstract).

Holland, J. (1987) Summer legumes. In: *Proceedings of the Grain Legume Research and Production Seminar, 11-12 March 1987, Wingewarra Street, Dubbo, Australia*. pp. 44-45.

ICRISAT (1980) *Annual Report 1978-79*. Patancheru, A.P., India: ICRISAT, pp. 199-202.

ICRISAT (1988) *Annual Report 1987*. Patancheru, A.P., India: ICRISAT, p. 215.

Kannaiyan, J., Haciwa, H.C., Greenberg, D.C., Mbewe, M.N., Irwing, N.S. and Sohati, P.H. (1988) Pigeonpea research in Zambia. *International Pigeonpea Newsletter* 7, 12-13.

Karsono, S. and Sumarno (1987) Population density in pigeonpea in Indonesia. In: Wallis, E.S. and Byth, D.E. (eds), *Food Legume Improvement for Asian Farming Systems: Proceedings of an International Workshop held in Khon Kaen, Thailand, 1-5 September 1986. ACIAR Proceedings no. 18.* ACIAR, Canberra, p. 238.

Kaul, J.N., Sekhon, H.S., Dhingra, K.K. and Tripathi, H.P. (1980) Date of planting and row-spacing studies with early maturing pigeonpea (arhar) varieties under irrigated conditions for double cropping. *Tropical Grain Legume Bulletin* 19, 20-23.

Kharwara, P.C. and Singh, L.N. (1986) Studies on intercropping with pigeonpea. *International Pigeonpea Newsletter* 5, 27-29.

Khatua, K.B., Samal, K.M. and Ghosh, P.C. (1977) Cropping pattern for rainfed highland. *Journal of Research of Orissa University of Agriculture and Technology* 7, 18-24.

Kumar, A. (1985) Effect of planting geometry and nitrogen fertilization in pigeonpea based intercropping system. MSc thesis, Indian Agricultural Research Institute, New Delhi, India.

Kumar, A. and Ahlawat, I.P.S. (1986) Effect of planting geometry and nitrogen fertilization in pigeonpea based intercropping systems. *Indian Journal of Agronomy* 31, 112-114.

Kushwaha, B.L. (1987) Performance of pigeonpea genotypes grown in association with short duration sorghum and urdbean. In: *Symposium on Alternate Farming Systems, 21-23 February 1987, IARI, New Delhi.* pp. 36-37.

Kyaw Moe (1989) Varietal improvement of chickpea, pigeonpea and other upland crops of cropping systems programme in Burma. Paper presented at the International Workshop on Varietal Improvement of Chickpea, Pigeonpea and Other Upland Crops in Rice-based and Other Cropping Systems, 12-22 March 1989, Kathmandu, Nepal.

Lal, S. and Ali, M. (1988) Yield potential of different pulses in northern India. In: *Proceedings of the FAI(NR)-PPCL Seminar on Importance of Phosphatic Fertilizers with Special Reference to Oilseeds and Pulses in Northern India, 21-22 June 1988, Lucknow, India.* pp. 41-53.

Lenka, D. and Satpathy, R.K. (1976) Response of pigeonpea varieties to levels of nitrogen and phosphate in laterite soil. *Indian Journal of Agronomy* 21, 217-220.

McGilchrist, C.A. and Trenbath, B.R. (1971) A revised analysis of plant competition experiments. *Biometrics* 27, 659-671.

Meekin, J.S., Troedson, R.J., Byth, D.E. and Wallis, E.S. (1988) Release of Quantum in Queensland, Australia. *International Pigeonpea Newsletter* 7, 6-8.

Meekin, J.S., Troedson, R.J., Wallis, E.S. and Byth, D.E. (1987) Pigeonpea: a new summer legume crop. *Queensland Agricultural Journal* 113, 117-122.

Misra, R.C., Tripathy, D. and Misra, R.K. (1980) *Arhar* in paddy cropping systems in Orissa. *Indian Journal of Genetics and Plant Breeding* 40A, 162-165.

Moinbasha, S. and Singh, R.A. (1988) Land-equivalent ratios of pigeonpea-based intercropping systems at different plant populations. *International Pigeonpea Newsletter* 7, 18-20.

Moody, K. and Shetty, S.V.R. (1981) Weed management in intercropping systems. In: *Proceedings of the International Workshop on Intercropping, 10-13 January 1979, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 229-237.

Narain, P., Verma, B. and Singhal, A.K. (1980) Nitrogen economics through intercropping of pigeonpea in rainfed sorghum. *Indian Journal of Agronomy* 25, 190-196.

Narayanan, A., Murthy, S.R.K. and Khader, M.A. (1981) Performance of pigeonpea in the post-rainy season. In: *Proceedings of the International Workshop on Pigeonpeas, volume 2, 15-19 December 1980, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 209-215.

Narayanan, A. and Sheldrake, A.R. (1979) Pigeonpea *(Cajanus cajan)* as a winter crop in peninsular India. *Experimental Agriculture* 15, 91-95.

Natarajan, M., Kannaiyan, J., Willey, R.W. and Nene, Y.L. (1985) Studies on the effects of cropping system on fusarium wilt of pigeonpea. *Field Crops Research* 10, 333-346.

Natarajan, M. and Willey, R.W. (1980a) Sorghum-pigeonpea intercropping and the effects of plant population density. 1. Growth and yield. *Journal of Agricultural Science, Cambridge* 95, 51-58.

Natarajan, M. and Willey, R.W. (1980b) Sorghum-pigeonpea intercropping and the effects of plant population density. 2. Resource use. *Journal of Agricultural Science, Cambridge* 95, 59-65.

Natarajan, M. and Willey, R.W. (1985) Effect of row arrangement on light interception and yield in sorghum-pigeonpea intercropping. *Journal of Agricultural Science, Cambridge* 104, 263-270.

Osiru, D.S.O. and Kibira, G.R. (1981) Sorghum/pigeonpea and finger millet/groundnut mixtures with special reference to plant population and crop arrangement. In: *Proceedings of the International Workshop on Intercropping, 10-13 January 1979, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 78-85.

Panwar, K.S. and Yadav, H.L. (1981) Response of short-duration pigeonpea to early planting and phosphorus levels in different cropping systems. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 37-44.

Patel, J.S., Khistaria, M.K., Paida, V.J., Parmar, M.T. and Patel, J.C. (1985) Intercropping of pearl millet and pigeonpea in rainfed conditions. *Indian Journal of Agronomy* 30, 283-286.

Patel, Z.G. and Bhardwaj, R.B.L. (1985) Intercropping in pigeonpea. *Gujarat Agricultural University Research Journal* 11, 10-13.

Patra, A.P. and Chatterjee, B.N. (1986) Intercropping of soybean with rice, maize and pigeonpea in the plains of West Bengal. *Indian Journal of Agricultural Sciences* 56, 413-417.

Prasad, K., Gautam, R.C. and Mehta, N.K. (1985) Effect of planting patterns and weed control methods on growth characters, yield and yield attributes of *arhar* intercropped with soybean. *Indian Journal of Agronomy* 30, 429-433.

Rafey, A. and Verma, U.K. (1988) Production potential of legumes, oilseeds and cereal in intercropping system with pigeonpea (*Cajanus cajan*). *Indian Journal of Agricultural Sciences* 58, 433-436.

Raheja, P.C. (1973) *Mixed Cropping. ICAR Technical Bulletin (Agric.) no.42*. Indian Council of Agricultural Research, New Delhi, India, 40 pp.

Rajaram, S. (1984) Effect of base crops on the growth and development of redgram SA 1 as an intercrop in rainfed black soils of Aruppukottai region. *Madras Agricultural Journal* 71, 480-481.

Ramadoss, G. and Thirumurugan, V. (1983) Influence of planting systems and different intercrops on yield and economics of long duration redgram (*Cajanus cajan* (L.) Millsp.). *Madras Agricultural Journal* 70, 578-580.

Ramanujam, S. (1981) Varietal adaptation to production systems. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 82-93.

Rao, M.R. and Sachan, R.C. (1988) Potential of short-duration pigeonpea for a multiple-harvest system. *International Pigeonpea Newsletter* 7, 14-17.

Rao, M.R. and Willey, R.W. (1980) Evaluation of yield stability in intercropping: studies on sorghum/pigeonpea. *Experimental Agriculture* 16, 105-116.

Rao, M.R. and Willey, R.W. (1981) Stability of performance of a pigeonpea/sorghum intercrop system. In: *Proceedings of the International Workshop on Intercropping, 10-13 January 1979, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 306-317.

Rao, M.R. and Willey, R.W. (1983) Effects of genotype in cereal/pigeonpea intercropping on the Alfisols of the semi-arid tropics of India. *Experimental Agriculture* 19, 67-68.

Rao, M.R., Willey, R.W., Sharma, D. and Green, J.M. (1981) Pigeonpea genotype evaluation for intercropping. In: *Proceedings of the International Workshop on Pigeonpeas, volume 2, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 263-270.

Rathore, A.S., Umat, R. and Deshpande, S.L. (1987) Response of sorghum genotypes on intercropping with pigeonpea. *International Pigeonpea Newsletter* 6, 41-42.

Reddi, K.C.S., Hussain, M.M. and Krantz, B.A. (1980) Effects of nitrogen level and spacing on sorghum intercropped with pigeonpea and green gram in semi-arid lands. *Indian Journal of Agricultural Sciences* 50, 17-22.

Reddy, M.S. and Willey, R.W. (1982) Improved cropping systems for the deep vertisols of the Indian semi-arid tropics. *Experimental Agriculture* 18, 277-287.

Roy Sharma, R.P., Sharma, H.M. and Thakur, H.C. (1981a) Studies on intercropping in long duration pigeonpea on sandy loam soil of north Bihar. *Indian Journal of Agronomy* 26, 77-82.

Roy Sharma, R.P., Thakur, H.C. and Sharma, H.M. (1981b) Pigeonpea as a rabi crop in India. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 26-36.

Sandhu, H.S., Brar, S.S., Dhillon, M.S., Gill, G.S. and Singh, G. (1981) Effect of sowing time, row spacing and plant population on the performance of *arhar* and succeeding wheat in *arhar*-wheat rotation. *Indian Journal of Agronomy* 26, 154-157.

Saraf, C.S., Singh, A. and Ahlawat, I.P.S. (1975) Studies on intercropping of compatible crops with pigeonpea. *Indian Journal of Agronomy* 20, 127-130.

Saxena, M.C. and Yadav, D.S. (1976) Parallel cropping of soybean with pigeonpea under humid sub-tropical conditions of Pantnagar. *Indian Journal of Agronomy* 21, 131-134.

Saxena, M.C. and Yadav, D.S. (1979) Parallel cropping with short-duration pigeonpea under the humid subtropical conditions at Pantnagar. *Indian Journal of Agricultural Sciences* 49, 95-99.

Sharma, D. and Sowley, G.K. (1984) Comparison of maize/pigeonpea intercropping patterns in northern Ghana. *International Pigeonpea Newsletter* 3, 24-25.

Sheldrake, A.R. (1979) A hydrodynamical model of pod-set in pigeonpea (*Cajanus cajan*). *Indian Journal of Plant Physiology* 22, 137-143.

Shelke, V.B. and Krishnamoorthy, C. (1980) Studies on crop geometry in dryland intercrop systems. *Indian Journal of Genetics and Plant Breeding* 40A, 70-75.

Shrivastava, M.P., Tiwari, A.S. and Bansal, K.N. (1988) Pigeonpea-wheat rotation in northern Madhya Pradesh, India. *International Pigeonpea Newsletter* 7, 21-22.

Singh, D.N. and Ali, M. (1985) Physiological aspects of growth, grain yield and resource use in pigeonpea genotypes under intercropping system. Paper presented at the National Seminar on Plant Physiology, 21-23 February, Banaras Hindu University, Varanasi, India.

Singh, K., Singh, M., Shukla, D.N. and Kushawaha, B.N.R. (1978) Effect of intercrops and row spacings on growth and yield of pigeonpea. *Indian Journal of Agricultural Research* 12, 27-31.

Singh, R.C., Faroda, A.S. and Singh, H. (1986) Response of pigeonpea to phosphate fertilization under different cropping systems. *Indian Journal of Agronomy* 31, 244-247.

Singh, R.P. and Subba Reddy, G. (1988) Identifying crops and cropping systems with greater production stability in water-deficit environments. In: Bidinger, F.R. and Johansen, C. (eds), *Drought Research Priorities for the Dryland Tropics*. Patancheru, A.P., India: ICRISAT, pp. 77-85.

Singh, S.P. (1981) Intercropping studies in sorghum. In: *Proceedings of the International Workshop on Intercropping, 10-13 January 1979, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 22-24.

Sivan, P., Chand, V. and Singh, B.D. (1987) Pigeonpea genotype evaluation in Fiji. In: Wallis, E.S. and Byth, D.E. (eds), *Food Legume Improvement for Asian Farming Systems: Proceedings of an International Workshop held in Khon Kaen, Thailand, 1-5 September 1986. ACIAR Proceedings no. 18.* ACIAR, Canberra, p. 243.

Soundarajan, D. (1978) Studies on intercropping in red gram under rainfed conditions. MSc thesis, Tamil Nadu Agricultural University, Coimbatore, India.

Srinivasan, A. and Ahlawat, I.P.S. (1984) Studies on planting pattern and phosphate fertilization of sole and mixed stands of pigeonpea. *Indian Journal of Agronomy* 29, 249-253.

Subramanian, A., Ramadoss, G. and Vairavan, K. (1984) Performance of mungbean under different systems of arhar. *Pulse Crops Newsletter* 4, 47-49.

Sukarin, W., Troedson, R.J., Wallis, E.S. and Byth, D.E. (1987) Effect of time of sowing on phenology of pigeonpea in Thailand. In: Wallis, E.S. and Byth, D.E. (eds), *Food Legume Improvement for Asian Farming Systems: Proceedings of an International Workshop held in Khon Kaen, Thailand, 1-5 September 1986. ACIAR Proceedings no. 18.* ACIAR, Canberra, p. 224.

Tarhalkar, P.P. and Rao, N.G.P. (1981) Genotype-plant density considerations in the development of an efficient intercropping system for sorghum. In: *Proceedings of the International Workshop on Intercropping, 10-13 January 1979, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 35-40.

Thirumurugan, V. and Ramadoss, G. (1984) Effects of planting systems and intercrops on yield and economics of red gram. *Pulse Crops Newsletter* 4, 49-50.

Tomar, S.S., Sharma, R.K. and Namdeo, K.N. (1984) Relative efficiency of multi-intercrop system in pigeonpea under rainfed condition. *Indian Journal of Agronomy* 29, 475-479.

Tripathi, H.P. (1987) Effect of sowing method on pigeonpea intercropped with black gram in Vindhyan lowland soils. *International Pigeonpea Newsletter* 6, 36-37.

Umrani, N.K., Patil, C.B. and Chavan, K.B. (1987) Effects of row proportions on sunflower-pigeonpea intercropping. *Indian Journal of Agricultural Sciences* 57, 468-471.

Umrani, N.K., Shinde, S.H. and Dhonde, P.M. (1984) Studies on intercropping of pulses in *kharif* sorghum. *Indian Journal of Agronomy* 29, 27-30.

van der Maesen, L.J.G. (1983) *World Distribution of Pigeonpea. Information Bulletin no. 14*. Patancheru, A.P., India: ICRISAT, 40 pp.

Venkateswarlu, J., Sanghi, N.K., Rao, U.M.B. and Rao, C.H. (1981) Maximizing production in sorghum/pigeonpea intercropping system in the semi-arid tropics. In: *Proceedings of the Workshop* *on Intercropping, 10-13 January 1979, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 30-34.

Venkateswarlu, S. (1986) Intercropping pigeonpea with short duration pulses in semi-arid Alfisols. *Indian Journal of Dryland Agricultural Research and Development* 1(1), 48-55.

Venkateswarlu, U. (1984) Studies on weed control in pure and mixed stands of pigeonpea (*Cajanus cajan* (L.) Millsp.). MSc thesis, Indian Agricultural Research Institute, New Delhi, India.

Venkateswarlu, U. and Ahlawat, I.P.S. (1986) Studies on weed management in pigeonpea based intercropping systems. *Indian Journal of Agronomy* 31, 184-187.

Wallis, E.S., Byth, D.E. and Whiteman, P.C. (1981) Mechanized dry seed production of pigeonpea. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 51-60.

Willey, R.W. (1981) A scientific approach to intercropping research. In: *Proceedings of the International Workshop on Intercropping, 10-13 January 1979, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 4-14.

Willey, R.W. and Rao, M.R. (1980) A competitive ratio for quantifying competition between intercrops. *Experimental Agriculture* 16, 117-125.

Willey, R.W. and Rao, M.R. (1981) Genotype studies at ICRISAT. In: *Proceedings of the International Workshop on Intercropping, 10-13 January 1979, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 117-127.

Willey, R.W., Rao, M.R. and Natarajan, M. (1981) Traditional cropping systems with pigeonpea and their improvement. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 11-25.

Yadahalli, Y.H. (1973) Intercropping of redgram with maize and ragi is profitable. *Current Research* 2, 37.

Yadav, H.L. (1984) Phosphorus response of pigeonpea intercropped with urdbean. *International Pigeonpea Newsletter* 3, 31-32.

Yadavendra, J.P., Patel, A.R. and Shah, R.M. (1987) Relay intercropping of pigeonpea in groundnut. In: Wallis, E.S. and Byth, D.E. (eds), *Food Legume Improvement for Asian Farming Systems: Proceedings of an International Workshop held in Khon Kaen, Thailand, 1-5 September 1986. ACIAR Proceedings no. 18.* ACIAR, Canberra, p. 246.

Chapter 13

PIGEONPEA: DISEASE MANAGEMENT

M.V. REDDY, S.B. SHARMA, and Y.L. NENE

Senior Plant Pathologist, and Nematologist, Legumes Program, and Deputy Director General, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Andhra Pradesh 502 324, India.

INTRODUCTION

Pigeonpea can be attacked by more than 100 pathogens (Nene *et al.*, 1989c). These include fungi, bacteria, viruses, nematodes, and mycoplasma-like organisms. Fortunately, only a few of them cause economic losses (Kannaiyan *et al.*, 1984), and the distribution of the most important diseases is geographically restricted. At present farmers mainly grow pigeonpea landraces and it is possible that they have some degree of tolerance to most of the pathogens (Nene, 1988). This situation could change once the diverse landraces are replaced by a few improved cultivars. The diseases of considerable economic importance at present are sterility mosaic (SM), fusarium wilt, phytophthora blight (PB), macrophomina root rot and stem canker, and alternaria blight on the Indian subcontinent; wilt and cercospora leaf spot in eastern Africa; and witches' broom (WB) in the Caribbean and Central America. Sterility mosaic, the most important disease on the Indian subcontinent, is not found in eastern Africa. Similarly WB is absent from two major pigeonpea-growing regions; the Indian subcontinent, and eastern Africa. More work has been done on SM, wilt, and PB than on other diseases.

MAJOR DISEASES

Fusarium Wilt (*Fusarium udum* Butler)

This is the most important soilborne disease of pigeonpea and was first described in 1906 from Bihar State, India (Butler, 1906). The disease appears in young, June-sown seedlings in August but the highest mortality occurs at flowering and podding time from November onwards. Although the disease first appears in patches in a field it can extend to the entire field if pigeonpea is repeatedly cultivated in the same field. The fungus can be isolated from apparently healthy 15-day old plants from a wilt-sick plot (Nene *et al.*, 1980). Even though plants are infected at an early stage, they seem able to "keep fighting" with the fungus until flowering and podding. The yield loss depends on the stage at which the plants wilt; it can approach 100% when wilt occurs at the pre-pod stage, about 67% when wilt occurs at maturity, and 30% when it occurs at the pre-harvest stages (Kannaiyan and Nene, 1981). The loss in plant stand due to early wilt is compensated to some extent by neighbouring plants' ability to produce more biomass. Wilt incidence generally increases when the crop is ratooned or retained as a perennial.

Disease Distribution and Importance

To date fusarium wilt has been reported from 15 countries; Bangladesh, Ghana, Grenada, India, Indonesia, Kenya, Malawi, Mauritius, Nepal, Nevis, Tanzania, Thailand, Trinidad, Uganda, and Venezuela (Nene *et al.*, 1989c), but it is relatively more important in India and eastern Africa. Surveys in those regions have indicated wilt to be a major problem in the Indian states of Bihar and Maharashtra, and in Kenya, Malawi, and Tanzania. The annual pigeonpea crop loss due to wilt in India alone has been estimated at US $ 36 million, while in eastern Africa annual losses were estimated at $ 5 million (Kannaiyan *et al.*, 1984).

Symptoms

Symptoms can appear 4 to 6 weeks after sowing. The initial visible symptoms are loss of turgidity in leaves, and slight interveinal clearing. The foliage shows slight chlorosis and sometimes becomes bright yellow before wilting. Leaves are retained on wilted plants. The initial characteristic internal symptom of wilt is the browning of the xylem vessels from the root system to the stems. The xylem gradually develops black streaks, and brown or dark purple bands appear on the stem surface of partially wilted plants extending upwards from the base. When the bark of such bands is peeled off, browning or blackening of the wood beneath can be seen. In wilt-tolerant genotypes these bands are confined to the basal part of the plant. Sometimes, especially in the later stages of crop growth, the branches dry from the top downwards, but symptoms are not seen on the lower portions of the main stem or branches. Similarly, small branches on the lower part of the plant also dry. When the main stem of such plants is split open, intensive blackening of the xylem can be seen. In humid weather, a pinkish mycelial growth is commonly observed on the basal portions of the wilted plants. Partial wilting is usually associated with lateral root infection. Tap root infection results in complete wilting. Chari *et al.* (1984) using an electric current, could predict infection before the appearance of wilt symptoms with 94% validity.

Interestingly, the pathogen is internally seedborne in tolerant cultivars, but not in susceptible or resistant ones (ICRISAT, 1987).

Causal Fungus

The fungus causing wilt in pigeonpea was described as *Fusarium udum* (Butler, 1910). Later Butler (1926) reached the conclusion that it could not be distinguished from *F. vasinfectum* that attacks cotton and sesamum. Padwick (1940) studied cultural characters of *F. udum* and found it differed from *F. vasinfectum* in that it produced abundant spores in sporodochia, and that these spores were strongly hooked at the apex. He proposed the name *Fusarium udum* Butl. var. *cajani*. Subramanian (1955) was of the opinion that it could not even be distinguished from *F. oxysporum* var. *cubense*. Snyder and Hansen (1940) named the fungus *F. oxysporum* f.sp. *udum*, a nomenclature supported by Chattopadhyay and Sen Gupta (1967). However, the name *F. udum* is commonly accepted as the macroconidia of *F. udum* are distinguished by a prominent hook (Booth, 1971).

The fungus becomes systemic invading tap root, lateral roots, collar, main stem, branches, leaflets, petioles, rachis, pedicel, and pod hull (Nene *et al.*, 1980). Rai and Upadhyay (1979) discovered the perfect state of *F. udum* on wilted and dead pigeonpea plants near Varanasi in Uttar Pradesh, India, and identified it as a new species of *Gibberella*. Because of the large size of the perithecia, and the 2-celled (and rarely 3-celled) ascospores it was named as *G. indica*. Singh (1980) also observed *Gibberella udum* near Allahabad in Uttar Pradesh, India and suspected the role of cloudy weather, high humidity, and combinations of high and low temperatures as responsible for its production. The work on the perfect state of *F. udum* needs confirmation.

F. udum, like other *Fusarium* spp., shows a great deal of variation in cultural characters. Butler's description (Butler, 1910) of *F. udum* was:

"Mycelium parasitic within the roots of the host plant, or saprophytic and then creeping, hyphae hyaline, slender, much branched, usually with little aerial growth; microconidia of the *Cephalosporium* type produced successively on the ends of short simple or clustered conidiophores and remaining bound in a drop of liquid after abjunction, unicellular or with one or more septa, elliptical, hyaline singly, salmon pink in mass, occasionally developing from the surface of minute spherical stromata and then of the *Tubercularia* type, 5.15 × to 2.4 μ in diameter; microconidial stage in culture usually moist and bacteria-like, white to salmon-pink, occasionally (on rice) orange red, never green or purple; macroconidia of the *Fusarium* type, formed as the microconidia but on shorter conidiophores and becoming free as soon as abjuncted, falcate 3- to 5-septate, hyaline, 15-50 × 3-5 μ in diameter, usually late in appearing; chlamydospores, round or oval, rather thick-walled, hyaline, sometimes in short chains, 5 to 10 μ in diameter".

Some other species such as *F. accuminatum*, *F. equiseti*, *F. lateritium*, *F. merismoides*, *F. moniliforme*, *F. oxysporum*, *F. vasinfectum*, *F. semitectum*, and *F. solani* have also been found associated with the disease, but these are of no significance.

Pathogenic Races

Several workers (Baldev and Amin, 1974; Shit and Sen Gupta, 1978; Pawar and Mayee, 1986; Reddy and Chaudhary, 1985; Gupta *et al.*, 1988) have reported the occurrence of pathogenic variability.

Studies carried out at ICRISAT Center, and multilocational testing of resistant genotypes in India also point to the possible presence of physiologic races in *F. udum*. However, further standardization of the inoculation technique, differential varieties, and the rating scale are needed to fully understand the nature of the pathogenic variabililty present in *F. udum*.

Epidemiology

The fungus is soilborne on diseased plant debris and it survives only on the tissues which it colonizes as a parasite (Subramanian, 1955). McRae (1924) reported that the fungus spreads about 3 m through the soil in one season, apparently along roots. The amount of wilt incidence appeared to be influenced by the retentive nature of the soil, but not directly by its water content (McRae, 1926; Mitra, 1925). Mundkur (1935) reported that low soil temperature and increasing plant maturity favoured wilt.

Shukla (1975) in a pot experiment found more wilt inoculum in sand (94%) than in heavy black soil (18%). Singh and Bhargava (1981) found the fungal population to be highest at 30% soil water-holding capacity and at the soil temperatures between 20 and 30°C.

The fungus was found to survive in infected plant stubble for 2.5 in Vertisols and 3 years in Alfisols (Kannaiyan *et al.*, 1981b).

Upadhyay and Rai (1983) reported that perithecia of *G. indica* produced on the collar region of wilted plants, produced conidia of *F. udum*, when cultured, and were pathogenic to pigeonpea; ascospores were also pathogenic.

Control Measures

Cultural Practices

Being a soilborne disease, any farming practice or cultural operation that reduces the soil population of *F. udum* should help to reduce wilt incidence. McRae (1923) reported that application of superphosphate increased wilt incidence and green manuring with *Crotolaria juncea* decreased it. The amount of plant death was somewhat less in plots that received heavy applications of nitrogen as farmyard manure (McRae, 1928). Superphosphate and green manure together increased wilt incidence. Zinc retarded colonization of pigeonpea *Fusarium*, and hastened the disappearance of the fungus from soil (Sarojini, 1950).

In field experiments, Bose (1938) showed control of wilt in the highly susceptible cultivar Pusa type T 5 by rotation with tobacco over several years. Dey (1947) reported reduction in incidence of wilt from 64 to 38% in a susceptible variety when it was intercropped with sorghum. The residual effect of this intercropping was also observed in the second season. Mixed cultivation of pigeonpea and sorghum also reduced wilt (Anonymous, 1949 in Nene *et al.*, 1985). Mathur (1954) observed that in mixed cropping, sorghum grown for grain rather than for fodder reduced wilt incidence in pigeonpea. Gupta (1961) reported considerable wilt control when pigeonpea was mixed-cropped with sorghum, and attributed this to the deeper rooting system of pigeonpea in the mixed-cropping situation.

Natarajan *et al.* (1985) reported that rotation with sorghum, tobacco, or fallow for 1-2 years; or intercropping with sorghum reduced wilt incidence in a sick plot. Upadhyay and Rai (1981) found high reduction in pigeonpea wilt incidence under mixed cropping with *Crotolaria medicaginea*.

Sowing susceptible cultivars in the postrainy season resulted in much lower disease incidence than when the same cultivars were sown earlier in the year (Kannaiyan and Nene, 1985a).

Host Plant Resistance

The well-known technique used to determine host plant resistance, i.e., transplanting seedlings whose roots have been injured and inoculated to autoclaved sand/soil in pots and assessing disease incidence – gave erratic results at ICRISAT Center (Nene *et al.*, 1981a). On the other hand, successful inoculation was achieved in tests in which *F. udum* multipled on sand-pigeonpea flour (9:1) medium, and autoclaved pigeonpea stem bits were mixed with non-autoclaved Alfisol in pots; a susceptible cultivar was sown, and the wilted plant material was re-incorporated for three cycles.

The use of sick plots is well known, and this procedure has been used for a long time to screen various crops against several vascular wilts. At ICRISAT Center it was found that the sickness develops more quickly in Alfisols than in Vertisols, and wilt shows up earlier in Alfisols (Nene *et al.*, 1980). In early tests the fungus was multiplied on materials other than pigeonpea stubble, but it was later realized that the best way to induce sickness is to incorporate into the soil stubble from diseased plants, and grow wilt-susceptible cultivars in intermittent rows all over the field.

The sowing pattern followed for screening is one susceptible control row after every two test rows in plots that are in the process of becoming "sick", and one susceptible control row after every four test rows in plots that have already become "sick" (Nene *et al.*, 1981a).

The search for sources of resistance to wilt in pigeonpea began as early as 1905 at Poona (now Pune) in India (Butler, 1908; 1910). Subsequently screening has been conducted at many locations in India, and lines reported resistant or promising by different workers are listed in Table 13.1. The long list of resistant sources indicates the abundance of available resistance, but unfortunately, few resistant cultivars are popular with farmers. The main reason for this seems to be lack of adequate efforts to breed varieties that are both wilt resistant and high yielding. One of the oldest wilt-resistant, long-duration varieties, NP(WR)15, has very small seeds. The medium-duration cultivars C 11 and BDN 1 that have large seeds and yield well do not have high level of resistance. Fortunately, the recently released variety Maruthi (ICP 8863) is becoming popular in Karnataka where its high yield, good seed size, and high stable wilt resistance (Figure 13.1) are appreciated by farmers. There is a need to develop high-yielding varieties with wilt resistance, and bold, white seed in the short-, medium-, and long-duration groups.

Recent multilocational testing in India (Nene *et al.*, 1989a) and eastern Africa helped to identify several lines resistant to wilt at different locations. Some lines; ICP 4769, 7118, 7182, 8863, 9168, 10958, 11299 also showed broad-based resistance. Several lines that showed resistance in India also showed resistance in eastern Africa. The lines that showed stable resistance in Kenya were ICP 8864, 9145, and 10960. The lines that were resistant in Malawi were ICP 7855, 9145, 9154, 9174, 9177, 10958, 11297, 11299, and 12738.

Shaw (1936) observed a segregation ratio of 9:7 (two complementary genes) in the F_2 generation of a cross between Pusa types T 5 and T 80 with resistance being dominant. In the mutant "Cawnpore" duplicate genes were found to govern resistance (IARI, 1946). Joshi (1957) suggested that wilt resistance was governed by a pair of dominant duplicate genes. Pawar and Mayee (1986) reported resistance in 15-3-3 and C 11 to be dominant over susceptibility. Clearly, there is a need to develop a better understanding of the inheritance of resistance, particularly in view of the fact that genotypes show different levels of resistance under field conditions.

Figure 13.1. Performance of pigeonpea (ICP 8863, Maruthi) (centre) in relation to a wilt-susceptible germplasm assession (ICP 2376) (left) and a wilt-tolerant cultivar (C 11) (right).
Photo: ICRISAT.

Table 13.1. Pigeonpea lines/cultivars reported resistant to fusarium wilt in India.

Location	Resistant lines	Reference
Andhra Pradesh	ST 1 (C 11), ST 2(C 28), ST 3 (C 36)	Vaheeduddin and Nanjundiah, 1956
Hyderabad	Yadgir No. 3, C 11	Anonymous, 1954a
	C 11, C 26	Bhaskaran, 1954
	ICP 1641, 3753, 3782, 4769, 5097, 6831, 7118, 7120, 7182, 7198, 7201, 7273, 7336, 7867, 8858 to 8869, C. Nos. 74342, 74360, and 74363, AWR 74/15, Bandapalera sel., Purple 1 sel., Bori 1 sel.	Nene and Kannaiyan, 1982
	ICPL 25, ICPL 31, ICPL 108	Kannaiyan *et al.*, 1983a
Bihar	ICP 8863	Haque *et al.*, 1984
	Kanke 9, Kanke 3	Bhargava, 1975
Pusa	Type A2(WR), Type A4	McRae, 1932
	Type 80, 16, 41, 50, 51, 82	McRae and Shaw, 1933
	11-80, 18-41, C 38, C 15, A 126-4-1	Mundkur, 1946
Delhi	IP 80, IP 41, Hybrid 5 (D 419-2-4)	Dastur, 1946
	Hybrid C 38-3-1, IP 80, IP 41	IARI, 1946
	IP 80, IP 41	Anonymous, 1948
	New Era 40-6	IARI, 1948
	NP 41, CO 15, W. Exp., Very Early, C 38-3-1, NP 69X, UP 132-F4-18B	Anonymous, 1951
	NP 41, C 38-1-2, D 419-2-4	IARI, 1953
Delhi	NP 41, C 15-WE, C 38-3-1	Anonymous, 1954b
	NP 69 x UP-132-3-2-2-2, NP 41	Anonymous, 1955
	C 15(WE), P3, P8, S 55	Vasudeva *et al.*, 1958
	NP(WR) 15, NP 41, NP 51, NP 80(A2)	Deshpande *et al.*, 1963
	NP(WR) 15, NP(WR) 18	Anonymous, 1965
	NP(WR) 15, NP(WR) 16, NP(WR) 42	Chaube, 1968

Table 13.1. continued.

Location	Resistant lines	Reference
Gujarat	BDN 2	Zaveri *et al.*, 1986
	GAUT 82-9, 82-74, 82-127, 83-23	Patel *et al.*, 1988
Karnataka	Maruthi (ICP 8863)	Konda *et al.*, 1986; Parameswarappa *et al.*, 1986
	ICPL 270	Parameswarappa *et al.*, 1987
Maharashtra	BDN 15-3-3, ICP 7336, ICP 8862, AWR 74/15	Zote *et al.*, 1987
	ICP 7182, 7336, 8863, 8869, BDN 1	Zote *et al.*, 1983
	15-3-3, DT 236-6-3-102, (C 11 x N 252), (C 11 x N 252)-10, Vita 1, Osmanabad 1-5, Udgir 500	Anonymous, 1976
	Osmanabad, NP(WR) 19, NP 69, S 103, Balapur 10, P 1005, Washmi 4, Chandrikapur 1, Paras 5, Jarud	Patil and Sable, 1973
Parbhani	Bori 11, Tuljapur 455, Latur 466-1, Latur 476-11, DT 230, Mu x K 132	Raut and Bhombe, 1971
Tamil Nadu	Co 2	Veeraswamy *et al.*, 1975
	Co 3	Sheriff *et al.*, 1977a
	S 18	Sheriff *et al.*, 1977b
Uttar Pradesh	NP 80	Dey, 1947
	Variety 17W/2	Anonymous, 1949 in Nene *et al.*, 1985
	T 17	Mathur, 1954
	Bori 192-12-5-2, Bori 192-15-2-2-11-42	Singh and Mishra, 1976
Nagpur	Strain No. 3	Plymen, 1933
	EB 38	Ravishanker, 1936
West Bengal	ICP 8863, ICP 10957, ICP 10958, ICP 11290, ICP 11292, ICP 11294	Gupta and Sen Gupta, 1988

Sterility Mosaic

Sterility mosaic (SM) is the most important disease of pigeonpea in India and Nepal. It was first reported from Pusa in Bihar, India (Mitra, 1931). Alam (1933) gave a detailed description of SM including its seasonal incidence and host-plant resistance. Capoor (1952) established the infectious nature of the disease through graft and sap transmission, but this sap transmission could not be confirmed by other workers (Kandaswamy and Ramakrishnan, 1960; Nene, 1972). Seth (1962) showed that the SM pathogen is transmitted by an eriophyid mite, *Aceria cajani* Channabasavanna, and this has since been confirmed by other workers (Nene, 1972; Nene and Reddy, 1976a).

The disease is present in the major pigeonpea-producing states of India. It is a serious problem in northeastern (Bihar and Uttar Pradesh), and southern (Tamil Nadu) states (Kannaiyan *et al.*, 1984). The disease appears to be restricted to Asia and has also been reported from Bangladesh, Nepal, and Thailand (Nene *et al.*, 1989c), Myanmar (Su, 1931), and Sri Lanka (Newton and Peiris, 1953). The pathogen causing the disease may be a virus but its exact identity is yet to be established.

Losses

The disease causes an estimated annual loss of 205,000 tonnes of grains in India alone (Kannaiyan *et al.*, 1984). A susceptible genotype infected in the early stages (first 45 days) of crop growth shows near complete sterility and yield losses up to 100%. As the plants grow older (> 45 days), their susceptibility to the SM pathogen decreases; such plants show partial sterility (Reddy and Nene, 1981). In the case of early infection, yield reduction is related to the percentage of infected plants, but in late infections, yield reduction is not correlated to the percentage of infected plants, since they show only partial sterility. Genotypes such as ICP 2376 that have ring spot symptoms do not show any sterility, and thus suffer no obvious yield loss. Genotypes such as NP(WR) 15, that develop mild mosaic symptoms are partially sterile; and their yield loss is less (19-64%). Disease incidence is usually higher in ratooned and perennial pigeonpea crops.

Symptoms

Diseased plants can be easily spotted from a distance in the field by their pale green and bushy appearance, and the lack of flowers and pods (Figure 13.2). Diseased plants are usually in groups. Sometimes a plant may not show symptoms in the first flush, but when ratooned the new growth shows clear symptoms due to late infection. These symptoms include; severe reduction in leaf size, an increased number of secondary and tertiary branches arising from the leaf axils, and complete or partial cessation in the development of reproductive structures (Nene, 1972). The initial symptoms of SM are vein-clearing in the younger leaves in seedlings, and in localised areas on the leaves of older plants. Primary leaves do not show any symptoms. While screening pigeonpea germplasm for resistance to SM at ICRISAT Center, three types of symptoms were commonly seen (Reddy and Nene, 1979): 1. severe mosaic on leaflets, plants do not produce flowers and pods; 2. ring spot, no sterility, this reaction illustrated in Figure 13.3a, is characterized by green islands surrounded by a chlorotic halo on leaflets, symptoms tend to disappear as the plants mature; 3. mild mosaic (Figure 13.3b) with only partial sterility.

Transmission

The SM causal agent is not transmitted through sap or seed. Graft transmission of SM was first shown by Capoor (1952) before the mite vector was reported. Since the mite vector of SM is extremely small, it is possible that it could go unnoticed on stem pieces that are used as scions. At ICRISAT Center, a tissue implantation method of graft inoculation after eliminating the mites has been successfully developed. In this method, infected stem pieces about 1-cm long, used as

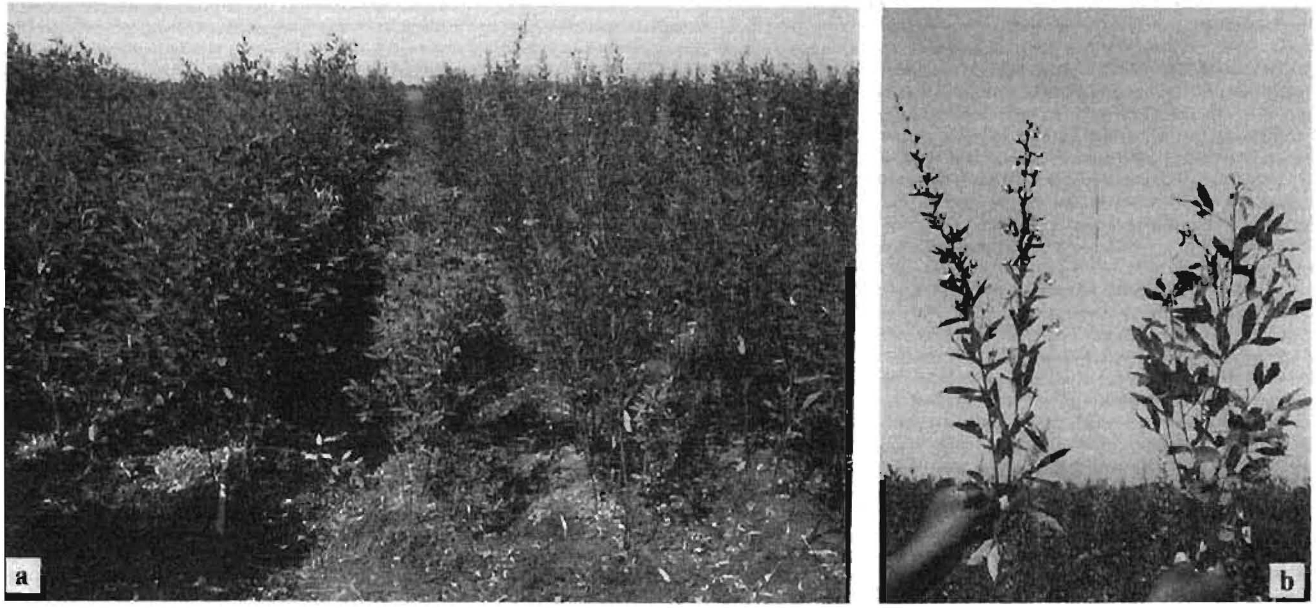


Figure 13.2a. Pigeonpea (ICP 8863) plants (centre) showing symptoms of sterility mosaic disease. Note stunting compared to healthy cultivars on either side. b. Healthy flowering twigs (left) and infected twig (right). Note lack of flowers and pale leaves.
Photo: ICRISAT.

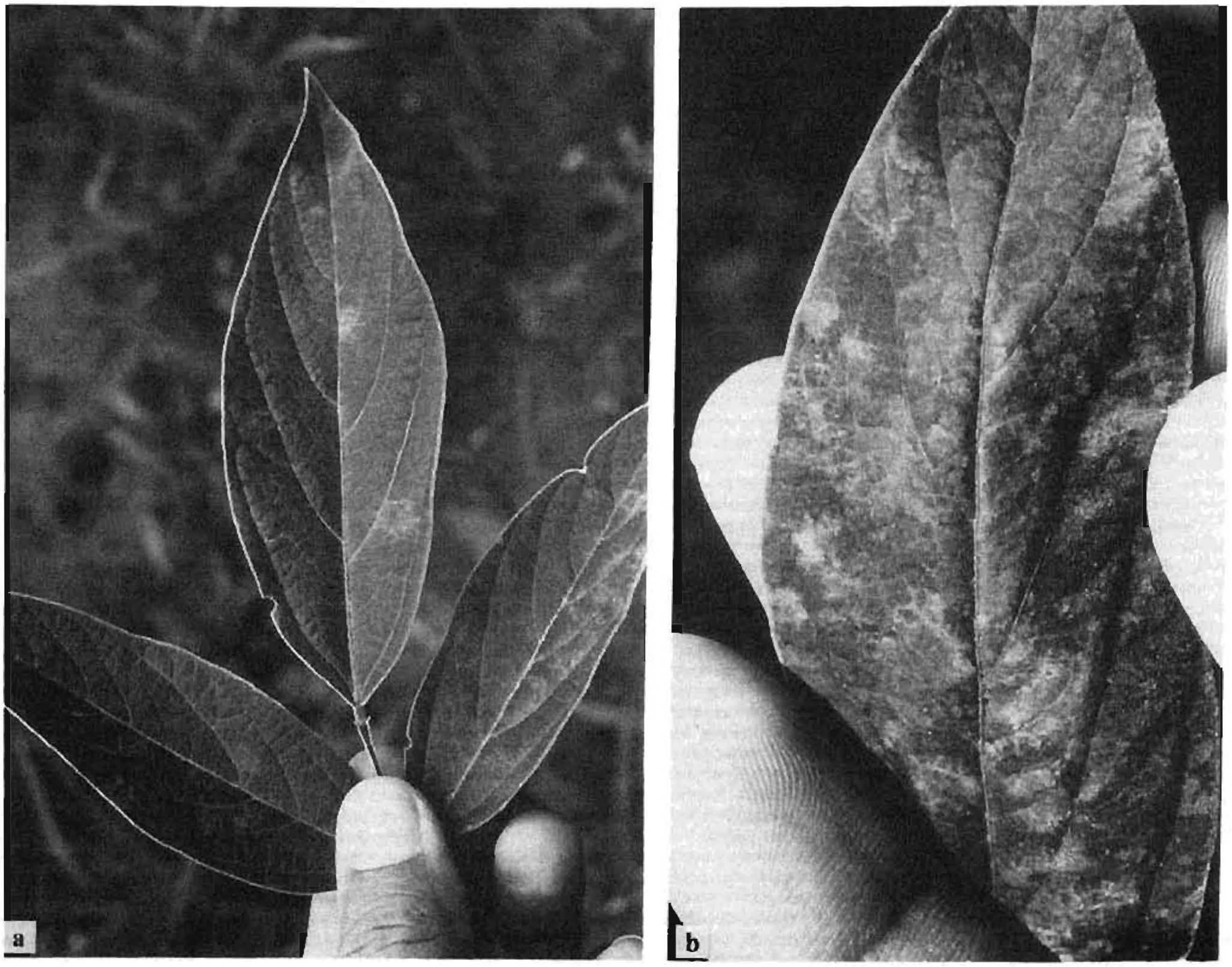


Figure 13.3. Pigeonpea leaves showing sterility mosaic disease symptoms: a. ring spot; and b. Mild mosaic.
Photo: ICRISAT.

scions, are pre-treated with 0.3% Metasystox® (oxydemeton-methyl), and implanted below the growing point of healthy pigeonpea plants by making a vertical slit in the stem. Symptoms of SM appear about a month later, and graft transmission is 12% successful.

Electron Microscopy

No virus or mycoplasma-like bodies, or inclusion bodies associated with virus infections have been consistently detected in partially purified preparations or sections of diseased tissues at ICRISAT Center.

Biology of the Mite Vector

Morphology and Habitat

Aceria cajani is a worm-like, eriophyid mite, about 200-250 μm long (Figure 13.4). It has two pairs of legs, attached one behind the other, on its anterior end where its mouth parts are also located; on its posterior end are two cirri which act as a hold-fast. The mites can be seen clearly under a stereo-microscope at a magnification of 40×. Sheila *et al.* (1988) studied mite morphology using a scanning electron microscope. The mites have short life cycles of less than 2 weeks that include egg, two nymphal, and adult stages. Eggs can be detected on the growing tips of pigeonpea plants; they are milky white, oval, translucent, and slightly smaller than the glands of trichomes. Mites feed by puncturing plant tissues and sucking sap through their slender stylet mouth parts. Since they do not possess wings or eyes, their dispersal is passive, and in nature is mainly by wind currents. The mites are light-shy and have been observed feeding on the lower side of leaflets, preferably at the terminals of a pigeonpea plant. When observed under a stereo-microscope, mites are seen partially or totally buried in the thick mass of hairs on pigeonpea leaves. *Aceria cajani* is host-specific to pigeonpea and under natural conditions survives on pigeonpea and its wild relatives, *Cajanus scarabaeoides* var. *scarabaeoides* and *C. cajanifolius*. The presence of a large number of mites on a pigeonpea leaflet goes unnoticed, mainly because they do not cause visible injuries to leaves.

Establishment of SM Pathogen-free Mite Colony

Mite colonies are generally found on SM-diseased plants, and in the absence of definite proof of the involvement of a pathogenic agent, doubts arise as to whether SM is caused by mite toxaemia. The cultivar ICP 8136 that favours mite multiplication, but is resistant to SM, was staple-inoculated in its primary leaf stage with infected leaves carrying mites (A.M. Ghanekar *et al.*, ICRISAT, unpublished). It did not develop SM symptoms for 30 days after inoculation. Leaflets carrying mites were also staple-inoculated onto plants of ICP 8136 and BDN 1 (SM- and mite-susceptible) at the primary leaf stage, and these plants were observed for 45 days. Neither the resistant nor the susceptible lines expressed SM symptoms. It appeared that a new brood of mites that emerged after 30 days on the resistant line ICP 8136 became free of the SM pathogen because the genotype did not allow the SM pathogen to multiply.

Pathogen-Vector Relationship

Janarthanan *et al.* (1972), reported that a single mite was sufficient to transmit the disease and that both nymphs and adults were equally efficient transmission agents. Studies at ICRISAT Center showed that acquisition access is between 5 to 10 minutes, and inoculation access is 30 minutes. Transmission of the pathogen by the mites is of the persistent type; i.e., once the pathogen is acquired by the mite it is retained for life, provided the mite continues to feed on a susceptible host, such as pigeonpea cultivar BDN 1. Since ICRISAT work has showed that a pathogen-free colony of mites can be produced on a resistant genotype, it is evident that the SM pathogen is not transovarially transmitted.

Multiplication of Mite Vector on SM-Resistant and Susceptible Pigeonpea Lines

Reddy and Nene (1980) found that resistant genotypes seldom support continued mite multiplication, but susceptible genotypes support increased mite numbers. Similar observations were made by Muniyappa and Nangia (1982).

Biotypes of the Mite Vector or Strains of the SM Pathogen

Since 1978, through the Indian Council of Agricultural Research (ICAR) - ICRISAT Uniform Trial for Pigeonpea Sterility Mosaic Resistance (IIUTPSMR), several resistant lines identified at ICRISAT Center have been tested at 10 different locations in India under the auspices of the All India Coordinated Pulses Improvement Project (AICPIP). As a result of this study, it is apparent that

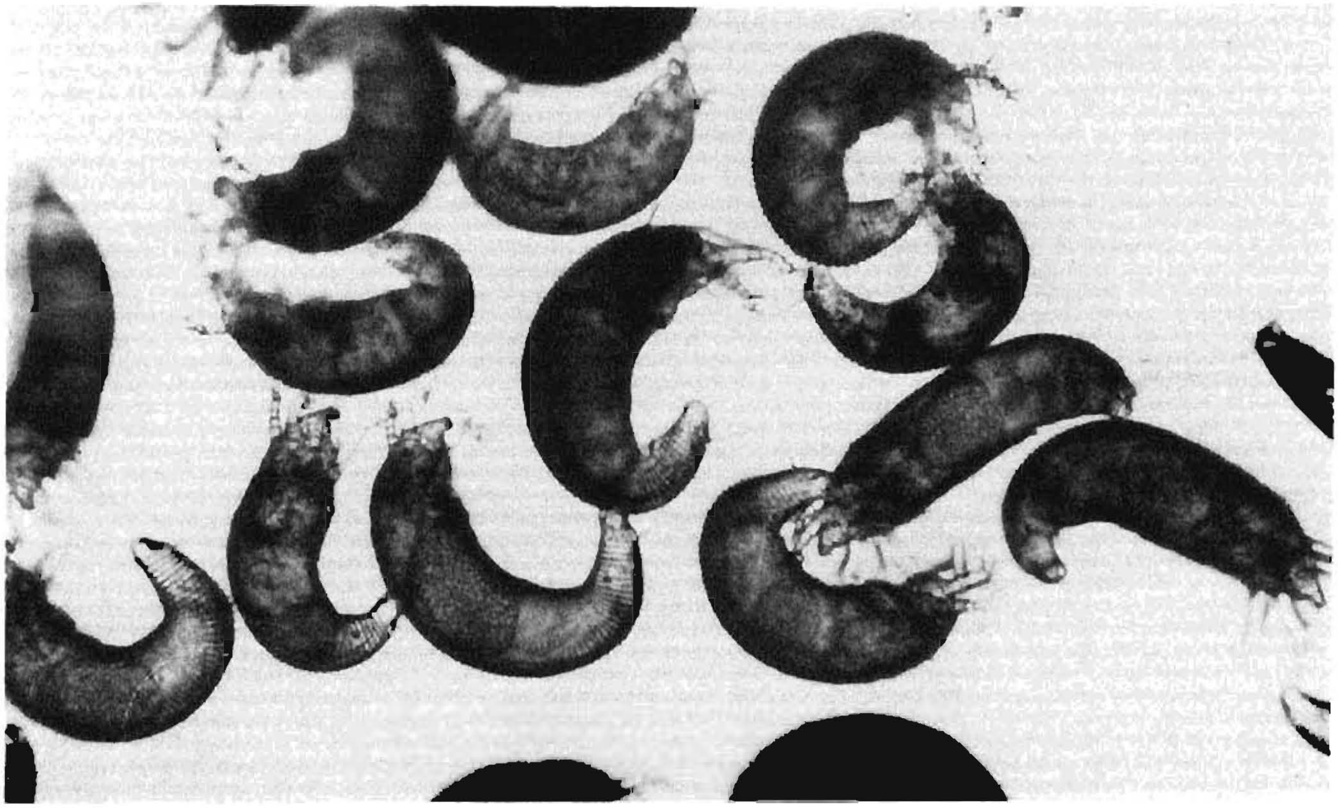


Figure 13.4. Micrograph of *Aceria cajani*, an eriophyid mite which is the vector of the pigeonpea sterility mosaic pathogen, × 660.
Photo: ICRISAT.

some germplasm lines resistant to SM at ICRISAT Center, are susceptible at other locations. This differential reaction over locations indicates that there are at least two biotypes of *A. cajani*, or strains of the SM pathogen in India. Tentatively it appears that strains from Bangalore, Dholi, Faizabad, and Pudukkottai fall into one group, and those from Badnapur, Gwalior, and Patancheru form a second group. Several lines resistant or tolerant at the second group of locations are susceptible at the first group of locations.

Disease Cycle in Nature

The disease cycle of SM is not fully understood. Since the pathogen is not seedborne, the disease is likely to be introduced by the mite vector into rainy-season crops from external sources. During the summer months (April-May) around Hyderabad, *A. cajani* survives on *Cajanus scarabaeoides* var. *scarabaeoides*, a wild relative of pigeonpea commonly seen on field bunds. Although some of the *C. scarabaeoides* var. *scarabaeoides* plants colonised by mites also show mild mosaic mottle symptoms, attempts to transmit the disease from such plants to pigeonpea have been unsuccessful to date. Under these circumstances, the role of mites found on *C. scarabaeoides* var. *scarabaeoides* is uncertain. Reddy *et al.* (1988) reported the survival of the SM pathogen and its vector in Uttar Pradesh, India on off-season pigeonpeas on sugarcane field bunds, volunteer and ratooned pigeonpeas around sugarcane fields, pigeonpeas grown along the irrigation channels, volunteer and ratooned pigeonpeas in fields that were irrigated in the main season, summer-grown crops, and pigeonpeas in kitchen gardens. In the southern Indian states of Karnataka and Tamil Nadu, a limited amount of SM-infected ratooned and perennial pigeonpeas harbouring the mite vector were present in the month of April in irrigated tracts (M.V. Reddy *et al.*, unpublished). In areas where volunteer pigeonpeas are not common, it is not known how the SM pathogen survives during the summer months and reappears in the rainy-season crop. It is observed that pigeonpea sown late (September) close to the rainy-season sowings develops more disease, indicating the spread of the disease from early infected plants in early sowings to the late-sown crop.

Observations on SM incidence in pigeonpea fields at ICRISAT Center indicate that plants are infected throughout the growing season, and that within an early infected crop there is a secondary spread of the disease in September and October. The disease can spread up to 2 km downwind from the source of the inoculum, but spread in an upwind direction is very limited (< 200 m), confirming that wind assists in mite dispersal (Reddy *et al.*, 1989).

A large season-to-season variation in the incidence of the disease in farmers' fields is observed in most parts of India. At present there is no information available to explain this variation.

Control Measures

Host Plant Resistance

Considerable progress has been made in developing inoculation techniques, identifying resistance sources, and developing cultivars resistant to the disease.

The infector-hedge field-inoculation technique was described by Nene *et al.* (1981a). It consists of growing a hedge of a susceptible cultivar on the upwind border of a field in advance of its use as a screening nursery. When the seedlings of the hedge are about 10 days old, they are inoculated with the SM pathogen, either by leaf-stapling (Nene and Reddy, 1976a), or by spreading diseased twigs infested with mites among the seedlings. The pathogen and mites multiply on the hedge plants and serve as source inoculum for disease spread through wind onto test materials during the cropping season. Once a good hedge is established, it can be effective for two or three seasons. The hedge is frequently pruned to promote fresh growth and encourage mite multiplication. While sowing test materials, rows of a susceptible cultivar (BDN 1 or ICP 8863) are sown after every 10 rows of test cultivars to serve as indicator rows for disease spread.

The spreader-row inoculation method is another field inoculation technique, wherein instead of a single hedge several rows of a susceptible cultivar are sown throughout the field about 4 months in advance of the test crop (Nene *et al.*, 1981a). The frequency of spreader to test rows is 1:10. In this method, although a more uniform disease spread is achieved more quickly than by the infector-hedge method, the maintainance of several spreader rows in the field poses land preparation and irrigation problems.

A leaf-stapling technique can be used to inoculate plants both in the field and in pots. A diseased leaflet is folded onto a primary leaf of a healthy seedling in such a way that the undersurface of the diseased leaflet comes in contact with both surfaces of the healthy one, and these are then stapled together (Figure 13.5). The advantages of this method are that it facilitates inoculation at the primary leaf stage, and disease symptoms are rapidly expressed (Nene and Reddy, 1976a). This technique is very useful in confirming resistance of the lines observed as promising under field conditions, and for disease inheritance and strain identification studies.

Alam (1931) was the first to make observations on resistance to SM when he reported Sabour 2E (Rahar) and some other Sabour types of pigeonpea to be resistant. Ramakrishnan and Kandaswamy (1972) from Coimbatore reported NP(WR) 15, P 4835, P 1778, P 1289, P 1100, and P 2621 as showing mild mosaic symptoms, and less than 3% SM incidence. Systematic efforts to identify

Figure 13.5. Pigeonpea seedlings in pots, inoculated with pigeonpea sterility mosaic by the leaf-stapling technique.
Photo: ICRISAT.

sources of resistance were initiated at ICRISAT Center in 1975 (Nene and Reddy, 1976b). By screening all the pigeonpea germplasm accessions held in the ICRISAT gene bank, 326 resistant lines (no visible symptoms) and 97 tolerant lines (ring spot symptoms) were identified (Nene *et al.*, 1981b). Among the 326 resistant lines, 62 were straight germplasm accessions, while the remaining were selections from accessions that showed segregation for resistance and susceptibility. Since 1978, by using the IIUTPSMR it has been possible to retest resistant sources identified at ICRISAT at 10 different locations within India to confirm their resistance to SM (Nene *et al.*, 1989b). As a result of this exercise, three lines ICP 786, 10976, and ICP 10977 have been identified as resistant or tolerant across all the locations.

With the availability of good sources of resistance to SM, resistance breeding work is in progress at several centres in India, including ICRISAT, Pantnagar, Pudukkotai, Dholi, Badnapur, Rahuri, and Faizabad. Among the earlier varieties developed; NP(WR) 15 has some tolerance to SM, Bahar is resistant to SM but highly susceptible to fusarium wilt, and the recently released ICRISAT early-maturing line ICPL 151 has tolerance to SM. Several other lines; ICPL 146, ICPL 269, ICPL 366, ICPL 8327, DA 11, DA 12, DA 13, DA 15, DA 51, MA 97, Sehore 367, DPPA 84-61-3, DPPA 84-8-3, Pant A 104, Pant A 8505, Pant A 8508, Bhavanisagar 1, and NPRR 1, that are under testing in All India Coordinated Trials have all shown resistance to SM.

Sharma *et al.* (1984) reported that susceptibility to SM disease was dominant over resistance and tolerance, and that the tolerant reaction was dominant over resistance in certain lines. Two loci and more than two alleles at each locus were suggested as controlling reactions in the F_1 and F_2 generations in different cross combinations.

Singh *et al.* (1983) found resistance to be governed by four independent nonallelic genes (Sv_1, Sv_2, sv_3, and sv_4). At least one dominant and one recessive genes are necessary for resistance to be expressed.

Chemicals

In field trials at ICRISAT Center seed dressing with a high dose of carbofuran as 25% Furadan 3G® was found to protect the plants from SM infection for up to 45 days after sowing. Rathi (1979) reported seed treatment with 10% aldicarb protected the crop till maturity.

At ICRISAT application of carbofuran 3% at 1.2 kg ai ha^{-1} and aldicarb at 1.5 kg ai ha^{-1} applied to the soil at sowing gave protection to pigeonpea against SM for 75 days after sowing; however, the treatment had no effect against late SM infections.

Three acaricides, Tedion ®, Morestan ®, and Kelthane ®, all at 0.1% concentration, were sprayed on SM infected plants harbouring eriophyid mites. All the three acaricides were highly effective, killing more than 90% of the mites.

Interaction of Sterility Mosaic with other Pigeonpea Diseases

Powdery Mildew

Reddy *et al.* (1984) reported that infection of pigeonpea with SM predisposes them to powdery mildew (*Oidiopsis* sp) infection.

Fusarium Wilt

Some protection against wilt due to SM infection, and inhibition of germination of *F. udum* spores in SM-infected leaf extracts has been reported (Chadha and Raychaudhuri, 1965). In ICRISAT fields, pigeonpea plants affected by SM exhibited fewer fusarium wilt and dry root rot symptoms. Usually, maximum wilt appears at flowering and podding; SM infection, by causing sterility, seems to make plants less susceptible to wilt and other root pathogens.

Phytophthora Blight [*Phytophthora drechsleri* Tucker f.sp. *cajani* (Pal *et al.*) Kannaiyan *et al.*]

A recently recognised disease of pigeonpea, phytophthora blight (PB) was first suspected at New Delhi in India in 1966 (Williams *et al.*, 1968). The disease was observed in epiphytotic form at New Delhi and Kanpur during 1968/69 (Pal *et al.*, 1970; Williams *et al.*, 1975). Pal *et al.* (1970) called the disease stem rot, but Williams *et al.* (1975) preferred to call it stem blight. As both leaf and stem blight symptoms are commonly observed at ICRISAT Center, the authors prefer to call the disease phytophthora blight. The disease appeared in a severe form in some of the experimental plots on Alfisols at ICRISAT Center during the 1976/77 season.

Surveys in India between 1975 and 1980 indicated PB to be widespread with an average incidence of 2.6%, next only to SM and fusarium wilt in diseases occuring on pigeonpea (Kannaiyan *et al.*, 1984). Its incidence was very high (26.3%) in West Bengal, and the disease has also been reported from Queensland, Australia (Wearing and Birch, 1988), Dominican Republic, Kenya, Panama, and Puerto Rico (Nene *et al.*, 1989c). At ICRISAT Center PB incidence was observed to be relatively high in short-duration pigeonpeas compared to that in medium- and long-duration types. The close spacing used for short-duration types could favour blight development. Phytophthora blight is more important in short-duration types as the loss in stand due to this disease drastically reduces yields, because these types have neither time nor plasticity to compensate for lost plants in the way that medium- and long-duration types can. It is possible that PB was earlier mistaken for fusarium wilt because the general symptoms of these two diseases are similar (Amin *et al.*, 1976).

Symptoms

Pigeonpea seedlings become infected with PB as soon as they emerge. Young seedlings are killed within 3 days, and may go unnoticed. The seedlings show crown rot symptoms, topple over, and dry. When the seedlings are older; i.e., about 1 month old, symptoms first appear as water-soaked lesions on the primary and trifoliolate leaves which become necrotic within 5 days. The leaflet lesions are circular to irregular in shape and can be as large as 1 cm in diameter (Figure 13.6). The whole foliage can become blighted within a week. Stem symptoms usually appear later on the main stem, branches, and petioles as brown to dark brown lesions, distinctly different from the healthy green portions. Stem symptoms appear from a few cm to approximately 1.5 m above ground level. The lesions on stems and branches increase rapidly and can extend to 15-20 cm, they usually girdle the stem causing portions of the plant above the lesions to dry out but remain attached to the plant. Infected stems break easily in the wind. Stem lesions initially have a plane surface which later becomes depressed. It is also common to find stems swollen into cankerous structures at the edges of the lesions; this usually happens in plants that are infected but not dried. The lesioned areas sometimes develop cracks and shred.

Stem lesions are often centred on a leaf scar, and extend in each direction from the apparent invasion site (Pal *et al.*, 1970; Williams *et al.*, 1975). Longitudinal cuts into newly formed lesions show brown-to-black discolouration of the bark and cambium, but not the older xylem (Williams *et al.*, 1975). Later, the older xylem tissue may become discoloured, and the stem may break at the lesion site. The roots of PB-infected plants are healthy.

Causal Fungus

Williams *et al.* (1968) first isolated a phycomycetous fungus from wilting pigeonpea plants with stem canker symptoms at New Delhi. Pal *et al.* (1970) identified the fungus causing PB as *Phytophthora drechsleri* Tucker var *cajani* Pal, Grewal, and Sarbhoy. Williams *et al.* (1975) reported that although the fungus was close to *P. drechsleri* it appeared to be a new species of *Phytophthora* because of its larger sporangia, undifferentiated sporangiophores, and abundant production of sex organs on

Figure 13.6. A pigeonpea leaf showing blight lesions caused by *Phytophthora drechsleri* f.sp. *cajani*.
Photo: ICRISAT.

several media. In 1978 they identified the fungus as *P. cajani* Amin, Baldev, and Williams (Amin *et al.*, 1978). Kannaiyan *et al.* (1980b) studied several isolates of the fungus from different parts of India and named it *P. drechsleri* Tucker f. sp. *cajani* (Pal *et al.*) Kannaiyan *et al.*, (Pdc) based on sporangium shape and size, oogonium and oospore formation, temperature requirements, and pathogenicity tests. The use of *forma speciales* was considered appropriate because of the specificity of these isolates to pigeonpea and its wild relatives.

The optimum temperature for growth of Pdc on clarified V-8 juice agar was 27 to 33°C, minimum 9°C, and maximum 36°C which matched with that of *P. drechsleri*. Sporangia were the proliferating type with sizes ranging from 42 to 83 × 28 to 48 µm (average 61.8 × 37.3 µm). The sporangial stalks within the same culture were either narrowly tapered or widened somewhat at the base of the sporangium. Pdc belongs to mating type A1 with bicellular antheridia in some interspecific crosses. Oogonium and oospore size show little variation (19-29 to 34-44 µm). Numerous bicellular antheridia are formed on carrot agar medium. Aplerotic oospores are produced in crosses with some mating types. Oogonia with echinulate or verrucose outer walls are observed only in certain crosses. Terminal and intercalary hyphal swellings with fingerlike projections are only observed at low temperatures (9-18°C). No chlamydospores were formed on any media at any temperature (Kannaiyan *et al.*, 1980b).

In addition to potato dextrose agar, media used to isolate or multiply Pdc include:

1. V-8 juice agar (V-8 juice 100 mL, $CaCO_3$ 2g, agar 20 g, distilled water 900 mL) (Nene *et al.*, 1981a)

2. Pigeonpea infusion agar (infusion from 40 g pigeonpea seed meal, agar 20 g, distilled water to make up 1000 mL) (Sheila *et al.*, 1983)
3. BHMPPVR selective medium (V-8 juice agar, Benlate ® 20 ppm, hymexazol 20 ppm, mycostatin 10 ppm, PCNB 20 ppm, pimaricin 5 ppm, vancomycin 200 ppm, rifamycin 10 ppm) (Bisht and Nene, 1988).

Epidemiology

Pal *et al.* (1970) observed that high humidity helps the rapid development of PB. Williams *et al.* (1975) related high disease incidence to poor soil surface drainage, but also found the disease in epiphytotic form in a well-drained field near New Delhi. At ICRISAT Center more disease was found in low-lying areas of fields where temporary water stagnation occurs after heavy rains. The disease incidence was relatively higher in Alfisols than Vertisols. Singh and Chauhan (1985) made similar observations.

How the pathogen perpetuates from one season to another is not very clear. In addition to pigeonpea, *Cajanus scarabaeoides* var. *scarabaeoides*, a wild relative of pigeonpea was found to be naturally infected with PB (Kannaiyan and Nene, 1985b) on the ICRISAT farm. However, its role in the perpetuation and spread of the disease to pigeonpea is yet to be established. Kannaiyan *et al.* (1983c) suggested that stubble from diseased pigeonpea plants may not support the survival of Pdc from one year to another as the fungus only survived for 3 months in bits of diseased stem. However, Agrawal and Khare (1988) found the pathogen could survive on infected pigeonpea stems in the field until July when the crop is normally sown; the survival rate was better lower in the soil profile when infected stems were buried in the soil at 5-15 cm depths than when they were left on the soil surface. Bisht (1985), using a selective medium named SM 19, and a leaf-baiting technique, established that Pdc survives in soil and infected crop debris for more than one year. He also found zoospores to be the primary source of inoculum, and that during rains, wind contributes to inoculum dispersal over short distances. Water flowing from infested fields carries zoospores of Pdc. Sarkar (1988a) found Pdc to survive in the form of chlamydospores in field soil and diseased stubble. However, the role of chlamydospores in PB epidemiology is yet to be established.

PB incidence in the field is correlated with its soil inoculum potential (Sarkar, 1988b). Inoculum potential in soil increased with the rains and low temperatures (22-26°C) at the beginning of the rainy season (July-August) and from then onwards drastically reduced. No fresh incidence was observed later in the season even when rains and low temperatures prevailed.

Pal and Grewal (1975) reported that in the absence of potassium (K), high doses of nitrogen (N) increased PB incidence. Addition of K decreased disease incidence regardless of the presence of N or phosphorous (P) in the soil. Singh and Chauhan (1985) reported more rapid development of blight at night in the field, and confirmed this under conditions of artificial darkness in a greenhouse.

Preliminary observations on the relationships between PB infection, temperature, and relative humidity under field conditions at ICRISAT Center indicated that disease development was faster when day and night temperatures were more or less the same, i.e., ranging between 20 and 25°C, the weather was cloudy, and relative humidity was between 70 and 80%.

Pathogenic Races

The information so far available indicates that Pdc in India is pathogenically variable. The first indication of this came when several pigeonpea lines resistant to the P2 isolate showed susceptibility in ICRISAT fields in the 1981/82 season. Isolations from such plants, and pathogenicity tests revealed this to be a more aggressive isolate distinct from P2, and it was therefore named P3. In the 1987/88 season many lines that showed tolerance to the P3 isolate showed high susceptibility; the fungus (P4) isolated from them was more aggressive than the P3 isolate. Multilocational

Table 13.2. Reactions[1] of pigeonpea genotypes to *Phytophthora drechsleri* f. sp *cajani* isolates from India in pot culture studies at ICRISAT Center.

	Isolates							
Genotype	P4	P3	BHU	KPR	P2	HIS	IARI	P2BF
ICP 6997	HS	S	S	S	S	M	M	M
ICP 7119	HS	S	S	S	S	S	S	M
ICP 7910	HS	S	S	M	S	M	M	R
ICP 113	HS	S	S	M	S	R	R	R
ICP 1788	HS	S	S	R	S	R	R	M
ICP 4882	HS	S	S	R	R	R	R	M
ICP 7657	HS	M	S	M	R	R	R	M
ICP 752	HS	M	S	M	M	R	R	R
ICP 2376	HS	S	S	R	M	R	R	R
KPBR 80-1-4	HS	M	M	R	R	R	R	R
ICP 7065	HS	S	S	R	M	R	R	M
ICP 7269	HS	S	S	M	R	M	R	R
ICP 7795	HS	M	M	R	R	R	R	M

1. R = resistant, 0-20% blight
M = moderately susceptible, 21-50% blight
S = susceptible, 51-80% blight
HS = highly susceptible, 81-100% blight

Source: Sarkar, 1988a.

evaluation of lines also indicated the possible variation in Pdc. The variable reactions in pot culture studies of 13 pigeonpea genotypes to 8 isolates of Pdc from different locations in India further confirm the variability present in Pdc (Table 13.2) (Sarkar, 1988a). The problem faced in coming to definite conclusions on the races in Pdc is the inconsistency in the reactions of pigeonpea genotypes to some isolates in repeated tests, and the loss of aggressiveness of some isolates when frequently sub-cultured.

Plant Age and Susceptibility to Disease

Field observations and pot culture experiments at ICRISAT Center indicate that pigeonpeas are generally more susceptible as seedlings than adults. In pot culture, 60-day-old inoculated plants of both susceptible and tolerant cultivars showed no visible susceptibility to PB (Table 13.3; Sarkar, 1988b). The reasons for such reduced susceptibility with increased age are not understood. Under field conditions it is not uncommon to observe plants dying even after 60 days. In such cases it is possible that the infection might have occurred at an early age, and that the disease progressed slowly, killing the plants later.

Mishra and Shukla (1986a) also reported maximum incidence (100%) in 15-day old seedlings; the incidence decreased with age to a minimum of 25% in 4-month-old plants.

Control Measures

Host Plant Resistance

Pal *et al.* (1970) used a "leaf scar" method to inoculate 1- to 2-month-old plants. This method entails inoculating the plants with mycelial mats of the fungus multiplied on potato dextrose agar

Table 13.3. Effect of age (days) of pigeonpea genotypes on susceptibility to phytophthora blight, measured as blight incidence (%)[1].

	Age (days)				
Genotypes	7	15	30	45	60
ICP 113	52±7.0	55±6.3	0	0	0
ICP 2376	81±5.2	79±5.4	41±6.9	10±4.2	0
ICP 7119	73±8.1	91±4.8	35±9.7	16±8.4	0
ICP 8863	46±6.5	40±6.0	0	4±2.7	0
ICP 11290	38±6.4	58±5.9	6±3.1	12±4.5	0

1. Mean % over 4 replications ± standard error.
Source: Sarkar, 1988b.

at the point of attachment of a leaf after its removal. Kannaiyan *et al.* (1981a) reported a pot-culture drench inoculation technique (Figure 13.7). In this technique 5-10-day-old seedlings are drench-inoculated with a mycelial suspension of Pdc, and the pots liberally watered to encourage blight development. Alternatively, inoculum is sprayed on 15- to 30-day-old plants in a pot, the plants are covered with polythene bags for 48 h, and later sprayed with water for 10 days.

Nene *et al.* (1981a) described a field inoculation technique. Mycelial mats of Pdc are mixed with the medium and 0.2% by weight of carborundum (600-mesh). A small amount of the resulting mashed mycelium is rubbed onto the base of 1-month-old plants. The field is repeatedly irrigated if dry weather prevails after inoculation.

Figure 13.7. Evaluation of pigeonpea germplasm accessions for resistance to phytophthora blight in pot culture.
Photo: ICRISAT.

A "diseased debris" inoculation technique has also been found very effective in evaluating large amounts of pigeonpea material at ICRISAT Center. A well-levelled Alfisol was found ideal for this purpose. The crop is sown as closely as possible (30×10 cm) on flat beds preferably before the monsoon arrives (during the first week in June). When the plants are about 1 month old, pigeonpea stems with PB lesions, collected during the previous season and stored dry, are scattered over the field. If the season is dry, sprinkler irrigation is provided. This technique produced near 100% disease incidence in susceptible controls sown after every four test rows at ICRISAT Center for three consecutive seasons (1986/87, 1987/88, and 1988/89). If the same field is used year after year, inoculation with diseased debris may not be necessary.

Pal *et al.* (1970) screened 268 pigeonpea lines using the leaf-scar method and reported three lines; AS 3, 2357, and 4419 to be moderately resistant. Kannaiyan *et al.* (1981a) evaluated 2385 pigeonpea lines and seven other *Cajanus* spp against the P2 isolate of Pdc using a pot culture technique, and reported 80 pigeonpea lines and two *Cajanus* spp (*C. platycarpus* and *C. sericeus*) as resistant.

Most of these lines were later found susceptible to a new isolate of the fungus (P3) that appeared naturally in the field at ICRISAT Center. Screening of a large number of germplasm accessions and breeding materials against the P3 isolate indicated that none has a high level of resistance to it. However, ICP 5097, 6344, 7200, 8564, 8610, 8692, 12749, and KPBR 80-2-1 showed field tolerance to both the isolates (M.V. Reddy *et al.*, unpublished; Figure 13.8).

Singh *et al.* (1985) evaluated 71 pigeonpea lines at Pantnagar in northern India and found ICPL 161, METH 12, Comp-1-ESR-6, Pant A3, and Pant A 83-14 to be resistant. Bhargava and Gupta

Figure 13.8. A pigeonpea line showing field tolerance to phytophthora blight (right), and a susceptible line (left).
Photo: ICRISAT.

(1983) studied the reactions of 46 lines in the field at Sehore, Madhya Pradesh, and found that most of the late-maturing lines they tested were resistant. Mishra and Shukla (1986b) reported KPBR 79-1 and 5786-1 to be resistant (0.1 to 5% infection) and KPBR 80-1 and KPBR 80-2 to be moderately resistant (5.1-10% infection) in field and pot culture tests.

Sharma *et al.* (1982) reported that resistance in pigeonpea to phytophthora blight is governed by single dominant gene designated *Pd*$_1$.

Fungicides

Studies on the control of PB using fungicides are very limited. Pal and Grewal (1983) reported Brestan-60 ® to be the best when applied before inoculation. Sinha (1983) reported seed treatment with metalaxyl (4 g ai kg^{-1} seed) controlled up to 35% incidence but only in the initial stages. Kannaiyan and Nene (1984) evaluated a seed-dressing formulation of metalaxyl (Apron 35 SD ®) under greenhouse and field conditions. Significant control of PB (over 90%) was achieved with metalaxyl (1.75 g ai kg^{-1} seed) in a greenhouse trial for 30 DAS. However, the fungicide was found ineffective against the disease in field tests. In the field, satisfactory control was achieved with 7 g ai kg^{-1} seed treatment without spray at 30 DAS. Seed dressing followed by one spray of metalaxyl 25 WP (at 500 ppm) 30 DAS could not protect the crop at 60 DAS. Bisht *et al.* (1988) confirmed that seed dressing with metalaxyl alone was not effective, but found foliar sprays alone or in combination with seed dressing to be effective. They also found the chemical to be more effective when used on the tolerant line ICP 1. Agrawal (1987) reported that in a field test metalaxyl applications at 30 and 45 DAS gave maximum reduction in blight incidence.

Chaube *et al.* (1984) reported that pigeonpea seeds readily absorb metalaxyl; in 5-day-old seedlings the highest concentration was in the roots followed by the stem and foliage, and that up to this stage the plants were protected against PB. In 20- and 30-day-old plants most of the fungicide was localised in the foliage, with the exception of the terminal buds and the stems that had extremely low amounts and hence were unprotected by the fungicide. Chaube *et al.* (1987b) reported that metalaxyl mainly remained in the plant parts to which it was applied, and that its translocation was enhanced by sugar application. Only 14.4, 6.3, and 3.3% of the fungicide applied as seed treatment could be recovered from 15-, 30-, and 45-day-old seedlings. Chaube *et al.* (1987a) investigated the poor efficacy of metalaxyl applied as seed dressing in protecting older pigeonpea plants against PB. The effect of metalaxyl on sporangial formation and germination was less than on mycelial growth. The amount of metalaxyl found in vulnerable plant parts (apical bud, stem, etc.) of 30-day-old plants raised from metalaxyl-treated seeds was inadequate to protect the plants.

Sheila and Nene (1987) studied the effect of two phytoalexin formulations on PB. Phytoalexin-84 ® and Induce ® reduced disease incidence when sprayed on plants or applied as a soil drench.

Cercospora Leaf Spots *(Cercospora* spp)

Four species of *Cercospora* have been reported to infect pigeonpeas in various parts of the world (Nene *et al.*, 1989c). The most common species, *C. cajani* Hennings (perfect stage - *Mycovellosiella cajani* (Henn.) Rangel ex. Trotter), has been reported from Bangladesh, Brazil, Colombia, Dominican Republic, Guatemala, India, Jamaica, Kenya, Malawi, Mauritius, Nigeria, Puerto Rico, Tanzania, Trinidad, Uganda, Venezuela, Zambia, and Zimbabwe. *Cercospora indica* Singh and *C. thirumalacharii* Pavgi and Upadhyay have been reported from India. *Cercospora instabilis* Rangel has been observed in Brazil, India, and Puerto Rico. Leaf spot caused by *C. cajani* is the most prevalent, and is therefore described in the following paragraphs.

Leaf spot caused by *C. cajani* was first reported by Stevenson in 1917 from Puerto Rico. The disease is not serious in relatively dry pigeonpea-growing areas, but can cause substantial losses in humid areas (Rubaihayo and Onim, 1975). Yield losses as high as 85% have been reported (Onim, 1980).

Symptoms appear as small, brown, circular leaf spots that increase in size and coalesce. Generally the older leaves show more infection, but under wet conditions even young leaves are infected. Infected leaves drop off and plants may be severely defoliated. Under humid conditions sporulation can be observed on leaf lesions.

No systematic work on the biology and epidemiology of this pathogen has been reported. However, Singh (1934) made detailed studies on the biology of *C. indica*. It is logical to expect that the pathogen survives on dead leaf debris and on perennial pigeonpeas.

It is possible to control the disease and increase yields through sprays with such fungicides as benomyl and mancozeb at regular intervals (Khan and Onim, 1972 in Nene *et al.*, 1985; Onim, 1980). Onim and Rubaihayo (1976) made serious attempts to breed for resistance and identified some lines (UC 2515/2, UC 796/1, UC 2113/1, and UC 2568/1) that showed high levels of resistance and increased yields.

Witches' Broom

Witches' broom (WB) has been reported from several countries; Australia, Bangladesh, Costa Rica, Dominican Republic, El Salvador, Haiti, Jamaica, New Guinea, Panama, Puerto Rico, Taiwan, Trinidad, and the USA (Nene *et al.*, 1989c). It was first reported from the western part of Puerto Rico in 1974 (Vakili and Maramorosch, 1974). It is probably the most serious disease in the Dominican Republic (Y.L. Nene, personal observation) where large areas have close to 100% incidence in certain years.

The disease is characterized by prolific and clustered branching of the plant (Figure 13.9). Leaves appear pale green and are reduced in size. The flowers are produced in clusters, their pedicels generally elongated; many fail to develop beyond the bud stage, and affected plants fail to set fruit. Sometimes only a part of the plant is affected (Brathwaite, 1981).

Vakili and Maramorosch (1974) first considered the disease to be of a mycoplasmal nature because they found mycoplasma-like organisms (MLO) in thin sections of affected tissues observed under the electron microscope. They suggested the leafhopper *Empoasca* sp. as the vector. Later Maramorosch *et al.* (1974) observed the presence of both MLO and a rhabdo-type virus in thin sections. The presence of MLO in plants showing WB symptoms has been confirmed by Hirumi *et al.* (1973) and McCoy *et al.* (1983). It is possible that some mixed infection produced both MLO and rhabdovirus in the studies of Maramorosch *et al.* (1974).

Although WB is considered serious in Central America, no systematic studies have so far been carried out to determine prevalence, losses, epidemiology, and ways to reduce the incidence.

MINOR DISEASES

Diseases that are observed occasionally and in localized areas are included in this section. Such diseases include; collar rot, dry root rot, phoma stem canker, alternaria leaf spot, powdery mildew, rust, bacterial leaf spot and stem canker, and yellow mosaic.

Collar Rot (*Sclerotium rolfsii* Sacc.)

The disease, also called southern blight in the Caribbean region, has been reported to occur in India, Puerto Rico, Trinidad, USA, and Venezuela (Nene *et al.*, 1989c). The disease incidence is

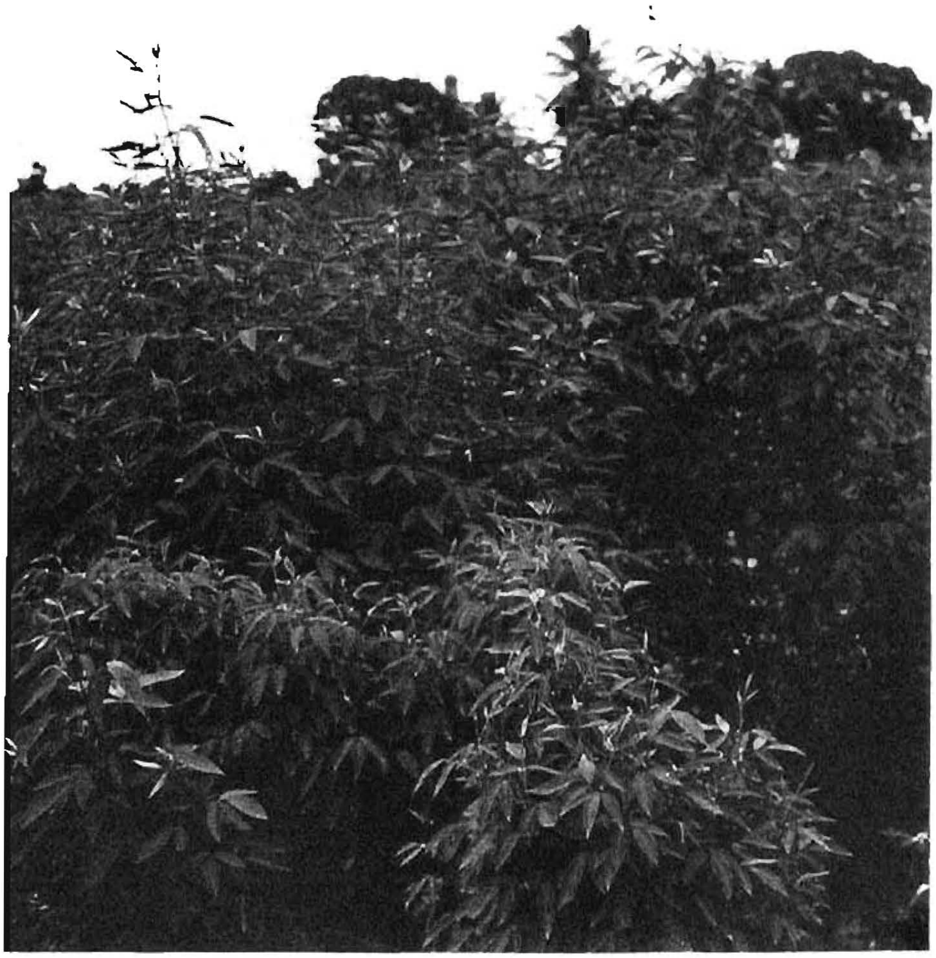


Figure 13.9. Pigeonpea plants affected by witches' broom disease in Puerto Rico.
Photo: ICRISAT.

usually observed at the seedling stage (Figure 13.10). It causes substantial seedling mortality within 45 DAS in situations where pigeonpea is sown in warm weather soon after a preceding cereal crop; and particularly when the crop stubble remains close to the soil surface. The pathogen finds an excellent substrate in undecomposed stubble, and emerging pigeonpea seedlings show mortality due to attack by the pathogen.

Disease incidence can be reduced if the previous crop stubble is buried deep, and is allowed to decompose well before pigeonpea is sown. Seed dressing with fungicides such as tolclofos-methyl (Rizolex ®) should also reduce seedling mortality. Genotypic differences in susceptibility have been observed (Kannaiyan *et al.*, 1983b).

Dry Root Rot [*Rhizoctonia bataticola* (Taub.) Butler (*Macrophomina phaseolina* (Tassi) Goid.)]

The disease has been reported to occur in India, Jamaica, and Trinidad (Nene *et al.*, 1989c). It was first reported from India by Ashby (1927). Typical symptoms include root and basal stem rot with a large number of minute, fungal sclerotia visible under the bark. Plants dry prematurely, particularly when they face drought stress. Infection of seedlings has also been reported (Chaudhuri and Ahmed, 1977). Leaf infection has been reported from India by Saksena *et al.* (1970). The authors have observed disease incidence to be severe in off-season, irrigated, summer crops in several

Figure 13.10. Pigeonpea seedlings (centre) killed following infection by *Sclerotium rolfsii*, surrounded by healthy seedlings.
Photo: ICRISAT.

parts of India; however, the disease is usually a minor one in the normal-season crop. The pathogen is both soil- and seedborne (Kannaiyan *et al.*, 1980a).

Seedling infection can be reduced by seed dressing with fungicides such as benomyl, thiram (Benlate T®) (Kannaiyan *et al.*, 1980a), and tolclofos-methyl (Rizolex®). Host resistance (cultivar S 18) has also been reported (Vidhyasekaran and Arjunan, 1976).

Phoma Stem Canker [*Phoma cajani* (Rangel) Khune and Kapoor]

This disease, reported from Brazil and India (Nene *et al.*, 1989c) generally occurs in adult plants, and is characterized by the appearance of brown, cankerous lesions on the stem. These lesions, that have grey centres and dark brown margins, may coalesce and girdle the stem. Lesioned portions often develop swellings (Figure 13.11). Numerous pycnidia are seen in the lesions. Affected branches dry prematurely (Khune and Kapoor, 1981). Leaves are also infected by the fungus. The pathogen survives on dead crop debris, but is not seedborne (Somani *et al.*, 1981). Some degree of host resistance has been reported (Singh *et al.*, 1986). Sanitary practices should help in managing the disease.

Alternaria Leaf Spot [*Alternaria tenuissima* (Kunze ex. Pers.) Wiltshire]

This leaf spot disease is reported only from India (Pavgi and Singh, 1971), where *A. alternata* has also been reported to cause a similar leaf spot (Mehta and Sinha, 1982). Initially small necrotic spots appear on the leaves, and these gradually increase in size to characteristic lesions with dark and light brown concentric rings with a wavy outline and purple margin. As infection progresses, the lesions enlarge and coalesce. The disease is mostly confined to older leaves in adult plants, but may infect new leaves of young plants, particularly in the postrainy-season crop. The pathogen

Figure 13.11. The base of a pigeonpea plant showing stem cankers caused by *Phoma cajani* infection.
Photo: ICRISAT.

is present in the environment and has a wide host range. It was detected on pigeonpea seeds in Puerto Rico (Ellis *et al.*, 1978). Resistant cultivars such as ICPL 366 and DA 2 are now available.

Powdery Mildew [*Oidiopsis taurica* (Lev.) Salmon]

The disease has been reported from several countries including; Ethiopia, India, Kenya, Malawi, Tanzania, Uganda, and Zambia (Nene *et al.*, 1989c). Probably the first report of its occurrence was from Tanzania (Wallace, 1930). Although powdery mildew symptoms appear more often on old leaves, young leaves can also be infected under favourable weather conditions (Figure 13.12). In cases of severe infection, affected leaves turn yellow and show twisting and crinkling (Narayanaswamy and Jaganathan, 1975). The host range of the pathogen is very wide, and the inoculum is always present in pigeonpea-growing, semi-arid regions. The disease has rarely been reported to cause severe losses; therefore very few reports of work on its management appear in the literature.

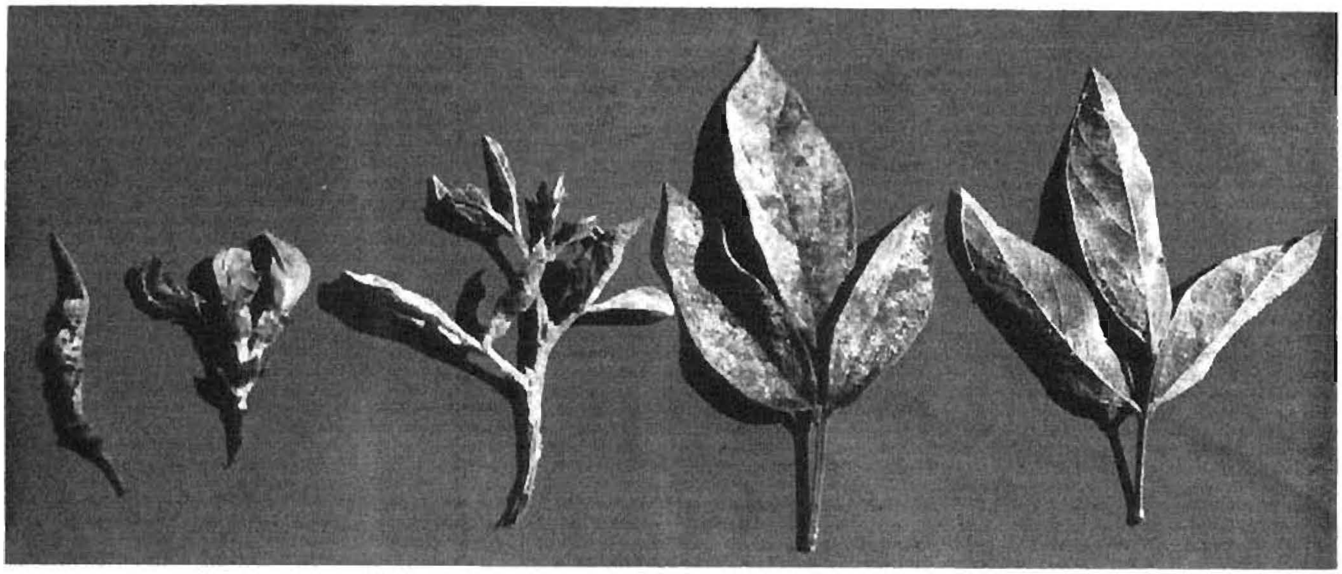


Figure 13.12. Symptoms of powdery mildew disease caused by *Oidiopsis taurica* on buds, pods,flowers and leaves of pigeonpea.
Photo: ICRISAT.

Rust (*Uredo cajani* Syd.)

Rust has been reported from many countries including Bermuda, Colombia, Guatemala, India, Jamaica, Kenya, Nigeria, Puerto Rico, Sierra Leone, Tanzania, Trinidad, Uganda. and Venezuela (Nene *et al.*, 1989c). The disease was probably first reported from India (Sydow and Butler, 1906). Even though the disease is observed in many countries, it has rarely been reported to cause severe losses. The leaves show characteristic dark brown, uredial pustules, and consequent leaf-drop is common (Figure 13.13). The telial stage has not been reported, and physiologic races could not be detected in the Caribbean (Mohammed, 1978). Host resistance is available (Barrett, 1925; Jackson, 1976).

Bacterial Leaf Spot and Stem Canker [*Xanthomonas campestris* pv. *cajani* (Kulkarni *et al.*) Dye *et al.*]

The disease was first reported from India in 1950 by Kulkarni *et al.* It has also been reported from Australia, India, Panama, Puerto Rico, and Sudan (Nene *et al.*, 1989c). The disease occurs in most years, but appears to cause losses only in certain seasons. Symptoms on leaves are characterized by the appearance of minute, brown lesions surrounded by a yellow halo (Figure 13.14). These lesions often coalesce and form larger ones. On the main stem and branches, rough, cankerous dark brown lesions of various shapes and size appear. In the case of severe infections, branches may dry prematurely or break at the infection site. The pathogen is specific to pigeonpea and is seedborne (Gaikwad and Kore, 1981; Rai and Singh, 1986).

It is possible to control the disease in the field with sprays of Streptocycline ® (streptomycin and tetracycline - 100 ppm) repeated at 10-day intervals (Singh *et al.*, 1978). It may be possible to erradicate the pathogen through seed treatment with appropriate antibiotics. Genotypic differences in susceptibility have been reported (Gaikwad and Kore, 1981; Reddy *et al.*, 1987).

Yellow Mosaic

Reported from India, Jamaica, Nepal, Puerto Rico, and Sri Lanka (Nene *et al.*, 1989c), this disease was probably reported first from Sri Lanka (Newton and Peiris, 1953). The disease first appears in the form of yellow, diffused spots scattered on the leaf lamina, not limited by veins and veinlets. Such spots slowly expand and in later stages of disease development, affected leaflets show broad, yellow patches alternating with green colour. Sometimes the entire lamina turns yellow. Leaf size is conspicuously reduced in early infections. In peninsular India, disease incidence is relatively higher in late-sown pigeonpea. More than 40% yield loss has been reported (Beniwal *et al.*, 1983; Mishra and Gurha, 1980).

The causal virus is mung bean yellow mosaic virus (Nene, 1972), a gemini virus that is not serologically related to the *Rhynchosia* virus reported on pigeonpea from Puerto Rico (Y.L. Nene, unpublished). The vector is *Bemisia tabaci* Genn. Since disease incidence is rarely severe, no reports on managing the disease have appeared in the literature.

Figure 13.13. Pigeonpea leaves with symptoms of rust disease caused by *Uredo cajani*.
Photo: ICRISAT.

Figure 13.14. Leaf spot symptoms on pigeonpea caused by *Xanthomonas cajani* infection.
Photo: ICRISAT.

NEMATODES

Sixty-five species in 24 genera of nematodes from 24 countries have been found associated with pigeonpea roots (Nene *et al.*, 1989c). Of these, root-knot, lesion, cyst, reniform, and spiral nematodes are considered important (Table 13.4; Sharma, 1988). In India, cyst, reniform, and root-knot nematodes are important.

Cyst Nematode (*Heterodera cajani* Koshy)

Heterodera cajani was initially recorded in 1964 from New Delhi, India as *Heterodera trifolii* by Swarup *et al.* (1964). Studies by Koshy (1967) revealed it to be a different species and named it as *H. cajani*. The nematode has also been reported from Egypt. Saxena and Reddy (1987) recorded 30% loss in yield in a field heavily infested with *H. cajani*. An initial population density of three juveniles cm^{-3} of soil can cause 25% reduction in plant biomass (Sharma and Nene, 1988).

Table 13.4. Important nematode pests of pigeonpea in various countries.

Country	Most important	Very important	Important
Brazil	*Meloidogyne javanica*	*Pratylenchus brachyurus*	*Helicotylenchus dihystera*
Egypt	*Heterodera cajani*	*M. incognita*	
Ethiopia	*Meloidogyne* sp		
Fiji	*Rotylenchulus reniformis*	*Meloidogyne* sp	*Radopholus similis*
Jamaica	*R. reniformis*	*Pratylenchus* sp	*Helicotylenchus* sp
Malawi	*M. javanica*		
Nepal	*Meloidogyne* sp		
Sudan	*P. sudanensis*	*Tylenchorhynchus* sp	*Ditylenchus* sp
Trinidad	*R. reniformis*	*Pratylenchus zeae*	*H. dihystera*
USA	*Meloidogyne* sp	*Pratylenchus* sp	
Zambia	*Meloidogyne* sp		
Zimbabwe	*Meloidogyne* sp	*Pratylenchus* sp	*Helicotylenchus* sp
India (states)			
Andhra Pradesh	*H. cajani*	*M. incognita*	*Pratylenchus* sp
Bihar	*H. cajani*	*Meloidogyne* sp	*Hoplolaimus* sp
Gujarat	*Meloidogyne* sp	*R. reniformis*	*Tylenchorhynchus vulgaris*
Haryana	*H. cajani*	*Meloidogyne* sp	*R. reniformis*
Karnataka	*H. cajani*	*Meloidogyne* sp	*R. reniformis*
Maharashtra	*M. incognita*	*R. reniformis*	
Rajasthan	*R. reniformis*	*H. cajani*	*Tylenchorhynchus* sp

Disease Characteristics

Close examination of the roots of 30- to 35-day-old infected plants reveals minute pearly white bodies that are females of *H. cajani* (Figure 13.15). These females gradually mature and turn brown; most of them are dislodged from the roots when the plants are lifted for examination.

Morphology

Males are vermiform, and females are obese and lemon-shaped. Cysts are lemon-shaped and light to dark brown in colour; 350-690 μm long and 175-500 μm wide. The vulval cone is ambifenestrate. The underbridge is well developed, sometimes with a thin transparent mass attached at the centre. Bullae are many, prominent, and peripheral (Sharma and Swarup, 1984). A gelatinous egg-sac is produced at the vulval cone, usually it is half to twice the size of the cyst (Figure 13.16a). Eggs are 78-125 μm long and 35-50 μm wide (Figure 13.16b). Second-stage juveniles are 345-515 μm long. Stylet length ranges from 22 to 26 μm.

Host Range

The nematode is mainly confined to plant species in the Leguminosae family. *Cajanus platycarpus*, *C. crassus* var. *crassus*, *Cicer arietinum*, *Cyamopsis tetragonoloba*, *Dolichos lablab*, *Dunbaria ferruginea*, *Flemingia strobilifera*, *Glycine max*, *Phaseolus aconitifolius*, *P. atropurpureus*, *P. aureus*, *P. calcaratus*, *P. lathyroides*, *P. lunatus*, *P. mungo*, *P. vulgaris*, *Pisum sativum*, *Rhynchosia bracteata*, *R. cana*, *R. densiflora*, and *Vicia sativa* have all been reported as hosts (Koshy and Swarup, 1972; Bhatti and Gupta, 1973; Sharma and Nene, 1985a). *Sesamum indicum* (family Pedaliaceae) is the only non-legume host.

Disease Cycle

Infective second-stage juveniles randomly penetrate the tap roots and lateral roots reaching the vascular tissue within 72 h. They place their heads adjacent to the stele, and begin to feed and swell. Cells near the feeding site become angular with thickend walls, and giant cells are formed containing dense granular cytoplasm with four to five nuclei (Koshy and Swarup, 1979). The nematode gradually passes through its third and fourth stages, and becomes an adult female. The female enlarges in size, damages the cortex, and erupts from the epidermis. Nematode parasitism results in widespread rupturing and discontinuity of the xylem vessels. Juveniles which establish in the cortex develop into males, and those which feed in the stelar region develop into females. The adult male matures in 10 days, while swollen, lemon-shaped females are formed after 12 days. Males are encountered in large numbers; but females can reproduce in the absence of males (Koshy and Swarup, 1971; Sharma and Swarup, 1984). Fifteen days after penetration, infective juveniles can be seen in the soil. Eggs are deposited in egg-sacs, and also within the female body which gradually transforms from white to a brown coloured protective cyst. A female produces 100 to

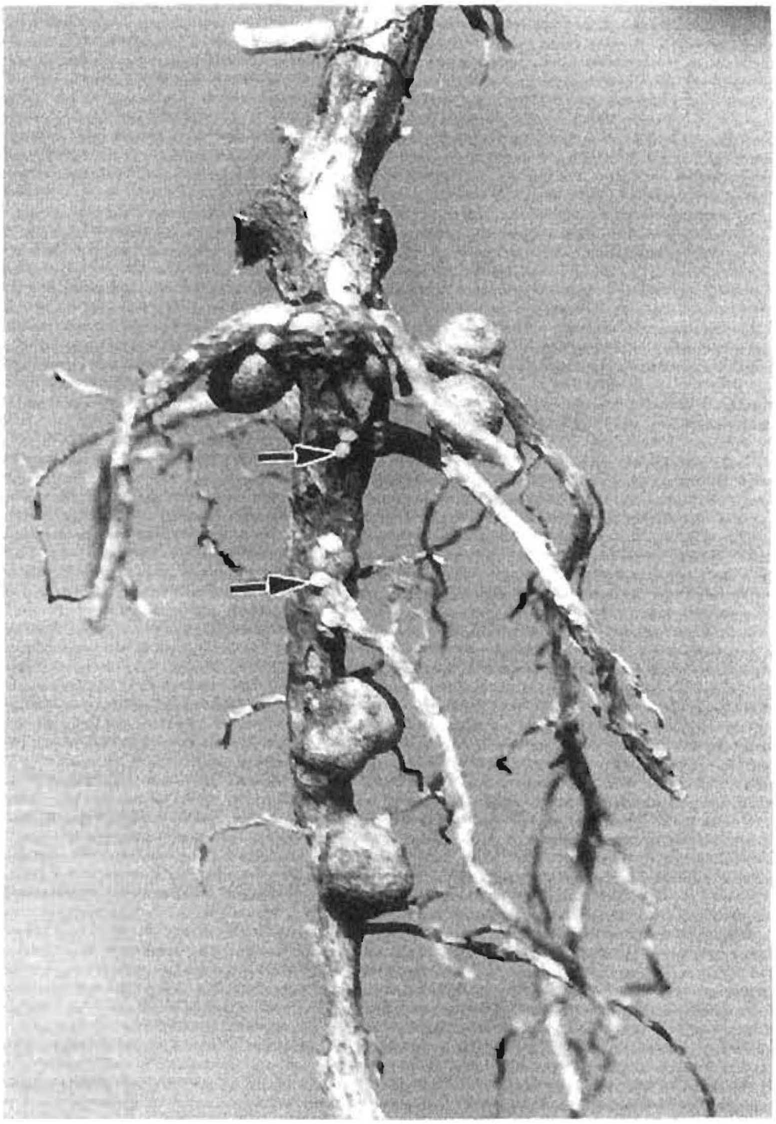


Figure 13.15. Females of the cyst nematode, *Heterodera cajani* (arrowed) on the root system of pigeonpea (ICPL 87).
Photo: ICRISAT.

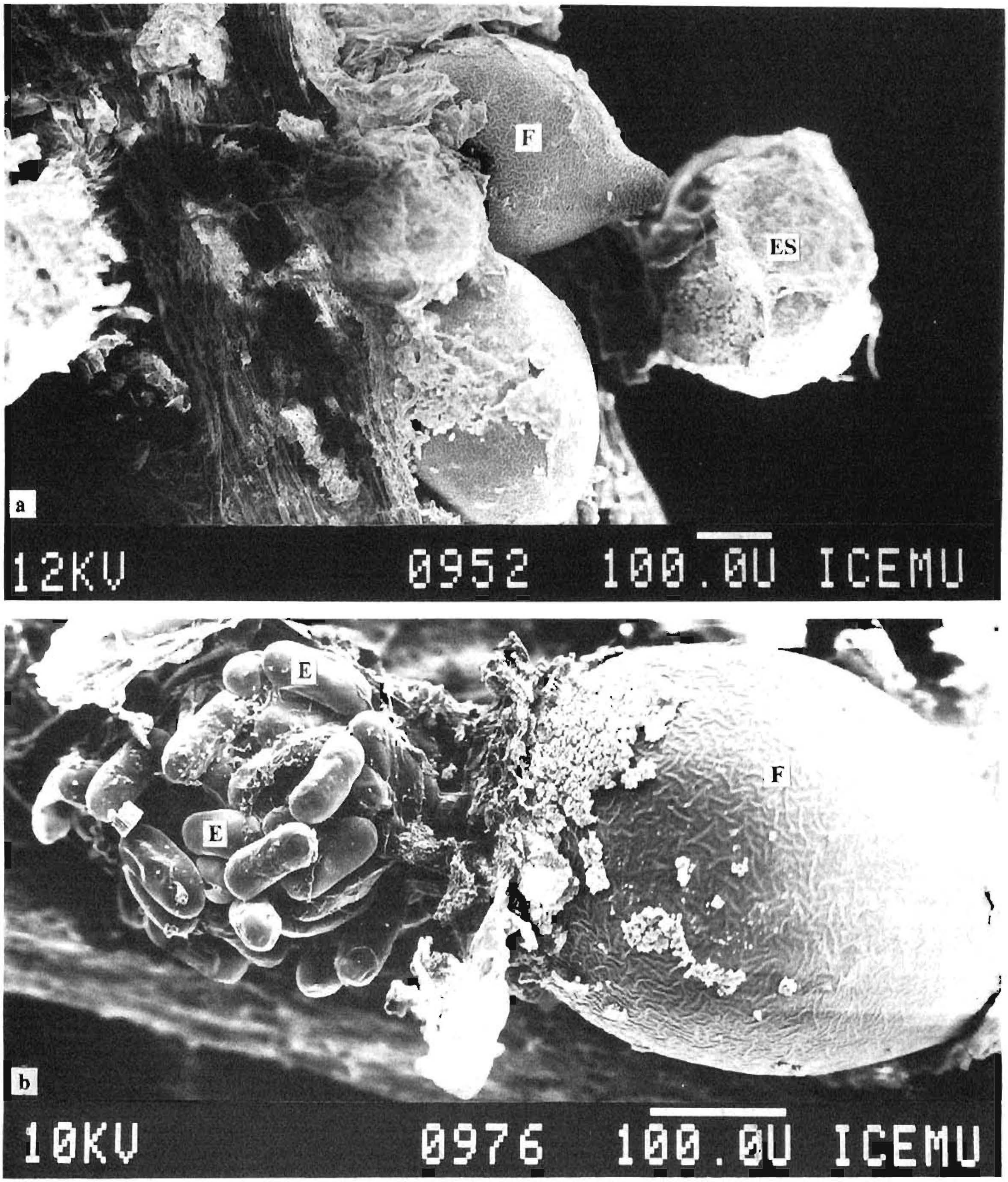


Figure 13.16. Scanning electron micrograph of cyst nematode, *Heterodera cajani*: a. Female (F) and egg-sac (ES); b. Eggs (E).

Photo: ICRISAT.

300 eggs, depending on the health of the host plant. The egg-sac generally contains one-third of the total eggs produced.

Interrelationships with other Microorganisms

Heterodera cajani enhances the pathogenicity of *Fusarium udum* in wilt-susceptible genotypes, and the fungus suppresses the reproduction of the nematode (Hasan, 1984; Sharma and Nene, 1989). The reaction of fusarium wilt resistant (ICP 8863) and tolerant (BDN 1) genotypes is not altered by the presence of the nematode. Nematode infection reduces the number of *Rhizobium* nodules on the pigeonpea, and nematodes can also infect the nodules (Sharma, 1985).

Control

Rotation with cereals such as sorghum, maize, or pearl millet will help to reduce nematode population densities. Koshy and Swarup (1972) and Sharma and Swarup (1984) have reported *Chionachne* sp, *Echinocloa colona*, *Paspalum scorbiculatum*, *Setaria italica*, *Trilobachne* sp, *Zea mays*, and *Z. mexicana* as non-hosts of *H. cajani*.

Solarizing soil by covering it with transparent polythene sheets during the summer months significantly reduces the population densities of *H. cajani* in Vertisols. Irrigation prior to covering soil with polythene significantly improves the effects of solarization (Chauhan *et al.*, 1988; Sharma and Nene, 1985b). This method may be very useful in regions where control of reniform and root-knot nematodes, and multiple pests and diseases is needed.

The use of a bacterium, *Pasteuria penetrans*, appears to be promising in controlling *H. cajani* (Sharma and Swarup, 1988).

Aldicarb ®, Carbofuran ®, fensulfothion, and phorate are effective in reducing *H. cajani* populations in the soil (Gunasekaran *et al.*, 1976; Zaki and Bhatti, 1986). These chemicals also reduce the populations of *R. reniformis* and *Meloidogyne* spp.

Reniform Nematode (*Rotylenchulus reniformis* Linford and Oliveira)

This nematode is found in 38 countries, primarily in tropical and subtropical regions of the world (Holdeman *et al.*, 1977 in Heald and Orr, 1984). It severely affects crop production in Fiji, where pigeonpea is a major subsistence and cash-earning pulse in the drier zones (Heinlein and Black, 1983).

Disease Characteristics

The most common below-ground symptom of nematode infection is the presence of soil-covered egg masses on the roots. The root-masses of infected plants are smaller than those of non-infected plants.

Morphology

Males and immature females are vermiform, but mature females are characteristically reniform. Adult males have poorly developed stylets. The oesophagus is degenerate with a reduced medium bulb and indistinct valve. Labial sclerotization and stylets are stronger in immature females than in males. A mature female can be readily identified on the root by its irregular neck, and obese and kidney-shaped body. The female produces a gelatinous matrix that covers its whole body and in which the eggs are externally deposited (Siddiqi, 1972).

Disease Cycle

This nematode has the unique ability to develop to the pre-adult infective stage through a series of three moults without feeding. Egg masses of *R. reniformis* contain up to 150 eggs. The nematode prefers to penetrate roots in the zone of elongation. The immature female feeds semi-endoparasitically, with the anterior one-third of the body inside the root. Heavy infection causes severe damage to the epidermis and cortex, and females establish feeding sites in the phloem cells. The female begins to enlarge on the ventral side around the vulval region, and continues to swell to become reniform in shape. Males are usually found close to female feeding sites. The reniform nematode is generally considered to be bisexual, with a sex ratio of 1:1, and reproduces by cross fertilization. The life cycle is completed in 24-29 days in females, and 16-20 days in males (Sivakumar and Seshadri, 1971).

Rotylenchulus reniformis can survive without any host for more than 300 days without losing its infectivity (Sharma, 1985).

Control

Application of dibromochloropropane (DBCP) (50 L ha^{-1}), metham sodium (250 L ha^{-1}), copper oxychloride (50 kg ha^{-1}), dimethoate, monocrotophos, aldicarb, thionazin (4 to 16 kg ha^{-1}), phenamiphos (10 kg ai ha^{-1}), and ethoprophos and oxamyl (2500 ppm foliar spray) have all been reported to effectively control *R. reniformis* (Singh, 1975; Sivakumar *et al.*, 1976; Reddy and Seshadri, 1972). Rotation of pigeonpea with rice or maize has been found to effectively check the nematode population build up in Fiji. *Tagetes erecta* behaved as a moderate host and did not reduce nematode populations, whereas *T. patula* reduced populations compared to those in fallow soil (Nakasono, 1973).

Pigeonpea genotypes ICP 12744, Basant, PDM 1, Norman, AGS 522, GAUT 82-75, GAUT 83-23, and GAUT 84-22 have been reported as resistant (Thakar and Yadav, 1985; Patel *et al.*, 1987a; Chavda *et al.*, 1988) in pot screening tests. However, the reaction of these genotypes in field conditions awaits confirmation.

Root-knot Nematode (*Meloidogyne* spp)

Five species of *Meloidogyne* are known to attack pigeonpea. These are *M. incognita* (Kofoid and White) Chitwood, *M. javanica* (Treub) Chitwood, *M. arenaria* (Neal) Chitwood, *M. hapla* Chitwood, and *M. acronea* Coetzee. The first two species are the most important because of their wider distribution in pigeonpea-growing regions of the world. *Meloidogyne incognita* and *M. javanica* are reported on pigeonpea in Australia, India, Malawi, Nepal, Trinidad, and USA; *M. javanica* is also reported in Brazil, Puerto Rico, Zambia, and Zimbabwe. These are hot-weather organisms, and are important in regions where summers are long and winters are short and mild. Pigeonpea yield losses due to the root-knot nematodes are estimated at 8-35% (Bridge, 1981).

Disease Characteristics

The above-ground symptoms of *Meloidogyne* spp infection are stunting, suppressed growth, chlorosis, reduction in leaf size and generally reduced plant vigour.

Production of root-knots (galls) on the root system is the most characteristic symptom of root-knot nematode attack (Figure 13.17). The size and shape of the galls vary.

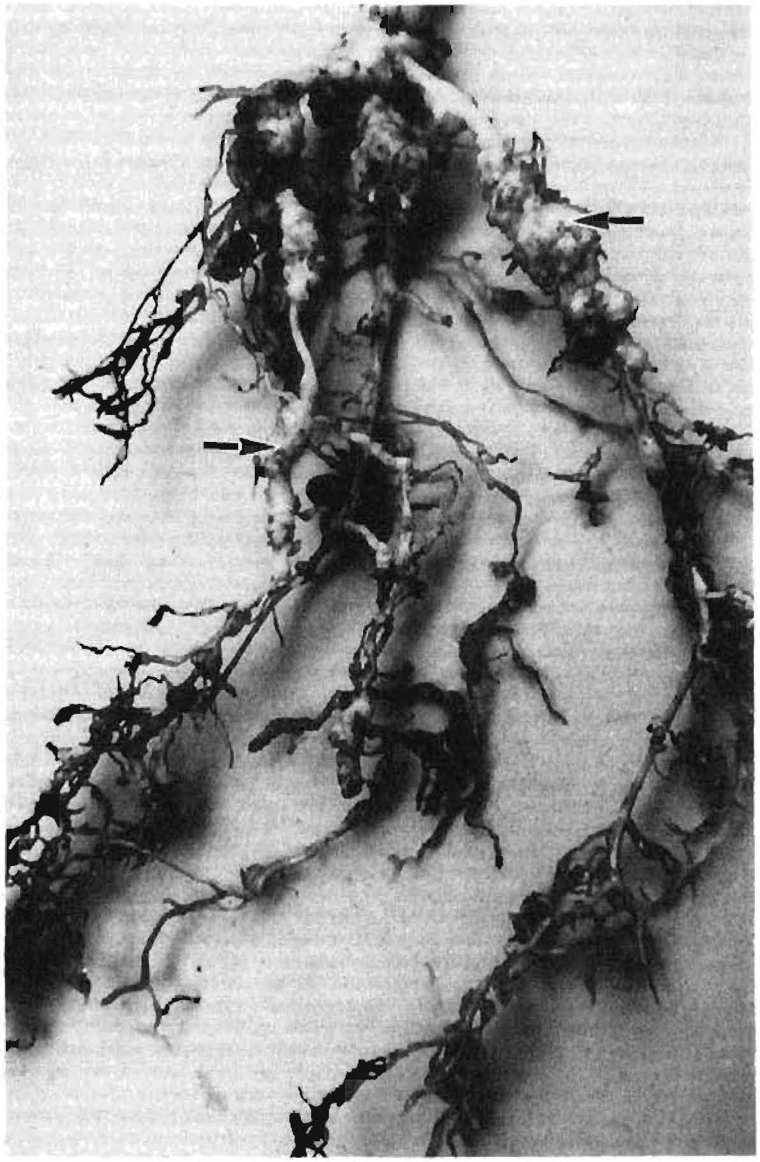


Figure 13.17. Galls (arrowed) on pigeonpea roots caused by infestations of the root-knot nematode, *Meloidogyne* spp.
Photo: ICRISAT.

Morphology

The morphology and taxonomy of these species has been described in detail by Franklin (1979) and Hirschmann (1985). *Meloidogyne* spp are sexually dimorphic. Males are vermiform, and females obese and pyriform in shape. The root-knot species *(M. arenaria, M. incognita, M. javanica,* and *M. hapla)* can be differentiated by the morphology of their perineal pattern, female stylets, male heads and stylets, and second-stage juveniles (Eisenback, 1985).

Disease Cycle

The one-celled egg passes through embryogenesis, resulting in a first-stage juvenile within the egg. The first moult takes place inside the egg, and the infective second-stage juvenile hatches out of the egg shell. The juvenile penetrates the roots and migrates through the root cells to reach the vascular system where it starts feeding. The feeding cells are called giant cells. The second-stage juvenile begins to swell and moult. Third and fourth stage juveniles do not posses a stylet but this reappears when the nematode undergoes its final moult. The nematode remains sedentary during feeding. The male is a sedentary parasite only during its juvenile development, and emerges as a slender worm possessing a stylet, oesophagous with a median bulb, spicules, and sperms in the testes. The male is generally not involved in reproduction. Adult females extrude a gelatinous matrix into which 200 to 500 eggs are deposited. The total duration of the life cycle under optimum conditions (25 to 30°C temperature) is 3 to 4 weeks.

Interrelationships with *Fusarium udum*

Root-knot nematode infection increases fusarium wilt incidence; *F. udum* causes more reduction in plant growth in the presence of both *M. javanica* and *M. incognita*. Resistance in wilt-resistant pigeonpea ICP 8863 to *F. udum* is moderated by the presence of root-knot nematodes (Sharma and Nene, unpublished).

Control

In Brazil a pigeonpea-wheat cropping system has been found to check the nematode population. Several lines of pigeonpea resistant to *Meloidogyne* spp. have been reported (Hasan and Khan, 1983; Patel *et al.*, 1987b; Sasser and Hartman, 1985; Sasser *et al.*, 1987; Thaker and Patel, 1985).

FUTURE

Though considerable progress has been made on some of the important diseases such as SM, wilt, and PB, a lot more needs to be done. For example, the causal agent of SM, which is the most important disease of pigeonpea, is not yet known. The epidemiology of the disease is also not completely understood. The pathogen and vector are known to survive in the summer on perennial, summer, and ratooned pigeonpeas. The role played by these off-season pigeonpeas in the spread of the disease in the main cropping season needs to be fully understood. The role of *C. scarabaeoides* var. *scarabaeoides* in the epidemiology of SM is not yet fully established. The reasons for large variations in the incidence of SM in different crop seasons need to be found out. Although high levels of resistance to SM are available, the nature of this resistance is not yet understood. The resistance sources need to be fully exploited by developing lines with high yield and SM resistance in short-, medium- and long-duration pigeonpea cultivars.

In fusarium wilt, the ecology of the disease needs to be studied further, It is known that the incidence of the disease varies from one location to another and depends on soil type, but the reasons for such a variation are not understood. Delayed sowings result in reduced wilt incidence but the reasons for this are not clear. The effect of irrigation and other agronomic inputs such as crop rotations and weeding on wilt incidence need to be studied. The variability in the pathogen, mechanism of resistance in the host, and genetics of resistance need to be better understood. The reasons for loss in tolerance of the plant with age to wilt are not experimentally established. Considerable scope exists for the integrated management of wilt using host resistance and cultural practices such as crop rotations, mixed cropping, adjustment of sowing time, etc.

In PB, there is a need to further understand the epidemiology of the disease and the variability in the pathogen, as well as identification of stable sources of resistance to the disease. Though it is clear that the pathogen can survive in the soil from one season to another, the mode by which it survives needs further investigation. Also, there is no explanation for the appearance of the disease in a field where pigeonpea has not been grown for the past several years.

There is hardly any information on witches' broom disease. The causal agent, vectors, disease cycle, and control measures need to be established. More work on foliar diseases caused by *Cercospora* and *Alternaria*, and root rot and stem canker caused by *Macrophomina phaseolina* needs to be undertaken.

The distribution and economic losses caused by nematodes need to be studied before control measures can be developed.

There is hardly any directed effort on the development of integrated control measures for the major diseases. Control measures have only been worked out for individual diseases. There is need to integrate control measures because more than one disease often occurs in the same field. Genetic sources of resistance to individual and multiple diseases are available. There is need to utilize these resistance sources, and to develop high-yielding cultivars with multiple disease resistances.

REFERENCES

Agrawal, S.C. (1987) Fungicidal control of stem blight of pigeonpea caused by *Phytophthora drechsleri* Tucker f.sp. *cajani*. *Indian Journal of Plant Protection* 15(1), 35-37.

Agrawal, S.C. and Khare, M.N. (1988) Survival of *Phytophthora drechsleri* f. sp. *cajani* causing stem blight of pigeonpea. *Indian Phytopathology* 41, 250-251.

Alam, M. (1931) *Administration Report of the Botanical Section, 1930-31*. Department of Agriculture, Bihar and Orissa, India, pp. 42-65.

Alam, M. (1933) Rahar sterility. *Proceedings of the Twentieth Annual Meeting of the Indian Science Congress, Poona, Section Agriculture* 43, 15-16.

Amin, K.S., Baldev, B. and Williams, F.J. (1976) Differentiation of Phytophthora stem blight from Fusarium wilt of pigeonpea by field symptoms. *FAO Plant Protection Bulletin* 24, 123-124.

Amin, K.S., Baldev, B. and Williams, F.J. (1978) *Phytophthora cajani*, a new species causing stem blight on *Cajanus cajan*. *Mycologia* 70, 171-176.

Anonymous (1948) Report of the Division of Mycology. *Scientific Reports of the Indian Agricultural Research Institute (IARI), 1945-46*. IARI, New Delhi, India, pp. 79-88.

Anonymous (1951) Report of the Division of Mycology and Plant Pathology. *Scientific Reports of the Indian Agricultural Research Institute (IARI), 1948-49*. IARI, New Delhi, India, pp. 177-190.

Anonymous (1954a) Agricultural Research. *Report, Indian Council of Agricultural Research (ICAR), 1951-52*. ICAR, New Delhi, India, pp. 11-53.

Anonymous (1954b) Report of the Division of Mycology and Plant Pathology. *Scientific Reports of the Indian Agricultural Research Institute (IARI), 1952-53*. IARI, New Delhi, India, pp. 78-89.

Anonymous (1955) Report of the Division of Mycology and Plant Pathology. *Scientific Reports of the Indian Agricultural Research Institute (IARI), 1953-54*. IARI, New Delhi, India, pp. 87-99.

Anonymous (1965) Improved crop varieties and their yields. *Indian Farming* 15(2), 35-40.

Anonymous (1976) Focus on agricultural research–Marathwada Agricultural University. *Pesticides* 10(2), 17-18.

Ashby, S.C. (1927) *Macrophomina phaseoli* (Maubl.) Comb. Nov: the pycnidial stage of *Rhizoctonia bataticola* (Taub.) Butl. *Transactions of the British Mycological Society* 12, 141-147.

Baldev, B. and Amin, K.S. (1974) Studies on the existence of races in *Fusarium udum* causing wilt of *Cajanus cajan*. *SABRAO Journal* 6, 201-205.

Barrett, O.W. (1925) The food plants of Puerto Rico, 1925. *Journal of the Department of Agriculture, Puerto Rico* 9, 61-208.

Beniwal, S.P.S., Deena, E. and Nene, Y.L. (1983) Effect of yellow mosaic on yield and its components in postrainy-season pigeonpea. *International Pigeonpea Newsletter* 2, 48.

Bhargava, P.K. and Gupta, R.K. (1983) Reaction of pigeonpea varieties to Phytophthora stem necrosis in field. *JNKVV Research Journal* 17(3/4), 301-303.

Bhargava, R.N. (1975) Two new varieties of arhar for Bihar. *Indian Farming* 25(1), 23.

Bhaskaran, K. (1954) Crops and crop improvement in Hyderabad. *Agricultural College Journal, Osmania University* 1, 60-63.

Bhatti, D.S. and Gupta D.C. (1973) Guar an additional host of *Heterodera cajani*. *Indian Journal of Nematology* 3, 160.

Bisht, V.S. (1985) *Phytophthora Blight–Recent Studies. Pigeonpea Pathology Progress Report*. Patancheru, A.P., India: Legumes Program, ICRISAT, 44 pp. (Limited distribution).

Bisht, V.S., Kannaiyan, J. and Nene, Y.L. (1988) Methods of metalaxyl application to control Phytophthora blight of pigeonpea. *International Pigeonpea Newsletter* 8, 9-11.

Bisht, V.S. and Nene, Y.L. (1988) A selective medium for *Phytophthora drechsleri* f. sp. *cajani* causing pigeonpea blight. *International Pigeonpea Newsletter* 8, 12-13.

Booth, C. (1971) *The Genus Fusarium*. Commonwealth Mycological Institute, Kew, UK, p. 114.

Bose, R.D. (1938) The rotation of tobacco for the prevention of wilt disease in pigeonpeas (*Cajanus cajan* [L.] Millsp.). *Agriculture and Livestock in India* 8, 653-668.

Brathwaite, C.W.D. (1981) Diseases of pigeonpea in the Caribbean area. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 129-136.

Bridge, J.C. (1981) Nematodes. In: *Pest Control in Tropical Grain Legumes*. Center for Overseas Pest Research, ODA, London, pp. 111-125.

Butler, E.J. (1906) The wilt disease of pigeonpea and pepper. *Agricultural Journal of India* 1, 25-36.

Butler, E.J. (1908) Selection of pigeonpea for wilt disease. *Agricultural Journal of India* 3, 182-183.

Butler, E.J. (1910) The wilt disease of pigeonpea and the parasitism of *Neocosmospora vasinfecta* Smith. *Memoirs of the Department of Agriculture in India, Botanical Series* 2, 1-64.

Butler, E.J. (1926) The wilt disease of cotton and sesamum in India. *Agricultural Journal of India* 21, 268-273.

Capoor, S.P. (1952) Observations on the sterility disease of pigeonpea in Bombay. *Indian Journal of Agricultural Sciences* 22, 271-274.

Chadha, K.C. and Raychaudhuri, S.P. (1965) Interaction between sterility virus and *Fusarium udum* Butl. in pigeonpea. *Indian Journal of Agricultural Sciences* 36, 133-139.

Chari, S.K.V.K., Kannaiyan, J., Nene, Y.L. and Nunn, E.W. (1984) Technique to detect infection by *Fusarium udum* in pigeonpea before symptom appearance. *Tropical Agriculture (Trinidad)* 61, 257-260.

Chattopadhyay, S.B. and Sen Gupta, P.K. (1967) Studies on wilt diseases of pulses. I: Variation and taxonomy of *Fusarium* species associated with wilt disease of pulses. *Indian Journal of Mycological Research* 5, 45-53.

Chaube, H.S. (1968) Combating diseases of arhar and gram. *Indian Farmers' Digest* 1, 26-27.

Chaube, H.S., Razdan, V.K. and Singh, U.S. (1987a) Effect of metalaxyl on growth, sporulation, and sporangial germination of *Phytophthora drechsleri* f. sp. *cajani*. *International Pigeonpea Newsletter* 6, 59-61.

Chaube, H.S., Singh, U.S., Razdan, V.K. and Kumar, S. (1987b) Studies on uptake, translocation, distribution and persistence of ^{14}C-metalaxyl in pigeonpea. *Indian Phytopathology* 40, 507-513.

Chaube, H.S., Singh, U.S. and Sinha, P.K. (1984) Translocation and persistence of metalaxyl in pigeonpea. *Indian Journal of Agricultural Sciences* 54, 777-779.

Chaudhuri, S. and Ahmed, T. (1977) Fungicides for the control of Rhizoctonia seedling blight of pigeonpea. *Pesticides* 11(8), 23-25.

Chauhan, Y.S., Nene, Y.L., Johansen, C., Haware, M.P., Saxena, N.P., Sardar Singh, Sharma, S.B., Sahrawat, K.L., Burford, J.R., Rupela, O.P., Kumar Rao, J.V.D.K. and Sithanantham, S. (1988) *Effect of Soil Solarization on Pigeonpea and Chickpea. Research Bulletin no. 11*. Patancheru, A.P., India: ICRISAT, 16 pp.

Chavda, J.C., Patel, B.A. and Patel, D.J. (1988) Screening of pigeonpea lines to *Rotylenchulus reniformis*. *International Nematology Network Newsletter* 5(3), 28-29.

Dastur, J.F. (1946) Report of the Imperial Mycologist. *Scientific Reports of the Indian Agricultural Research Institute (IARI), 1944-45.* IARI, New Delhi, India, pp. 66-72.

Deshpande, R.B., Jeswani, L.M. and Joshi, A.B. (1963) Breeding of wilt resistant varieties of pigeonpea. *Indian Journal of Genetics and Plant Breeding* 23, 58-63.

Dey, P.K. (1947) *Plant Pathology Report, 1944-45.* Department of Agriculture, Uttar Pradesh, India, pp. 38-40.

Eisenback, J.D. (1985) Diagnostic characters useful in the identification of the four most common species of root-knot nematodes (*Meloidogyne* spp.). In: Sasser, J.N. and Carter C.C. (eds), *An Advanced Treatise on Meloidogyne, volume 1, Biology and Control.* North Carolina State University Graphis, Releigh, North Carolina, USA, pp. 95-112.

Ellis, M.A., Paschal II, E.H., Ravalo, E.J. and Rosario, E. 1978. Effect of growing location on internally seed-borne fungi, seed germination, and field emergence of pigeonpea in Puerto Rico. *Journal of Agriculture of the University of Puerto Rico* 62, 355-360.

Franklin, M.T. (1979) Taxonomy of the genus *Meloidogyne.* In: Lamberti, F. and Taylor, C.E. (eds), *Root-knot Nematodes (Meloidogyne species); Systematics, Biology and Control.* Academic press, London, pp. 37-54.

Gaikwad, B.M. and Kore, S.S. (1981) Bacterial leaf spot and stem canker of pigeonpea *(Cajanus cajan)* caused by *Xanthomonas cajani. Indian Journal of Mycology and Plant Pathology* 11, 50-56.

Gunasekaran, C.R., Muthukrishnan, T.S. and Rajendran, G. (1976) Evaluation of chemicals for controlling pigeonpea cyst nematode *Heterodera cajani* in red gram. *Madras Agricultural Journal* 63, 382-383.

Gupta, A.D. and Sen Gupta, P.K. (1988) Reaction of pigeonpea *(Cajanus cajan)* lines to wilt pathogen, *Fusarium udum. Indian Journal of Agricultural Sciences* 58, 586-548.

Gupta, Om, Kotasthane, S.R. and Khare, M.N. (1988) Strain variation in *Fusarium udum* in Madhya Pradesh, India. *International Pigeonpea Newsletter* 7, 22-25.

Gupta, S.L. (1961) The effect of mixed cropping of arhar (*Cajanus indicus* Spreng.) with jowar (*Sorghum vulgare* Pers.) on incidence of arhar wilt. *Agriculture and Animal Husbandry in Uttar Pradesh* 3(10-12), 31-35.

Haque, M.F., Jha, D.K., Mukherjee, A.K., van der Maesen, L.J.G. and Kannaiyan, J. (1984) Evaluation of ICRISAT germplasm for wilt incidence in the plateau region of Chota Nagpur in India. *International Pigeonpea Newsletter* 3, 36-37.

Hasan, A. (1984) Synergism between *Heterodera cajani* and *Fusarium udum* attacking *Cajanus cajan. Nematologia Mediterranea* 12, 159-162.

Hasan, A. and Khan, A.M. (1983) Resistance of some pigeonpea cultivars to root-knot nematode. *International Pigeonpea Newsletter* 2, 56.

Heald, C.M. and Orr, C.C. (1984) Nematode parasites of cotton. In: Nickle, R.W. (ed), *Plant and Insect Nematodes.* Marcel Dekker, Inc., New York, pp. 147-166.

Heinlein, M. and Black, I.D. (1983) The use of fallows, planting techniques and nematicide application for control of *Rotylenchulus reniformis* in pigeonpeas. *Fiji Agricultural Journal* 45, 35-42.

Hirschmann, H. (1985) The classification of the family Meloidogynidae. In: Sasser, J.N. and Carter, C.C. (eds), *An Advanced Treatise on Meloidogyne, volume 1, Biology and Control.* North Carolina State University Graphics, Raleigh, North Carolina, USA, pp. 35-45.

Hirumi, H., Maramorosch, K. and Hichez, E. (1973) Rhabdovirus and mycoplasma-like organism: natural dual infection of *Cajanus cajan. Phytopathology* 63, 202 (Abstract).

IARI (1946) *Scientific Reports of the Indian Agricultural Research Institute (IARI), 1945-46.* IARI, New Delhi, India, 109 pp.

IARI (1948) *Scientific Reports of the Indian Agricultural Research Institute (IARI), 1947-48.* IARI, New Delhi, India, 182 pp.

IARI (1953) *Scientific Reports of the Indian Agricultural Research Institute (IARI), 1950-51.* IARI, New Delhi, India, 120 pp.

ICRISAT (1987) *Annual Report 1986.* Patancheru, A.P. India: ICRISAT, p. 177.

Jackson, P.E. (1976) Gungo peas *(Cajanus cajan). Bulletin, Ministry of Agriculture and Fisheries, Jamaica, New Series* 64, 164-166.

Janarthanan, R., Navaneethan, G., Subramanian, K.S. and Samuel, G.S. (1972) Some observations on the transmission of sterility mosaic of pigeonpea. *Current Science* 41, 646-647.

Joshi, A.B. (1957) Genetics of resistance to diseases and pests. *Indian Journal of Genetics and Plant Breeding* 17, 305-317.

Kandaswamy, T.K. and Ramakrishnan, K. (1960) An epiphytotic of pigeonpea sterility mosaic at Coimbatore. *Madras Agricultural Journal* 47, 440-441.

Kannaiyan, J., Jain, K.C., Raju, T.N. and Nene, Y.L. (1983a) Wilt resistance sources in vegetable pigeonpea. *International Pigeonpea Newsletter* 2, 42-43.

Kannaiyan, J., Jain, K.C., Raju, T.N. and Nene, Y.L. (1983b) Sclerotium blight of pigeonpea. *International Pigeonpea Newsletter* 2, 51-52.

Kannaiyan, J. and Nene, Y.L. (1981) Influence of wilt at different growth stages on yield loss in pigeonpea. *Tropical Pest Management* 27, 141.

Kannaiyan, J. and Nene, Y.L. (1984) Efficacy of metalaxyl for control of Phytophthora blight of pigeonpea. *Indian Phytopathology* 37, 506-510.

Kannaiyan, J. and Nene, Y.L. (1985a) Effect of sowing date on wilt incidence in pigeonpea. *International Pigeonpea Newsletter* 4, 33.

Kannaiyan, J. and Nene, Y.L. (1985b) *Atylosia scarabaeoides*, an alternative host to *Phytophthora drechsleri* f. sp. *cajani. International Pigeonpea Newsletter* 4, 35-36.

Kannaiyan, J., Nene, Y.L., Raju, T.N. and Sheila, V.K. (1981a) Screening for resistance to Phytophthora blight of pigeonpea. *Plant Disease* 65, 61-62.

Kannaiyan, J., Nene, Y.L. and Reddy, M.V. (1981b) Survival of pigeonpea wilt *Fusarium* in Vertisols and Alfisols. In: *Proceedings of the International Workshop on Pigeonpeas, volume 2, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 291-295.

Kannaiyan, J., Nene, Y.L., Reddy, M.V., Ryan, J.G. and Raju, T.N. (1984) Prevalence of pigeonpea diseases and associated crop losses in Asia, Africa and the Americas. *Tropical Pest Management* 30(1), 62-71.

Kannaiyan, J., Nene, Y.L. and Sheila, V.K. (1980a) Control of mycoflora associated with pigeonpea seeds. *Indian Journal of Plant Protection* 8, 93-98.

Kannaiyan, J., Raju, T.N. and Nene, Y.L. (1983c) Survival of pigeonpea Phytophthora blight fungus in infected stubble. *International Pigeonpea Newsletter* 2, 49-50.

Kannaiyan, J., Ribeiro, O.K., Erwin, D.C. and Nene, Y.L. (1980b) Phytophthora blight of pigeonpea in India. *Mycologia* 72(1), 169-181.

Khune, N.N. and Kapoor, J.N. (1981) A new disease of pigeonpea. *Indian Phytopathology* 34, 258-260.

Konda, C.R., Parameswarappa, R. and Rao, T.S. (1986) Pigeonpea ICP 8863 - a boon to Fusarium wilt endemic areas of Karnataka. *International Pigeonpea Newsletter* 5, 36-37.

Koshy, P.K. (1967) A new species of *Heterodera* from India. *Indian Phytopathology* 20, 272-274.

Koshy, P.K. and Swarup, G. (1971) On the number of generations of *Heterodera cajani*, the pigeonpea cyst nematode in a year. *Indian Journal of Nematology* 1, 88-90.

Koshy, P.K. and Swarup, G. (1972) Susceptibility of plants to pigeonpea cyst nematode, *Heterodera cajani*. *Indian Journal of Nematology* 2, 1-6.

Koshy, P.K. and Swarup, G. (1979) Histopathology of pigeonpea roots infested with *Heterodera cajani* Koshy, 1967. *Indian Journal of Nematology* 9, 178-179.

Kulkarni, Y.S, Patel, M.K. and Abhyankar, S.G. (1950) A new bacterial leaf spot and stem canker on pigeonpea. *Current Science* 19, 384.

Maramorosch, K., Hirumi, H., Kimura, M., Bird, J. and Vakili, N.G. (1974) Pigeonpea witches' broom disease. *Phytopathology* 64, 582-583 (Abstract).

Mathur, R.S. (1954) Diseases of pulse crops in Uttar Pradesh. *Agriculture and Animal Husbandry in India* 5, 24-28.

McCoy, R.E., Tsai, J.H., Norris, R.C. and Gwin, G.H. (1983) Pigeonpea witches' broom in Florida. *Plant Disease* 67, 443-445.

McRae, W. (1923) Report of the Imperial Mycologist. *Scientific Reports of the Agricultural Research Institute, Pusa, 1922-23*. Pusa, India, pp. 53-60.

McRae, W. (1924) Report of the Imperial Mycologist. *Scientific Reports of the Agricultural Research Institute, Pusa, 1923-24*. Pusa, India, pp. 41-51.

McRae, W. (1926) Report of the Imperial Mycologist. *Scientific Reports of the Agricultural Research Institute, Pusa, 1925-26*. Pusa, India, pp. 54-69.

McRae, W. (1928) Report of the Imperial Mycologist. *Scientific Reports of the Agricultural Research Institute, Pusa, 1926-27.* Pusa, India, pp. 45-55.

McRae, W. (1932) Report of the Imperial Mycologist. *Scientific Reports of the Agricultural Research Institute, Pusa, 1930-31*. Pusa, India, pp. 73-86.

McRae, W. and Shaw, F.J.W. (1933) Influence of manures on the wilt disease of *Cajanus indicus* Spreng, and isolation of types resistant to the disease. Part II. The isolation of resistant types. *Scientific Monograph, Imperial Council of Agricultural Research, Pusa 7.* Pusa, India, pp. 37-68.

Mehta, P.P. and Sinha, R.K.P. (1982) A new leaf spot disease of arhar from India. *Science and Culture* 48, 44.

Mishra, A.N. and Shukla, P. (1986a) Relation between the age of pigeonpea plant and its susceptibility to Phytophthora blight. *Indian Journal of Mycology and Plant Pathology* 16, 292.

Mishra, A.N. and Shukla, P. (1986b) Screening of pigeonpea germplasms against Phytophthora blight. *Farm Science Journal* 1(1-2), 84-85.

Mishra, D.P. and Gurha, S.N. (1980) Losses due to yellow mosaic in winter crop of pigeonpea in India. *Tropical Grain Legume Bulletin* 19, 18-19.

Mitra, M. (1925) Report of the Imperial Mycologist. *Scientific Reports of the Agricultural Research Institute, Pusa, 1924-25*. Pusa, India, pp. 45-57.

Mitra, M. (1931) Report of the Imperial Mycologist. *Scientific Reports of the Agricultural Research Institute, Pusa, 1929-30*. Pusa, India, pp. 58-71.

Mohammed, Caroline L. (1978) Preliminary investigation in pigeonpea rust, *Uredo cajani* Syd. MSc thesis, University of West Indies, St. Augustine, Trinidad, Trinidad and Tobago, 190 pp.

Mundkur, B.B. (1935) Influence of temperature and maturity on the incidence of sunnhemp and pigeonpea wilt at Pusa. *Indian Journal of Agricultural Sciences* 5, 606-618.

Mundkur, B.B. (1946) Report of the Imperial Mycologist. *Scientific Reports of the Indian Agricultural Research Institute (IARI), 1944*. IARI, New Delhi, India, pp. 57-63.

Muniyappa, V. and Nangia, N. (1982) Pigeonpea cultivars and selections for resistance to sterility mosaic in relation to the prevalence of eriophyid mite *Aceria cajani* Channabasavanna. *Tropical Grain Legume Bulletin* 25, 28-30.

Nakasono, K. (1973) Relationship between cultivation of *Tagetes* plants and changes in population of the reniform nematode, *Rotylenchulus reniformis*. *Japanese Journal of Nematology* 3, 38-41.

Narayanaswamy, P. and Jaganathan, T. (1975) A note on a powdery mildew disease of pigeonpea (*Cajanus cajan* [L.] Millsp.). *Science and Culture* 41, 133-134.

Natarajan, M., Kannaiyan, J., Willey, R.W. and Nene, Y.L. (1985) Studies on the effects of cropping system on fusarium wilt of pigeonpea. *Field Crops Research* 10, 333-346.

Nene, Y.L. (1972) *A Survey of Viral Diseases of Pulse Crops in Uttar Pradesh. Research Bulletin no. 4.* Govind Ballabh Pant University of Agriculture and Technology, Pantnagar, Uttar Pradesh, India, 191 pp.

Nene, Y.L. (1988) Multiple-disease resistance in grain legumes. *Annual Review of Phytopathology* 26, 203-217.

Nene, Y.L., Kaiser, W.J., Grewal, J.S., Kannaiyan, J. and Beniwal, S.P.S. (1985) *An Annotated Bibliography of Pigeonpea Diseases 1906-81*. Patancheru, A.P., India: ICRISAT, 111 pp.

Nene, Y.L. and Kannaiyan, J. (1982) Screening pigeonpea for resistance to Fusarium wilt. *Plant Disease* 66, 306-307.

Nene, Y.L., Kannaiayan, J., Haware, M.P. and Reddy, M.V. (1980) Review of the work done at ICRISAT on soil-borne diseases of pigeonpea and chickpea. In: *Proceedings of the Consultants'*

Group Discussion on the Resistance to Soilborne Diseases of Legumes, 8-11 January 1979, ICRISAT Center, India. Patancheru, A.P., India: ICRISAT, pp. 3-39.

Nene, Y.L., Kannaiyan, J. and Reddy, M.V. (1981a) *Pigeonpea Diseases: Resistance-Screening Techniques. Information Bulletin no.* 9. Patancheru, A.P., India: ICRISAT, 14 pp.

Nene, Y.L., Kannaiyan, J., Reddy, M.V. and Remanandan, P. (1981b) *Sources of Resistance to Selected Pigeonpea Diseases. Pulse Pathology Progress Report 16*. Patancheru, A.P., India: Legumes Program, ICRISAT (Limited distribution).

Nene, Y.L., Kannaiyan, J., Reddy, M.V., Zote, K.K., Mahmood, M., Hiremath, R.V., Shukla, P., Kotasthane, S.R., Sengupta, K., Jha, D.K., Haque, M.F., Grewal, J.S. and Pal, M. (1989a) Multilocational testing of pigeonpea for broad-based resistance to fusarium wilt in India. *Indian Phytopathology* 42, 449–453.

Nene, Y.L. and Reddy, M.V. (1976a) A new technique to screen pigeonpea for resistance to sterility mosaic. *Tropical Grain Legume Bulletin* 5, 23.

Nene, Y.L. and Reddy, M.V. (1976b) Screening for resistance to sterility mosaic of pigeonpea. *Plant Disease Reporter* 60, 1034-1036.

Nene, Y.L., Reddy, M.V., Beniwal, S.P.S., Mahmood, M., Zote, K.K., Singh, R.N. and Sivaprakasam, K. (1989b) Multilocational testing of pigeonpea for broad-based resistance to sterility mosaic in India. *Indian Phytopathology* 42, 444–448.

Nene, Y.L., Sheila, V.K. and Sharma, S.B. (1989c) *A World List of Chickpea (Cicer arietinum L.) and Pigeonpea (Cajanus cajan L.) Millsp.) Pathogens. Legumes Pathology Progress Report-7.* Patancheru, A.P., India: ICRISAT, 23 pp.

Newton, W. and Peiris, J.W.L. (1953) Virus diseases of plants in Ceylon. *FAO Plant Protection Bulletin* 2(2), 17-21.

Onim, J.F.M. (1980) Foliar fungicides for the control of *Mycovellosiella cajani* causing the leaf spot of pigeonpea. *Indian Journal of Agricultural Sciences* 50, 615-619.

Onim, J.F.M. and Rubaihayo, P.R. (1976) Screening pigeonpea for resistance to *Mycovellosiella cajani*. *SABRAO Journal* 8, 121-125.

Padwick, G.W. (1940) The genus *Fusarium*. V. *Fusarium udum* Butler, *F. vasinfectum* Atk. and *F. lateritium* Nees var. *uncinatum* Wr. *Indian Journal of Agricultural Sciences* 10, 863-878.

Pal, M. and Grewal, J.S. (1975) Resistance of pigeonpea to Phytophthora blight–1. Total phenolic content. *Indian Phytopathology* 28, 559-560.

Pal, M. and Grewal, J.S. (1983) Chemical control of Phytophthora blight of pigeonpea. *Indian Phytopathology* 36, 380-381.

Pal, M., Grewal, J.S. and Sarbhoy, A.K. (1970) A new stem rot of arhar caused by *Phytophthora*. *Indian Phytopathology* 23, 583-587.

Parameswarappa, R., Rao, T.S. and Konda, C.R. (1987) ICPL 270: a high-yielding, wilt-resistant pigeonpea variety. *International Pigeonpea Newsletter* 6, 20.

Parameswarappa, R., Rao, T.S., Konda, C.R., Rao, T.M., Raghumurthy, M., Emmimath, V.S. and Sangappa, H.K. (1986) Maruthi - a wilt resistant redgram variety. *Current Research, University of Agricultural Sciences, Bangalore* 15(7/8), 69-70.

Patel, B.A., Chavda, J.C., Patel, S.T. and Patel, D.J. (1987a) Reaction of some pigeonpea lines to reniform nematode (*Rotylenchulus reniformis*). *International Pigeonpea Newsletter* 6, 57-59.

Patel, B.A., Chavda, J.C., Patel, S.T. and Patel, D.J. (1987b) Susceptibility of some pigeonpea lines to root-knot nematodes (*Meloidogyne incognita* and *M. javanica*). *International Pigeonpea Newsletter* 6, 55-57.

Patel, J.A., Nafde, S.D., Patel, D.B., Zaveri, P.P. and Pathak, A.R. (1988) Field screening of pigeonpea lines for resistance to wilt at Vadodara, Gujarat, India. *International Pigeonpea Newsletter* 7, 27-28.

Patil, B.G. and Sable, J.E. (1973) A note on the screening of tur against wilt disease. *Punjabrao Krishi Vidyapeeth Research Journal* 2, 73-76.

Pavgi, M.S. and Singh, R.A. (1971) Parasitic fungi from North India-VIII. *Mycopathologia et Mycologia Applicata* 43, 117-125.

Pawar, N.B. and Mayee, C.D. (1986) Reaction of pigeonpea genotypes and their crosses to Fusarium wilt. *Indian Phytopathology* 39, 70-74.

Plymen, F.J. (1933) *Report of the Department of Agriculture, Central Provinces, Nagpur, 1932-33.* Department of Agriculture, Nagpur, India, 40 pp.

Rai, B. and Upadhyay, R.S. (1979) Discovery of perfect state of *Fusarium udum* Butler. *Proceedings of the Annual Conference of the Society for Advance Botany* 5, 25 (Abstract).

Rai, M. and Singh, D.V. (1986) Survival and virulence of *Xanthomonas campestris* pv. *cajani* in debris, seed, soil and *in vitro*. *Indian Phytopathology* 39, 467-469.

Ramakrishnan, K. and Kandaswamy, T.K. (1972) *Investigations on Virus Diseases of Pulse Crops in Tamil Nadu: Final Technical Report.* Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu, India, 53 pp.

Rathi, Y.P.S. (1979) Temik treatment of pigeonpea seeds for prevention of sterility mosaic. *Acta Botanica Indica* 7(1), 90-91.

Raut, N.K. and Bhombe, B.B. (1971) A review of the work selection of tur varieties resistant to Fusarium wilt at College of Agriculture, Parbhani (MS). *Magazine, College of Agriculture, Parbhani* 12, 37-42.

Ravishanker (1936) Isolation of wilt-resistant tur. *Nagpur Agriculture College Magazine* 10, 162-167.

Reddy, D.D.R. and Seshadri, A.R. (1972) Studies on some systemic nematicides. II.Further studies on the action of thionazin and aldicarb on *Meloidogyne incognita* and *Rotylenchulus reniformis*. *Indian Journal of Nematology* 2, 182-190.

Reddy, M.V., Beniwal, S.P.S., Sheila, V.K., Sithanantham, S. and Nene, Y.L. (1989) Role of an eriophyid mite *Aceria cajani* (Acari: Eriophyidae) in transmission and spread of sterility mosaic of pigeonpea. In: Channabasavanna, G.P. and Viraktamath, C.A. (eds), *Progress in Acarology.* Oxford and IBH Publishing Co. Pvt. Ltd., New Delhi, India, pp. 121-127.

Reddy, M.V., Kannaiyan, J. and Nene, Y.L. (1984) Increased susceptibility of sterility mosaic infected pigeonpeas to powdery mildew. *International Journal of Tropical Plant Diseases* 2, 35-40.

Reddy, M.V. and Nene, Y.L. (1979) Ring spot symptom: a genotypic expression of pigeonpea sterility mosaic. *Tropical Grain Legume Bulletin* 15, 27-29.

Reddy, M.V. and Nene, Y.L. (1980) Influence of sterility mosaic resistant pigeonpeas on multiplication of the mite vector. *Indian Phytopathology* 33, 61-63.

Reddy, M.V. and Nene, Y.L. (1981) Estimation of yield loss in pigeonpea due to sterility mosaic. In: *Proceedings of the International Workshop on Pigeonpeas, volume 2, 15-19 December 1980, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 305-312.

Reddy, M.V., Raju, T.N. and Nene, Y.L. (1987) Field screening of pigeonpea germplasm for resistance to bacterial leaf spot and stem canker. *International Pigeonpea Newsletter* 6, 62-65.

Reddy, N.P.E. and Chaudhary, K.C.B. (1985) Variation in *Fusarium udum*. *Indian Phytopathology* 38, 172-173.

Reddy, S.V., Reddy, M.V., Ghanekar, A.M., Nene, Y.L. and Amin, K.S. (1988) Annual recurrence of pigeonpea sterility mosaic in eastern Uttar Pradesh, India. *International Pigeonpea Newsletter,* 7, 30-31.

Rubaihayo, P.R. and Onim, J.F.M. (1975) A study of some characters of pigeonpea. *SABRAO Journal* 7, 183-187.

Saksena, H.K., Singh, S.B. and Kumar, K. (1970) Leaf spot and blight diseases of arhar caused by *Rhizoctonia*. In: *Recent Advances in Crop Production: Proceedings of the Symposium, February 1970, U.P. Institute of Agricultural Sciences, Kanpur.* Uttar Pradesh Institute of Agricultural Sciences, Kanpur, India, pp. 241-247.

Sarkar, Nandita (1988a) *Taxonomic and Epidemiological Studies on Phytophthora Blight of Pigeonpea. Pulse Pathology Progress Report* 52. Patancheru, A.P., India: Legumes Program, ICRISAT, 43 pp. (Limited distribution).

Sarkar, Nandita (1988b) *Epidemiological Studies on Phytophthora Blight of Pigeonpea. Pulse Pathology Progress Report* 53. Patancheru, A.P., India: Legumes Program, ICRISAT, 17 pp. (Limited distribution).

Sarojini, T.S. (1950) Soil conditions and root diseases. I. Micro-nutrient elements and disease development of *F. udum* on red gram. *Journal of the Madras University, Section B* 19, 1-32.

Sasser, J.N. and Hartman, K.M. (1985) Evaluation of some pigeonpea lines for resistance to the root-knot nematodes, *Meloidogyne* spp. *International Pigeonpea Newsletter* 4, 44-45.

Sasser, J.N., Hartman, K.M. and Carter, C.C. (1987) *Summary of Preliminary Crop Germplasm Evaluations for Resistance to Root-knot Nemotodes*. Raleigh, North Carolina, USA, 88 pp.

Saxena, R. and Reddy, D.D.R. (1987) Crop losses in pigeonpea and mungbean by pigeonpea cyst nematode, *Heterodera cajani*. *Indian Journal of Nematology* 17, 91-94.

Seth, M.L. (1962) Transmission of pigeonpea sterility by an eriophyid mite. *Indian Phytopathology* 15, 225-227.

Sharma, D., Gupta, S.C., Rai, G.S. and Reddy, M.V. (1984) Inheritance of resistance to sterility mosaic disease in pigeonpea-I. *Indian Journal of Genetics and Plant Breeding* 44, 84-90.

Sharma, D., Kannaiyan, J. and Reddy, L.J. (1982) Inheritance of resistance to blight in pigeonpeas. *Plant Disease* 66, 22-25.

Sharma, R. and Swarup, G. (1988) *Pathology of Cyst Nematodes*. Malhotra Publishing House, New Delhi, India, 152 pp.

Sharma, S.B. (1985) *Nematode Diseases of Chickpea and Pigeonpea. Pulse Pathology Progress Report* 43. Patancheru, A.P., India: Legumes Program, ICRISAT, 103 pp. (Limited distribution).

Sharma, S.B. (1988) *Nematode Diseases of Groundnut, Pigeonpea, Chickpea, Sorghum, and Pearl Millet. Legumes Pathology Progress Report* 1. Patancheru, A.P., India: Legumes Program, ICRISAT, 45 pp. (Limited distribution).

Sharma, S.B. and Nene, Y.L. (1985a) Additions to host range of pigeonpea cyst nematode, *Heterodera cajani*. *International Pigeonpea Newsletter* 4, 42.

Sharma, S.B. and Nene, Y.L. (1985b) Effect of pre-sowing solarization on plant parasitic nematodes in chickpea and pigeonpea fields. *Indian Journal of Nematology* 15, 277-278.

Sharma, S.B. and Nene, Y.L. (1988) Effect of *Heterodera cajani* Koshy, *Rotylenchulus reniformis* Linford and Oliveira and *Hoplolaimus seinhorsti* Luc on pigeonpea biomass. *Indian Journal of Nematology* 18, 273-278.

Sharma, S.B. and Nene, Y.L. (1989) Interrelationship between *Heterodera cajani* and *Fusarium udum* in pigeonpea. *Nematropica* 19, 21-28.

Sharma, S.B. and Swarup, G. (1984) *Cyst Forming Nematodes of India*. Cosmo Publications, New Delhi, India.

Shaw, F.J.F. (1936) Studies in Indian pulses: the inheritance of morphological characters and of wilt resistance in rahar (*Cajanus indicus* Spreng.). *Indian Journal of Agricultural Sciences* 6, 139-187.

Sheila, V.K., Manohar, S.K. and Nene, Y.L. (1988) Biology and morphology of *Aceria cajani*. *International Pigeonpea Newsletter* 7, 28-29.

Sheila, V.K. and Nene, Y.L. (1987) Effect of 'phytoalexin' formulations against *Phytophthora drechsleri* f. sp. *cajani*. *International Pigeonpea Newsletter* 6, 61-62.

Sheila, V.K., Nene, Y.L. and Kannaiyan, J. (1983) A simple culture medium for *Phytophthora drechsleri* f. sp. *cajani*. *Indian Phytopathology* 36, 152-154.

Sheriff, N.M., Khan, W.M.A. and Annappan, R.S. (1977a) Red gram Co.3–an economic mutant strain for Tamil Nadu. *Madras Agricultural Journal* 64, 561-564.

Sheriff, N.M., Khan, W.M.A. and Iyemperumal, S. (1977b) A note on the study of redgram mutants for resistance to root-rot disease under field conditions. *Madras Agricultural Journal* 64, 691.

Shit, S.K. and Sen Gupta, P.K. (1978) Possible existence of physiological races of *Fusarium oxysporum* f.sp. *udum*, the incitant of the wilt of pigeonpea. *Indian Journal of Agricultural Sciences* 48, 629-632.

Shukla, D.S. (1975) Incidence of Fusarium wilt of pigeonpea in relation to soil composition. *Indian Phytopathology* 28, 395-396.

Siddiqi, M.R. (1972) *Rotylenchulus reniformis. CIH descriptions of plant-parasitic nematodes, Set 1, no.* 5. Commonwealth Institute of Helminthology, England.

Singh, A.P. and Bhargava, S.N. (1981) Survival studies on three species of *Fusarium* causing wilt of pigeonpea. *Phytopathologische Zeitschrift* 100, 300-311.

Singh, B.V., Pandya, B.P., Gautam, P.L., Beniwal, S.P.S. and Pandey, M.P. (1983) Inheritance of resistance to sterility mosaic virus in pigeonpea. *Indian Journal of Genetics and Plant Breeding* 43, 487-493.

Singh, B.V., Pandya, B.P. and Rathii, Y.P.S. (1985) Field screening of pigeonpea lines for resistance to phytophthora blight at Pantnagar, India. *International Pigeonpea Newsletter* 4, 34-35.

Singh, D.V. and Mishra, A.N. (1976) Search for wilt resistant varieites of red gram in Uttar Pradesh. *Indian Journal of Mycology and Plant Pathology* 6, 89.

Singh, D.V., Nath, L. and Kishun, R. (1978) Chemical control of bacterial leaf spot of pigeonpea. *Pesticides* 12(10), 29-30.

Singh, G., Kapoor, S., Verma, M.M. and Bhan, L.K. 1986. Field resistance of pigeonpea varieties to phoma stem canker and leaf spots caused by *Phoma cajani*. *International Pigeonpea Newsletter* 5, 34-36.

Singh, K.P. (1980) The association of *Gibberella udum* with the wilted arhar plants recorded again. *Indian Phytopathology* 33, 161.

Singh, N.D. (1975) Influence of oxamyl application on *Meloidogyne incognita* and *Rotylenchulus reniformis* penetration into roots of tomato, lettuce and pigeonpeas. *Nematropica* 5, 29.

Singh, U.B. (1934) Studies on *Cercospora indica*, new species parasitic on *Cajanus indicus* Spreng. *Indian Journal of Agricultural Sciences* 4, 343-360.

Singh, U.P. and Chauhan, V.B. (1985) Relationship between field levels and light and darkness on the development of Phytophthora blight of pigeonpea (*Cajanus cajan* (L.). Millsp.). *Phytopathologische Zeitschrift* 114, 160-167.

Sinha, P.K. (1983) Studies on Phytophthora blight of pigeonpea. MSc thesis, Govind Ballabh Pant University of Agriculture and Technology, Pantnagar, India, 110 pp.

Sivakumar, C.V., Lakshmanan, P.L. and Palanisamy, S. (1976) Control of root-knot and reniform nematodes with low doses of granular systemic nematicides. *Indian Journal of Nematology* 6, 78-80.

Sivakumar, C.V. and Seshadri, A.R. (1971) Life history of the reniform nematode, *Rotylenchulus reniformis* Linford and Oliveira, 1940. *Indian Journal of Nematology* 1, 7-20.

Snyder, W.C. and Hansen, H.N. (1940) The species concept in *Fusarium*. *American Journal of Botany* 27, 64-67.

Somani, R.B., Khune, N.N. and Wangikar, P.D. (1981) Phoma stem canker: a new menace to arhar crop in Vidarbha. In: *Abstracts of papers of the Third International Symposium of Plant Pathology, 14-18 December 1981, New Delhi, India.* New Delhi: Indian Phytopathological Society, pp. 88-89.

Stevenson, J.A. (1917) Diseases of vegetable and garden crops. *Journal of the Department of Agriculture, Puerto Rico* 1, 93-117.

Su, U. (1931) Plant disease in Burma. *International Bulletin of Plant Protection* 5, 141-142.

Subramanian, C.V. (1955) The ecological and the taxonomic problems in Fusaria. *Proceedings of the Indian Academy of Sciences, Section B* 41, 102-109.

Swarup, G., Prasad, S.K. and Raski, D.J. (1964) Some *Heterodera* species from India. *Plant Disease Reporter* 48, 236.

Sydow, H. and Butler, E.J. (1906) Fungi Indiae orientalis. Part I. *Annals of Mycology* 4, 425-445.

Thakar, N.A. and Patel, C.C. (1985) Susceptibility of some pigeonpea varieties to root-knot nematodes, *Meloidogyne incognita* and *M. javanica*. *International Pigeonpea Newsletter* 4, 43-44.

Thakar, N.A. and Yadav, B.S. (1985) Screening pigeonpeas for their resistance to reniform nematode. *International Pigeonpea Newsletter* 4, 42-43.

Upadhyay, R.S. and Rai, B. (1981) Effect of cultural practices and soil treatments on incidence of wilt disease of pigeonpea. *Plant and Soil* 62, 309-312.

Upadhyay, R.S. and Rai, B. (1983) A new disease cycle of wilt of pigeonpea. *Current Science* 52, 978-981.

Vaheeduddin, S. and Nanjundiah, S.M. (1956) Evolving wilt resistant strains in tur (*Cajanus cajan* L.). *Proceedings of the Indian Science Congress* 43(4), 20 (Abstract).

Vakili, N.G. and Maramorosch, K. (1974) "Witches broom" disease caused by mycoplasma-like organisms on pigeonpea (*Cajanus cajan*) in Puerto Rico. *Plant Disease Reporter* 58, 96.

Vasudeva, R.S., Subbaiah, T.V., Sastry, M.L.N., Rangaswamy, G. and Iyengar, M.R.S. (1958) "Bulbiformin", an antibiotic produced by *Bacillus subtilis*. *Annals of Applied Biology* 46, 336-345.

Veeraswamy, R., Rangaswamy, P. and Sheriff, N.M. (1975) CO 2 redgram – a new strain with early maturity and improved plant type. *Madras Agricultural Journal* 62, 541-543.

Vidhyasekaran, P. and Arjunan, G. (1976) A new redgram variety resistant to root rot *(Macrophomina phaseolina)*. *Madras Agricultural Journal* 63, 175-176.

Wallace, G.B. (1930) Mycological work. *Report, Department of Agriculture, Tanganyika 1928/29, Part* 2. Department of Agriculture, Tanganyika, pp. 35-36.

Wearing, A.H. and Birch, C.J. (1988) Root rot of pigeonpea. *International Pigeonpea Newsletter* 8, 13.

Williams, F.J., Amin, K.S. and Baldev, B. (1975) Phytophthora stem blight of *Cajanus cajan*. *Phytopathology* 65, 1029-1030.

Williams, F.J., Grewal, J.S. and Amin, K.S. (1968) Serious and new diseases of pulse crops in India in 1966. *Plant Disease Reporter* 52, 300-304.

Zaki, F.A. and Bhatti, D.S. (1986) Control of pigeonpea cyst nematode, *Heterodera cajani* Koshy, 1967 by chemical seed treatment. *Indian Journal of Nematology* 16, 106-108.

Zaveri, P.P., Shah, R.M., Pathak, A.R., Patel, J.A., Kher, H.R., Patel, R.S. and Tikka, S.B.S. (1986) BDN 2 a wilt tolerant superior cultivar of pigeonpea for Gujarat. *International Pigeonpea Newsletter* 5, 38-39.

Zote, K.K., Dandnaik, B.P. and Khalikar, P.V. (1987) Reaction of pigeonpea varieties/lines to Fusarium wilt disease. *Journal of Maharashtra Agricultural Universities* 12(1), 102-103.

Zote, K.K., Thombre, P.G., Khalikar, P.V., Dandnaik, B.P., Chavan, G.V. and Olekar, S.S. (1983) Breeding pigeonpea for resistance to wilt and sterility mosaic. *International Pigeonpea Newsletter* 2, 43-44.

Chapter 14

PIGEONPEA: PEST MANAGEMENT

W. REED and S.S. LATEEF

Former Principal Entomologist, and Senior Entomologist, Legumes Program, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Andhra Pradesh 502 324, India.

INTRODUCTION

Pigeonpea provides very attractive and nutritious food, not only for humans but also for many animals. The seeds, and other parts of the plant, are fed upon by many insects, with over 200 species having been recorded in India alone (Lateef and Reed, in press). Some of these insects cause sufficient crop losses to be regarded as major pests, but the majority are seldom abundant enough to cause much damage, or are of sporadic or localized importance, and as such may be regarded as minor pests. In addition, hundreds of other species of insects and other animals are found on pigeonpea plants and many of these are beneficial, for they feed upon the pests, either as predators or parasitoids. It is extremely important that farmers should become familiar with the insects and other animals that inhabit pigeonpea crops and not simply rush in to treat the plants with pesticides as soon as they see a few insects!

Insects are found chewing or sucking pigeonpea plants from seedling to harvest, and no part of the plant is immune to attack. Plants that are heavily attacked before the flowering stage can lose a large proportion of their leaf area and will apear to be very badly damaged. However, pigeonpea has been described as a very forgiving plant, for it can recover from the many setbacks that it may encounter. Studies at ICRISAT (Sheldrake and Narayanan, 1977) showed that the removal of up to 75% of pigeonpea leaves for extensive periods resulted in only slight, and statistically insignificant, losses in seed yield.

Most pigeonpea genotypes produce an over abundance of buds and flowers, and most of these will be shed (Sheldrake *et al.*, 1979), so the loss of a large proportion to insect attacks may not result in measurable yield loss. Even the total loss of the flowers may not greatly reduce yield, for the plants can grow on to produce a compensatory flush, that will have a large yield potential, provided the pest attacks abate, and the soil fertility, moisture, and climate remain favourable.

Pod damage or loss can greatly reduce crop yield, for the pigeonpea's potential to compensate for pod damage is limited. Thus, the pod-damaging insects are the most important pests on this crop. This chapter will largely concentrate upon the pod-damaging pests and their control, since these will determine whether the farmer will be able to harvest a large yield of pods at the end of the season, or whether he will simply be left with a large crop of firewood.

Other chapters in this book will stress the wide variability between pigeonpea genotypes, both in structure and duration. Such differences are of great importance when considering pest management for this crop. The pest problems, and the potential for their economic control, are very different in the tall, medium- or long-duration varieties that are traditionally grown as intercrops, and the short-statured, short-duration pigeonpeas that are becoming popular as high-yielding sole crops. In order to improve the quality, yield, and profitability of pigeonpea cultivation it is important that the scientist and the farmer should be aware of the interactions among the plants, the pests, and the environment. Such interactions will be frequently referred to throughout this chapter.

THE PESTS

It would be possible to more than fill this book with the information that research at ICRISAT alone has uncovered on just one of the major pests of pigeonpea, so it is impossible to provide a comprehensive account of the many pests in this chapter. The authors therefore provide a very abbreviated account of the pests that are most likely to be found damaging the crop during its various growth stages, and give brief details of the life history of the most important pests. Illustrations and descriptions of many of the pests are provided in the Pigeonpea and Chickpea Insect Identification Handbook, ICRISAT Information Bulletin no.26 (Reed *et al.*, 1989) and ICRISAT legumes entomologists will be pleased to provide specific information on individual pests on request.

Pests of Sown Seed and Seedlings

Rats and some birds, including pigeons, dig out and eat the sown seeds. Rats in particular, soon learn to locate the seeds, even when they are deeply sown. Later-sown patches in earlier-sown fields and "gap fill" sowings are commonly destroyed, and hand-sown seeds are more commonly damaged than those that are machine sown. Millipedes and soil beetles, particularly *Gonocephalum* spp are also occasionally found feeding upon the seeds in the soil.

Several insects, including the adults of some weevils (*Myllocerus* spp and *Phyllobius* spp), and other beetles feed upon the cotyledons. Lepidopteran larvae, including the cutworms (*Agrotis* spp) are also occasionally found feeding on the seedlings. Aphids, particularly *Aphis craccivora* Koch., may build up in large numbers and slow down growth, particularly in dry periods. However, although the seedlings are hosts for many insects and may lose much of their leaf area, few are killed, and this early damage does not usually adversely affect later plant growth. The only major exception is in areas where white grubs (*Lachnosterna* sp) are very common, as in some parts of central India, for these pests cut the seedling below the cotyledons and thus kill the plants.

Pests of the Vegetative Growth Stage

The most commonly recorded insects attacking pigeonpea during its vegetative growth stage are the jassids, particularly *Empoasca kerri* Pruthi. These small green insects feed mainly on the underside of the leaves and cause yellowing of the leaf margins. Very heavy infestations, as are sometimes seen in Kenya and in some areas of northern India, can result in premature defoliation and reduced yields, particularly under dry conditions. Aphids and mites can also become damaging under such conditions. Another sucking pest of sporadic importance is *Bemisia tabaci* (Genn.), a whitefly that is normally found in very low populations on pigeonpea leaves in the fields, but is the vector of a virus that causes the yellow mosaic disease on this crop.

The most important mite is *Aceria cajani* (Channabasavanna) the vector of sterility mosaic disease. Red spider mites, including *Schizotetranychus cajani* (Gupta) in India, are also commonly found feeding on the underside of the leaves, particularly where insecticides have been used, and can cause defoliation, with the leaves showing typical white or yellow spots on the upper surface. Red spider mite, aphids, and whitefly often build up to damaging populations on pigeonpea plants grown in greenhouses, probably because their natural enemies are excluded.

Several lepidopteran larvae feed on the leaves, the most common of these are the leaf webbers that tie together leaves and terminal buds with silk threads and feed and pupate inside this web. The most common of these in India is *Grapholita critica* (Meyr.) (formerly known as *Cydia* and *Eucosma*). The infestation of the small yellow larvae of *G. critica* is very common in some areas and years when all the plants in a crop may have many webs. Some growing points will be killed and the plants will look very untidy. However, such attacks do not usually persist and observations at ICRISAT Center and elsewhere showed no detectable difference at the peak flowering stage between plants that had been severely infested earlier, and those on which the infestations had been controlled. Similar webs are formed by the spotted larvae of *Maruca testulalis* (Geyer), particularly at the flower bud stage (Figure 14.1). Attacks by this insect can persist into the podding stage, and in some areas of Asia and Africa this is the most damaging pest of the crop in some years. Of the many other larvae that are found feeding on the leaves *Amsacta* spp and *Trichoplusia* spp are the most common, but are seldom numerous enough to cause concern.

Of the other insects that feed on the leaves, *Myllocerus* spp adults are very common. These small weevils nibble the leaf edges, and heavy infestations may appear to be cause for concern. Such damage is unlikely to affect the yields but the larvae of these, and other beetles, feed on the roots of several crop plants, including pigeonpea, and heavy infestations can result in wilting. Several species of grasshoppers feed on the leaves but are seldom numerous enough to cause serious damage, except in those areas of Africa and Asia where locusts can destroy this, and most other crops.

Several insects feed in and on the stems. The most damaging is the stem fly, *Ophiomyia centrosematis* (de Meijere) the larva of which feeds inside the stem and can kill young plants. Fortunately, this pest is only sporadically common. Larvae of the jewel beetle, *Sphenoptera indica* (Laporte and Gorg.), and other beetles are occasionally found boring in the stems, but they are seldom common enough to cause concern. Several sucking insects feed upon the stems including aphids and scales, but the most common are the cow bugs, *Oxyrhachis* and *Otinotus* spp. These insects are often protected from their natural enemies by ants which feed on their sugary exudates. Pigeonpea plants can tolerate heavy infestations with no obvious effects on yield.

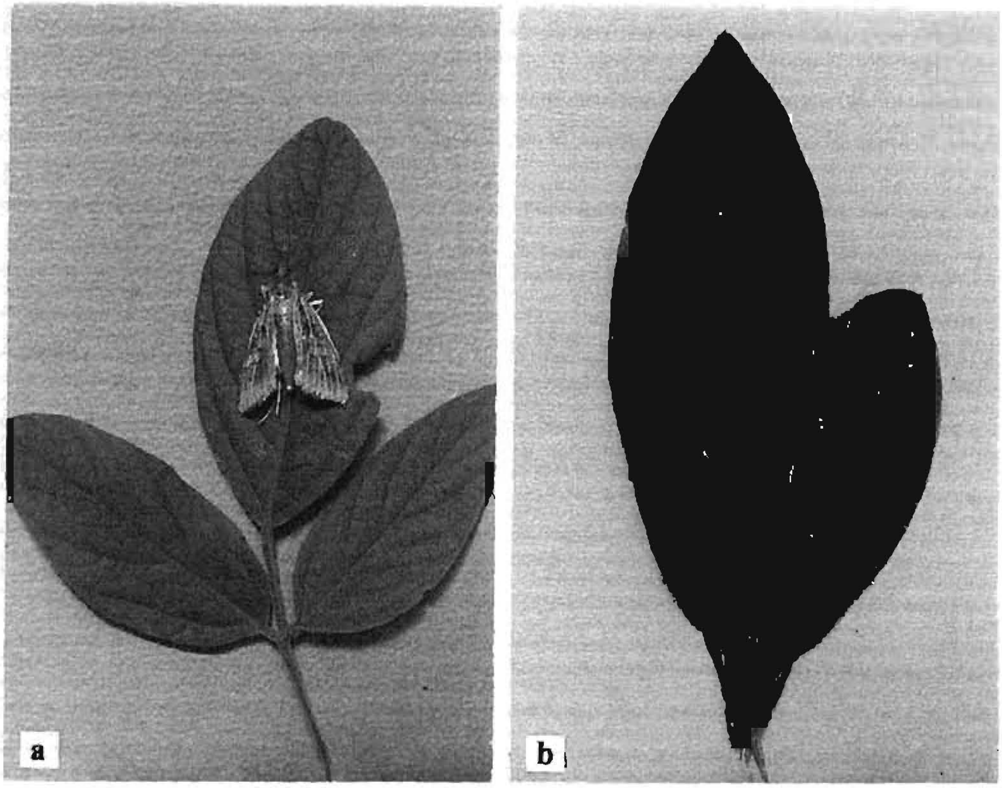


Figure 14.1. *Maruca testulalis*: a. Adult; b. Larvae inside webbed pigeonpea leaves and flowers.
Photo: ICRISAT.

Pests of the Roots

Termites are often found feeding in the stem base and roots of dead and dying plants. In many cases such damage is secondary, for the plants can be seen to have suffered from a disease or from mechanical damage. But, in a few fields, particularly in northern India, considerable numbers of otherwise apparently healthy plants are killed by *Microtermes* spp.

White grubs, the larvae of several species of beetles including *Lachnosterna (Holotrichia) consanguinea* (Blanchard), kill a few plants in some areas, but pigeonpea appears to be less susceptible than many other crops.

The small white larvae of the nodule-damaging fly, *Rivellia angulata* (Hendel), feed inside the nodules formed by rhizobia. At ICRISAT Center, and at other locations in India, more than 90% of the nodules have been found to be destroyed in some fields, particularly on Vertisols (Sithanantham *et al.*, 1981). Attempts to quantify any yield loss that may result from such damage have not been successful, but typical nitrogen deficiency symptoms and reduced plant growth were evident in pot trials where large proportions of the nodules were damaged by this insect (Sithanantham *et al.*, 1987).

Several species of nematodes attack the roots, and some can cause severe stunting. These pests are dealt with in Chapter 13.

Pests of the Flowers and Pods

The most damaging pests of pigeonpea are those that attack the flowers and pods, and of these the most important by far is the pod borer, *Helicoverpa armigera* (Hüb.) formerly known as *Heliothis armigera*.

The *Helicoverpa* moths fly during the night and lay their eggs on a very large range of plants. They are strongly attracted to pigeonpea when the flowers appear, and the small white eggs are laid singly on leaves, flowers, and pods. The eggs hatch after 3 or 4 days, and the tiny larva at first feeds by scraping the surface tissue. It then bores into buds and flowers and the larger larvae bore into the pods, eating the developing seeds and leaving characteristic large round holes along each locule. A large larva can destroy many flowers and several pods each day. The fully grown larvae that are about 3 cm long can be pink, yellow, green, brown, or black but all have characteristic longitudinal markings along their sides (Figure 14.2).

The larva leaves the plant in 3 weeks or less after hatching, and buries itself in the soil, where it pupates. The medium-sized, brown moths emerge from the soil in about 2 weeks, so the life cycle can be completed in little more than a month. As each female can lay more than 1000 eggs, infestations can increase very rapidly.

Several other lepidopteran larvae attack the flowers and pods. The most important of these is *Maruca testulalis* which is very common in many areas in Africa and Asia. The larvae of *Lampides boeticus* (L.) and *Catochrysops strabo* (Fab.), (blue butterflies), and *Exelastis atomosa* (Wals.) (plume moth), are common in several parts of Asia and can cause substantial losses in some years. Larvae

Figure 14.2. Pod borer, *Helicoverpa armigera* larva and damaged pigeonpea pods.
Photo: ICRISAT.

of *Etiella zinckenella* (Treits.), a pest of several grain legumes, are often found in mature pods. *Adisura* spp larvae, may be fairly common in some areas, but are seldom recorded because they are superficially similar to *Helicoverpa* larvae. Other species of *Helicoverpa* including *H. zea* (Boddie) and *H. virescens* (Fab.), in the Americas (Saunders *et al.*, 1983) and *Helicoverpa punctigera* (Wallengren) in Australia are also reported to damage the crop (Reed *et al.*, 1989).

Many species of thrips, including *Megalurothrips usitatus* (Bagnall), are found feeding in the flowers. These have been reported to cause yield loss in some areas (Rawat *et al.*, 1969; Pollard and Guiseppi-Elie, 1981) but at ICRISAT Center flowers infested with 20 or more thrips have been observed to develop into healthy pods.

Several species of large blister beetles, including *Mylabris pustulata* (Thunberg) in India, invade pigeonpea and feed on the flowers (Figure 14.3). These can be very damaging in areas where only a few small plots are in flower when the beetles are active, but where larger areas are in flower the pests are diluted across the crop, and the damage is insignificant. The larvae of these beetles feed on the eggs of grasshoppers and other insects in the soil and are generally beneficial.

Indozocladius (Ceutorrhynchus) asperulus (Faust), the flower bud weevil is a minor pest in some

Figure 14.3. Blister beetle, *Mylabris pustulata* damaging pigeonpea flowers.
Photo: ICRISAT.

areas of India. Other weevils, including *Apion* spp and *Callosobruchus* spp feed inside the pods. The latter are of considerable importance, for they are the major pests of the stored seed.

The second most damaging pest of pigeonpea in Asia is the podfly, *Melanagromyza obtusa* (Malloch). This small black fly lays its eggs through the wall of the young pod, and its larva feeds in a seed. The small brown puparium is also formed inside the pod (Figure 14.4) so this pest is protected from predators, and contact insecticides, throughout most of its life. The fly emerges from the pod through a characteristic round hole.

In favourable conditions the life cycle is completed in less than 3 weeks, so populations rapidly build up to very damaging levels. Although this pest has been reported in Africa, it is almost certain that it does not occur there. Such reports have been shown to refer to *Melanagromyza chalcosoma* (Spencer), a very similar pest of several grain legumes.

Several sucking bugs, particularly *Clavigralla* spp and *Nezara viridula* (L.), feed on pigeonpea pods. The seeds in the attacked pods become shrivelled and are useless. These pests are very common in Africa and Asia, particularly in dry seasons. They are underestimated pests, and the seed damage that they cause is often attributed to drought.

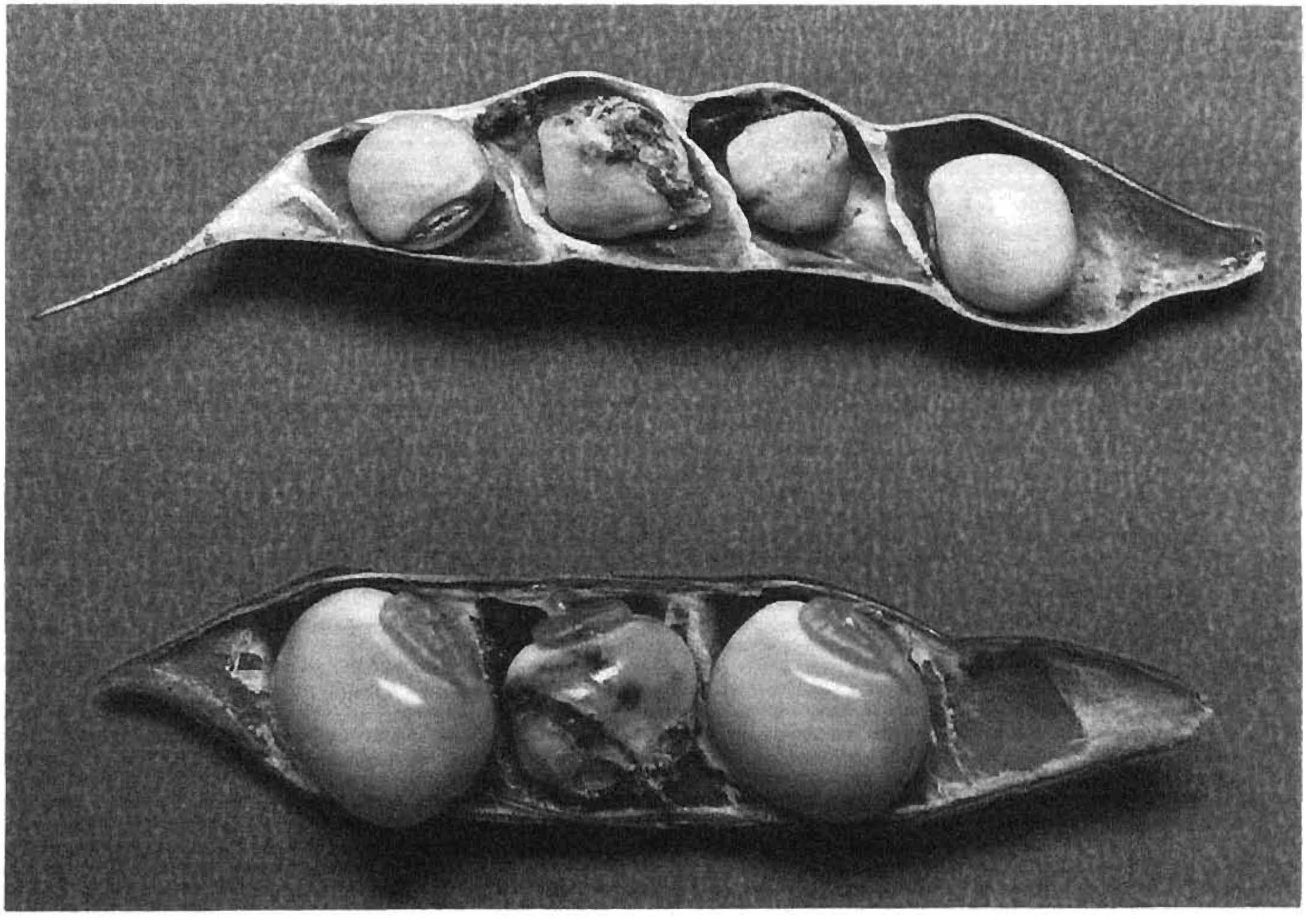


Figure 14.4. Pigeonpea pods damaged by podfly, *Melanagromyza obtusa*, the eggs, larvae, and pupae develop inside the pods, so there is no external evidence of infestation until the adult fly emerges through the pod wall.
Photo: ICRISAT.

PEST LOSS ASSESSMENT

Although very many insects and other animals feed on pigeonpea, only a few cause substantial yield loss and so merit expenditure on research and control. The pests vary across areas and seasons, so regular surveys over several years may be required before the relative importance of the various pests in each area can be determined. Table 14.1 summarises the pod damage data from a series of surveys of farmers fields in India.

It can be seen from Table 14.1 that pod-borer (mainly *Helicoverpa*) damage was most important in southern and central India, but the podfly was the most damaging pest in the north. Such data are very useful, as they do allow us to quantify the yield losses caused by the pests. Comparisons of the yields from plots that are adequately protected by insecticide with yields from unprotected plots will reveal the "avoidable loss", but such trials are usually conducted on research station fields where pest attacks are often very atypical of those in farmers fields. For example, a hymenopteran insect, *Tanaostigmodes cajaninae* LaSalle (Figure 14.5) often destroys 30% or more of the pods in ICRISAT Center's fields, but surveys show that this insect is rare in farmers' fields. This pest builds up on research stations where pigeonpea pods are available for several months because a range of genotypes of varying maturity durations are grown (Lateef *et al.*, 1985).

Table 14.1. Pigoenpea pod damage by insects in samples from farmers' fields in India.

Zones (cultivar maturity duration)	Number of fields sampled	Pod damage (%)			
		Pod borers	Podfly	Pod wasp	Total
Northwest (short)	49	29.7	14.5	0.03	44.0
North (long)	359	13.2	20.8	0.5	33.8
Central (medium and long)	446	24.3	22.3	1.6	48.0
South (short and medium)	443	36.4	11.1	2.2	49.9

Source: Lateef and Reed, 1983.

Special care must be taken in the design and interpretation of insecticide trials intended to quantify pest-caused losses. The yield data from small, adjacent, protected and unprotected plots may be atypical of the yields that would be obtained from much larger comparisons because of the interplot effects, that are mainly the result of mobile pests and natural enemies dispersing from one plot to another (Joyce, 1982).

Pest attacks vary, not only across regions, but also at a single location, and across and within years. For example, data from the pesticide-free areas at ICRISAT Center, from 1975 to 1982 showed considerable year-to-year variation. Pest attack, as measured by the average percentages of pods damaged, ranged from 24% in 1980/81 to 68% in 1978/79. Damage was greater in the crops grown on Vertisols than on Alfisols in every year, averaging 62% on the black soil and 42% on the red. Within each season, the pest attacks were very different on the pigeonpea varieties of differing durations, as can be seen in Table 14.2.

The extra short-duration varieties that were harvested in September were very heavily attacked by pod borers, and the medium-duration types, harvested in November, were even more severely damaged by these pests (up to 98% pod damage in some years). The long-duration types, that matured in January, tended to have lower pod borer damage, probably because *Helicoverpa* populations had declined and were attracted to chickpea. But, on these types the podfly was an important pest.

Figure 14.5. Pigeonpea pods damaged by the pod wasp, *Tanaostigmodes cajaninae*; (top to bottom) adult, pupa, and larva.
Photo: ICRISAT.

Thus, crop loss assessment is not simple or easy, and the many claims that losses caused by individual insects in an area have been accurately quantified should be viewed with caution. Perhaps the most important statistic is the "avoidable loss" calculated from a series of large plot comparisons on typical, but well grown, crops in farmers' fields. If these reveal losses to the pest complex in excess of 20%, then pest control inputs may be profitable and research may be justified. In many areas, the pest-caused losses in some years are so great that no seed can be harvested and the need for pest control is obvious.

Table 14.2. Mean percentage of pods damaged by the major insect pests in pigeonpea cultivars of different matuturity durations at ICRISAT Center, 1982/83.

Cultivar maturity duration	Number of cultivars tested	Pod damage mean % (± SE)	
		Pod borer	Podfly
Short	12	41.8(±1.17)	2.4(±0.15)
Short-medium	6	53.3(±2.54)	6.7(±0.87)
Medium	12	93.4(±0.67)	3.7(±0.27)
Long	8	24.2(±0.94)	25.6(±1.18)

CULTURAL METHODS OF PEST CONTROL

Farmers have grown pigeonpea for millennia, and have evolved traditional, practicable means of pest loss limitation that allow them to grow this crop profitably in most years. It is not always easy to distinguish the reasons or benefits that lie behind traditional farming practices, and it is tempting to reject the traditional practices, replacing them with modern technology that appears to give greater profit. However, it is important that we should ensure that our modern technology really can give the farmer more, not just in one season but over a lengthy period of varying conditions, before we reject practices that have served many generations of farmers well.

Perhaps the most obvious factor in traditional pigeonpea growing is that it is most frequently grown as an intercrop. In surveys of farmers' fields throughout India, of the 1226 fields from which the cropping pattern was recorded, only 306 (25%) were of sole-crop pigeonpea. All of the others had one or more companion crops in varying proportions, but often with pigeonpea as the minor component. In most cases the companion crops were harvested before the pigeonpea flowered, so leaving it to grow on without competition. Where the pigeonpea rows are separated by three rows, or less, of other crops the pigeonpea grows on to form a complete canopy.

It is tempting to assume that intercropping will reduce the pest-caused losses on pigeonpea. For example, it may be difficult for some potential pests to locate pigeonpea plants separated from each other by other crop species, and colonies of some pest insects on a plant or row will not be able to spread throughout the crop so easily as they could in a sole crop. We might also expect a range of beneficial insects, both predators and parasitoids, to build up on the earlier-maturing companion crops, some of which will transfer to the pigeonpea when those other crops were harvested.

There is little doubt that single pigeonpea plants tend to suffer much less pod borer damage than plants grown in plots. Scientists working at ICRISAT have often come across single plants, along the roadside or field edges, that bore large numbers of pest-free pods while nearby crops were very heavily infested with *Helicoverpa*. The authors collected seed from these single plants, hoping that they may be pest resistant, but in all cases the progenies were found to be susceptible. Such escape from pest attacks may partly explain the popularity of pigeonpea as a backyard vegetable in the many areas where pigeonpea is not grown as a field crop because it is so susceptible to pests.

Data from surveys in farmers' fields and trials, both on ICRISAT research farm and in farmers' fields, comparing sole crops with intercrops have failed to show consistent reductions of pest caused damage by intercropping. Nor was any consistent increase in parasitism found in *Helicoverpa* collected from pigeonpea intercropped with sorghum compared with those from sole-crop pigeonpea (Bhatnagar and Davies, 1981). This was surprising for the sorghum intercrops supported large populations of *Helicoverpa* that were heavily parasitized. It was found that the most common parasitoids of this pest on sorghum were rare on pigeonpea and vice versa. Thus it appears that intercropping has little or no pest reduction advantage, so other factors must be sought to explain the widespread popularity of intercropped pigeonpea.

Most of the pigeonpea grown in the traditional intercropped systems is of medium- to long-duration cultivars, with much of the crop's growth and its flowering stage occurring after the harvest of the companion crops. There is some evidence to suggest that cultivar durations have been unconsciously selected to avoid the potential peak pest attacks in each area. For example, in northern India most farmers grow long-duration varieties that come into flower soon after the winter, when insect populations are at a relatively low level, while in Andhra Pradesh, many farmers grow cultivars that flower in October, so escaping the peak *Helicoverpa* populations that occur in August/September and November/December in most years. However, it must be stressed that the evolution of local traditional farming systems has been shaped by several constraints, and the primary requirements for this crop are that there should be adequate soil moisture during the growth phase, and relatively dry and sunny weather during the flowering and podding stages.

One of the most important factors in traditional agricultural pest management is the strict adherence to well defined crop seasons. When all farmers in an area synchronously sow crops of similar duration there is a reduced opportunity for pests to build up on early sown crops and then disperse onto the later sown. Where all of the pigeonpea in an area is simultaneously attractive to a pest the available population is diluted across the area and pest-caused losses are minimized. Care must be taken when introducing a new variety into an area to ensure that pests are not given the opportunity to disperse from the new variety to the traditional crop, or vice versa.

Research is in progress at the All India Coordinated Pulses Improvement Project (AICPIP) in northern India to further exploit such phenological and ecological factors in pest management, particularly to reduce losses caused by podfly, the major pest of the long-duration crops that are very productive in that area. AICPIP scientists are selecting genotypes that flower as soon as possible after winter, when podfly populations are low, and that complete their podding in the shortest time so there will be little opportunity for the pest to complete more than one generation in the crop (Lal *et al.*, 1986).

Most pigeonpea varieties are potentially perennial, but there is considerable mortality caused by pests and diseases in the second and subsequent years. In particular, the older plants tend to be colonized by several species of scale insects, but by growing the crop as an annual the farmer virtually eliminates these pest problems. In some areas however, perennial pigeonpeas are grown because they are heavily infested by a scale insect, *Laccifer lacca* (Kerr) that produces valuable lac.

In some cases farmers find it worthwhile to manually destroy pests. For example, a few blister beetles can quickly damage very many flowers, but they are easily picked off the plants and squashed. As they do not multiply on the crop and there are limited numbers in an area, concerted action will virtually eliminate this pest. However, care must be taken in handling these insects for they can cause unpleasant blisters. The authors have also seen farmers, and their families, picking other insects including *Helicoverpa* from their crops. As there may be a half million or more larvae per hectare, this would appear to be a hopeless task, but when a farmer sees his crop being destroyed desperate efforts seem justified.

Other cultural methods of pest management include crop rotation, that will reduce attacks by some soil pests including nematodes. Ploughing may kill many pests, not only by crushing, but also by exposing them to desiccation and to predators, such as birds. Removal of the weeds may reduce populations of some pests, but may also reduce beneficial insect populations.

NATURAL AND BIOLOGICAL PEST CONTROL

Very many factors can adversely affect pest populations. High, or low temperatures may slow down or stop their feeding and reproduction. Rainfall may wash some insects from the plants and drown them. Strong winds may dislodge some pests from the plants, and prevent immigrating adults from landing on the crop. These abiotic factors combine with naturally occurring predators, parasitoids, and pathogens to constitute "natural pest control".

Action to enhance the reduction of pest populations by biological agents is generally referred to as biological control. This may be through actions that enhance the build up or effectiveness of the natural enemies, or through "classical biological control" where natural enemies are imported (sometimes from other continents) to supplement the local natural control elements.

The authors have found that all of the major pests of pigeonpea are fed upon by many natural enemies. Intensive studies of the biocontrol elements on pigeonpea and other crops at ICRISAT Center from 1976 to 1986, and research at other locations, has provided a huge mass of information, which is only briefly summarised here. Most of the predators, that include insects, spiders, reptiles, birds, and mammals, feed upon several pest species, and upon their natural enemies. Several of the parasitoids, which are mainly insects, are specific to only one pest. Some of the pathogens, i.e., bacteria, fungi, and viruses, are also specific. These natural enemies normally restrict the populations of most potential pests to non-damaging levels. Interference with the ecosystem, particularly through the misuse of pesticides can result in the destruction of natural enemies, and allow pest populations to explode.

Each pigeonpea crop develops its own unique ecosystem from the seedling stage onwards. It inherits fauna from the soil in which it is sown, and from surrounding plant communities. Several species multiply within the crop, and there is considerable dispersion of the fauna, both into and out of the crop.

It has earlier been stressed that insects feeding on the plants during the vegetative stage generally have little effect on the final yield, so the destruction of the fauna by insecticides at this stage is of little or no benefit. Rather, the natural enemies that feed upon the vegetative pests may later transfer their attentions to the major pests that attack the flowers and pods. Similarly, it would be expected that the natural enemies of the pests on the companion crops would transfer to pigeonpea after those crops had been harvested. Unfortunately it was found that the majority of the parasitoids did not transfer to the major pigeonpea pests, either from the vegetative pigeonpea pests, or from the companion crop. For example, the leaf webber *(G. critica)* which is often the most common insect feeding on young pigeonpea, was recorded as a host for at least 10 species of parasitoids (Bhatnagar and Davies, 1979), and 28 species have been recorded from *Helicoverpa* in central India. But, only one of these was recorded from both pests. Similarly, in the very common sorghum/pigeonpea intercrops, the parasitoid complex recorded from *Helicoverpa* on sorghum was very different to that from the same pest on pigeonpea (Bhatnagar *et al.*, 1982).

There has been considerable research on the use of egg parasitoids, particularly *Trichogramma* spp, for the control of *Helicoverpa*. These tiny insects can be reared relatively cheaply in large numbers, and there are many reports that inundative releases have given good control of *Helicoverpa* in extensive field tests. Unfortunately, *Trichogramma* does not like pigeonpea! Over 26% of the *Helicoverpa* eggs collected from sorghum at ICRISAT Center, but less than 0.1% of those from pigeonpea, were parasitized. Sithanantham *et al.* (1982) found that *Trichogramma chilonis* (Ishii) was deterred from parasitizing *Helicoverpa* and other eggs on pigeonpea, particularly those on the pods. Sithanantham *et al.* (1982) attempted to select *Trichogramma* species that would more readily accept this plant, and pigeonpea varieties, that did not deter such parasitism. Although they found substantial differences between the species and varieties it became clear that *Trichogramma* has little potential on pigeonpea so the research was terminated.

As most of the parasitoids found in *Helicoverpa* on pigeonpea were dipteran, it was considered worthwhile to try to establish an exotic dipteran, *Eucelatoria bryani* Sabrosky on this crop. This insect had been imported by the Commonwealth Institute of Biological Control from the USA where it is an important *Helicoverpa* parasitoid. It was successfully bred on *Helicoverpa* larvae in the laboratory for many generations, but attempts to establish it in the field were not successful.

There has been relatively little research on the predators in this crop, largely because such studies in the field require many hours of tedious observation to produce quantitative data, and cage or laboratory studies are likely to produce atypical results. There is little doubt that predators are very important in the control of many pigeonpea pests. The authors have observed 19 species of insects, and many species of spiders and birds preying on the eggs and larvae of *Helicoverpa*. Feeding tests in the laboratory have shown that spiders such as *Clubiona* sp can consume 59.3 eggs or 3.2 small *Helicoverpa* larvae per day (ICRISAT, 1982). Most of the life stages of the podfly are protected from predators, but many of the adults have been observed trapped in spiders' webs.

There appear to have been no reported attempts to enhance predation in pigeonpea. It has been suggested that posts should be erected in fields to provide nesting sites for mud wasps such as *Delta* spp that carry off many large *Helicoverpa* larvae to feed their young. It is also possible to rear large numbers of predators such as *Chrysopa* in the laboratory, but such measures are unlikely to be economic (King *et al.*, 1982).

Perhaps the greatest potential for biological control in pigeonpea lies in the use of the nuclear polyhedrosis virus as a biological insecticide for the control of *Helicoverpa* (Figure 14.6). A series of field trials on pigeonpea showed that such sprays can give considerable reduction of *Helicoverpa* populations, but the control and plot yields produced by this treatment were inferior to those in

Figure 14.6. Larva of *Helicoverpa armigera* infected with nuclear polyhedrosis virus.
Photo: ICRISAT.

endosulfan-treated plots (ICRISAT, 1988a). If the effectiveness of such sprays could be increased there would be several advantages in their use. As the virus is relatively specific the natural enemies would not be adversely affected, and there appear to be no toxic hazards to man or his domestic animals. Crude preparations of the virus can be made very cheaply by mixing larvae that have been killed by the virus with water. However, there is some concern that such crudely prepared mixtures may be dangerous, for although this virus is safe there are many other pathogens in dead insects, and we cannot guarantee that all are harmless. The virus was produced commercially in a purified form in the USA, but it did not prove to be a commercial success and its production was discontinued.

Another pathogen that has obvious potential as a biological pesticide is *Bacillus thuringiensis* Berliner, and various formulations are commercially available. Tests of some of these on pigoenpea have not given very encouraging results. However, new and more potent strains are becoming available and these may have exciting potential.

INSECTICIDE USE

Pigeonpea will inevitably lose some, often most, of its potential yield to pests even though natural control and the compensatory ability of this crop may substantially reduce the loss. The judicious use of insecticides will further reduce the pest-caused losses, but application of insecticides, particularly on the tall traditional crops is far from easy.

It has already been stressed that pigeonpea can adequately compensate for most damage occurring during the vegetative stage. Usually, there will be little or no profit in applying insecticides to this crop before the flower buds appear, or before the companion crop is harvested. The height of most traditional pigeonpea crops at the flower bud stage is well over 1m and may exceed 2m. The target for insecticide coverage will be the flowers and pods, most of which will be at, or above, the shoulder level of the farmer. Well grown traditional crops develop a dense canopy and it is difficult to walk through such crops with an insecticide applicator, except in widely spaced intercrops from which the companion crop has been removed. Spraying or dusting crops above waist level is difficult, unpleasant, and may be dangerous. High-clearance tractors or aircraft can be used to spray pigeonpea, but they are seldom available when needed, and are usually prohibitively expensive.

In spite of the many difficulties, increasing numbers of farmers are using insecticides on pigeonpea. A major breakthough has been the development of the short-duration varieties that generally grow to no more than a metre in height, and so can be much more easily treated than the traditional varieties (Figure 14.7).

Figure 14.7. A short-duration, determinate type of pigeonpea cultivar that can be conveniently sprayed.

Photo: ICRISAT.

Choice of Insecticide

Pesticides must be **effective, profitable,** and **safe**. For most farmers the ideal insecticide would be a cheap chemical that kills all pests and persists on the plant, so that one application would protect the crop. DDT came close to such an ideal. Unfortunately such chemicals also kill most other animals, including the natural enemies, and persistent pesticides can give long-term pollution, and thus are banned in most countries.

No available pesticide is effective against all of the pests that attack pigeonpea, so the choice of insecticide must depend upon the pest that currently threatens the crop. In general, contact and stomach poisons tend to be most effective against the chewing pests, while systemic insecticides which penetrate and are carried around inside the plant are particularly effective against the sucking pests. Most widely used agricultural insecticides applied at the generally recommended dosages on pigeonpea will not produce phytotoxicity, but carbaryl has frequently been reported to scorch the foliage.

Insecticide availability varies from country to country and new chemicals become available every year, so recommendation of specific insecticides in a book such as this may be inappropriate, and will soon be obsolete. At this time endosulfan and the synthetic pyrethroids (e g., cypermethrin, deltamethrin, and fenvalerate) are particularly popular for the control of the chewing insects (including *Helicoverpa*) while dimethoate and carbofuran are commonly used against the sucking insects and mites. Since no safe chemical will control all the pests, mixtures or "cocktails" of chemicals have been commonly marketed. The sale of such cocktails is discouraged in some countries, but there may be circumstances where it is beneficial to mix chemicals to control a damaging pest complex.

When to Apply the Pesticide

Timely application is essential. The appropriate pesticide should be applied on a "need basis" in response to pest counts. All too often the farmer sees his crop being devastated by the pests and then goes off to buy the insecticide, so losing both the crop and his money. Insecticides must be applied as soon as it is evident that a damaging attack is probable, but before the pests have caused much damage. For *Helicoverpa*, and other chewing pests, insecticides should be applied when their eggs are seen on the crop. It is relatively easy to see and count the white *Helicoverpa* eggs, but almost impossible to see or count the young larvae. The large larvae, and the damage they cause, are easily seen, but much more chemical is required to kill them and the damage cannot be repaired.

Economic Threshold

Pesticides should only be used when it is evident that the pest-caused damage that will be prevented will considerably exceed the cost of the treatment. This economic threshold is normally calculated as the number of pests per plant or unit area that will trigger the profitable use of pesticide. Economic thresholds vary across areas and years, depending on the cost of the treatment (pesticide plus application), and the price for which the pigeonpea can be sold. The calculation of economic thresholds is not easy and requires data collected from a series of pesticide trials.

Thresholds are normally expressed in average numbers of pests per plant. However, this brings in the obvious problem of the different plant sizes that result from the use of different plant varieties and spacings. For example, one *Helicoverpa* egg or larva per plant will be well below the economic threshold on crops with 3 large plants m^{-2} (30,000 large plants ha^{-1}, but very damaging in fields containing more than 30 plants m^{-2}. The obvious remedy is to count pests per unit area, but scouts find this difficult.

As a very rough generalisation, insecticide application may be economically justified when there are more than 15 *Helicoverpa* eggs or larvae on a well grown pigeonpea plant. It must be stressed that insecticide use is only likely to be profitable on well grown crops which have a good yield potential. Pesticides cannot conjure high yields from poorly grown crops.

Calendar-based Application

The application of pesticides "according to the calendar" is widely practised on pigeonpea in areas where *Helicoverpa* is a major pest in most years. Regular applications of pesticides regardless of whether there is a pest problem will give more profit to the pesticide manufacturer than to the farmer. But, the farmers adopt this practice because they will have experienced the trauma of crop loss and do not know how to use pesticides on a need basis, or have no confidence in their ability to do so. When they have invested a great deal of labour and other resources in a crop, the additional cost of pesticides as an insurance against crop loss appears good value.

The easiest way to extend the practice of counting pests in the crop and applying pesticides according to economic thresholds, is to introduce a new crop rather than trying to rectify what appear to be bad habits in an established system. The new short-duration pigeonpea gives us this opportunity in many areas, and it should be extended as a package that includes needs-based pesticide application. In most areas and years the short-duration pigeonpeas will require protection from pests.

As a minimum, farmers must be encouraged to monitor their crops from the flower bud stage, and to be prepared to spray as soon as they see more than a few *Helicoverpa* eggs or larvae on the crop. They should then repeat the application at 10-day intervals if there are still many pests on the crop. This combination of calendar and need-based application will be more readily accepted than a more complex scouting and counting routine. The alternative is a well organized pest attack warning service, conducted by competent and enthusiastic extension workers; this may be viable, but there are usually problems in funding and maintaining such initiatives.

Monitoring the Pests

Counting pests on the crop requires adequate training and the scout has to be well motivated, because the task becomes tedious. Alternative means of monitoring pest populations are being extensively researched. The obvious alternative is to attract the pests to traps where they can be counted. Several night-flying insects, including *Helicoverpa* are attracted to lights,and it is not difficult to construct a cheap trap that will catch them. Also, cheap pheromone traps are available for several pest species, including *Helicoverpa*; a pheromone being a chemical scent that is exuded by a female insect to attract a mate.

Unfortunately, such traps do not appear to be adequate substitutes for counting the pests on the crop. A 6-year study that compared catches of *Helicoverpa* moths in light and pheromone traps with the numbers of their larvae found on the crops (Figure 14.8) showed low correlations (r= 0.6) between the catches and counts (ICRISAT, 1988b). Light-trap catches are considerably influenced by moonlight and other factors, while pheromone trap catches are influenced by wind velocities. Thus, simple counts of moths caught in the traps cannot be relied upon as indicators of whether or not to apply pesticide.

In some areas farmers have been persuaded to purchase light and pheromone traps for pest control. This is almost certainly a waste of money, for research has shown that although these

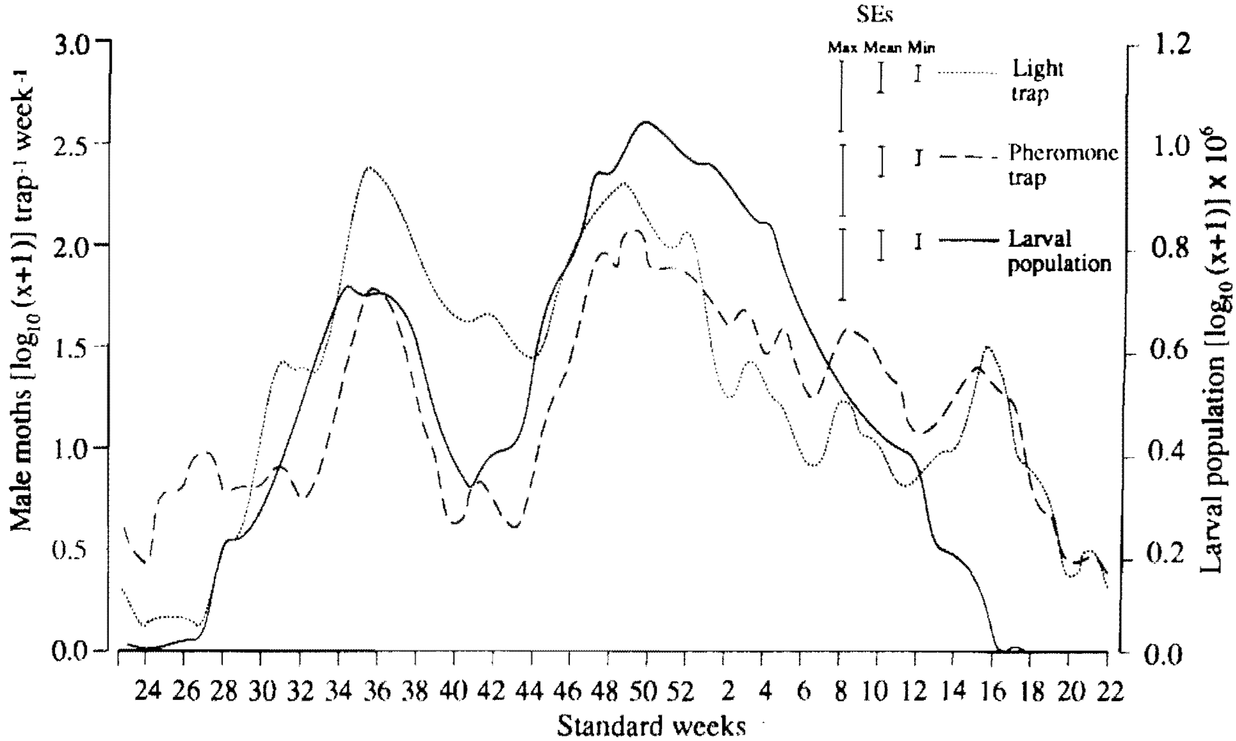


Figure 14.8. Mean catches per standard week of *Helicoverpa armigera* male moths in light and pheromone traps, and the larval populations, estimated from counts on all hosts at ICRISAT Center, 1981–87.

Source: ICRISAT, 1988b.

traps may catch many moths, they catch only a tiny proportion of the available populations, and have no measurable effect on infestations.

Among the major pigeonpea pests, the podfly is very difficult to control. The podfly is particularly prevalent on long-duration cultivars that are tall, and therefore very difficult to treat with insecticides. Also, most of the podfly's life stages (egg, larva, and puparium) are inside pods where they are protected from all but the systemic insecticides. Monitoring the podfly populations is also a problem for, as there are no external symptoms, many pods have to be opened to check on infestations. The adult flies are not easily counted in the field, and in spite of extensive research, no satisfactory monitoring traps have been developed. The adult fly is vulnerable to contact insecticides such as endosulfan, but numerous trials have indicated little or no profit from the use of insecticides against this pest.

Pesticide Application

The pesticide chemicals must be spread evenly over the target areas of the crop (usually the upper foliage, flowers, and pods) in order to control the pests. As only small amounts of chemicals are required (less than 100 g ha^{-1} for many modern pesticides) these must be thoroughly mixed with large quantities of a carrier to ensure adequate crop coverage. Most application is in the form of sprays, using water as the carrier, through manually operated pumps. Large quantities of water, up to 1000 L ha^{-1} are often recommended to ensure adequate coverage. However, such high-volume spraying expends a great deal of time and energy, and much of the spray liquid drips from the plant to the soil where it is wasted. More powerful, and costly, motorized mist blowers can give good plant coverage using much less water (<200 L ha^{-1}).

Such spraying requires considerable quantities of clean water, which is seldom readily available close to the farmer's field. Such problems encourage the use of dusts, in which the insecticide is mixed with an inert, finely divided carrier such as kaolin. Cheap and efficient crop-dusting machinery is seldom available, so farmers resort to shaking the dust onto the plants through muslin bags, or even throwing handfuls of dust in the air in the hope that the wind will spread it evenly over the crop. Much of the dust falls to the soil, and heavy rain will wash many formulations from the plants.

An apparently attractive alternative means of application, particularly where water is scarce, is provided by battery driven, spinning-disc sprayers (Figure 14.9) which generate many small droplets and can give adequate crop coverage with less than 15 L ha^{-1}.

This ultra-low volume spraying is commonly referred to as controlled droplet application (CDA), for the size of the droplets can be controlled within a fairly narrow range by varying the disc speed and the flow rate of the liquid (Mathews, 1979). Care must be taken to ensure that the

Figure 14.9. Spraying pigeonpea with a battery-driven, spinning-disc sprayer.
Photo: ICRISAT.

droplet size is small enough to give adequate crop coverage, but not so small that the droplets drift without landing on the crop. For this type of spraying oils are better carriers than water, since small water droplets may evaporate before they reach the plants. Unfortunately, most insecticide formulations are not soluble in readily available non-toxic oils, and few insecticides are marketed in appropriate oil based formulations.

Spraying any type or dusting should not be undertaken in strong winds (> 15 km h^{-1}), or when heavy rain threatens.

Problems Associated with Insecticide Use

Toxicity Dangers

Most insecticides can not only kill insects, but most other animals including man, so great care must be taken in their handling, application, and storage. Many of the older insecticides have been withdrawn from the market because of concern about their toxicity to mammals, and many of the newer chemicals are relatively safe to use, but all insecticides must be regarded as poisonous and handled accordingly.

Insecticides should not be allowed to contract bare skin, so protective clothing, inlcuding gloves, must be worn when handling, mixing, or applying them. When spraying or dusting, the applicator must be held downwind of one's body and one should never walk through a recently treated crop.

The law in most countries require that insecticide container labels should give clear instructions on correct use and the precautions that must be observed. The user should read these instructions before opening the container and follow them, but few users do so. Pesticides should never be transferred to unmarked containers, nor to those that normally contain food or drink. Empty pesticide containers should be destroyed, and never used to carry food or drink. Pesticides must always be stored out of the reach of children and other irresponsible people.

In spite of all the warnings, many people are killed, or made acutely ill, by pesticides in every year. Many more develop chronic illness through repeated exposure to pesticides, usually because they do not wear protective clothing, or are careless in handling the pesticides. At ICRISAT Center all those who work with pesticides undergo regular medical checks, including blood tests.

The pigeonpea consumer is also at risk if persistent chemicals have been sprayed onto the pods. Most of the insecticide will not reach the consumer for it is on the pod walls that are removed during threshing. However, there is a greater risk when the pods are sold as green vegetables, particularly when the whole pods are eaten.

Natural Enemy Destruction

Insecticides kill not only the pests but also their natural enemies. If all the pests are adequately controlled, this would appear to be of little importance. But in some cases, minor pests that are normally reduced to low populations by their natural enemies can develop as a major problem if they are resistant to the insecticide. Red spider mite outbreaks are common on crops sprayed with insecticides that are not acaricidal. Another example is that of *Tanaostigmodes cajaninae* LaSalle, the pod wasp, which is rare in farmers' fields but has become a major pest on some research farms such as ICRISAT where pigeonpea pods are available for extended periods, and insecticides are more effective against the natural enemies than the pest (Lateef *et al.*, 1985).

Resistance to Insecticides

Perhaps the most disastrous consequence of widespread reliance on pesticide use is the selection of insecticide-resistant insects. The best known case is that of *Helicoverpa* spp on cotton in the

USA (and in Australia), where these pests have become resistant to the commonly used pesticides (Wilson, 1974; Reynolds *et al.*, 1975). As insecticide use had earlier eliminated the natural enemies, the *Helicoverpa* became devastating and farmers had no alternative to abandoning cultivation. At the time of writing this chapter, there are indications that *Helicoverpa* on cotton and pigeonpea in some areas of southern India is becoming increasingly difficult to kill with endosulfan and synthetic pyrethroids. If this proves to be resistance farmers will be clamouring for alternative means of controlling this pest.

HOST PLANT RESISTANCE

It has already been stressed that there is great genetic variation in pigeonpea, and that many genotypes can compensate for substantial pest-caused damage. Not all varieties show such tolerance; for example cultivar APAU 2208 gave high yields after losing its first flush of flowers whereas GS 1 yielded very little in similar circumstances (ICRISAT, 1980). The value of such compensatory ability is obvious, provided it is combined with the potential to give a high yield of good quality grain. But such tolerance may exact a price, for the plants may hold back resources to fuel the compensatory growth and plant survival into future years.

Some research at ICRISAT Center has been devoted to the development of annual pigeonpeas with the expectation that, in such types, all of the plant resources will be channelled into seed production, so the plant will die after giving the maximum possible yield. Such a plant type will be of utility where adequate plant protection can be assured. But, for most farmers, the need is for varieties that will give reasonable yields in most years without expensive pest control inputs. Such varieties have been naturally selected by generations of farmers who did not have access to chemical insecticides. Thus ICRISAT has devoted a considerable proportion of its pest management research resources to the selection and development of plants that tolerate or resist pest-caused losses.

Differences in Susceptibility

Early work at ICRISAT Center and elsewhere showed considerable differences in the susceptibility of the available pigeonpea genotypes to pest attacks. For example, the determinate types, in which pods are produced in bunches at the ends of the branches were found to suffer much greater losses (Table 14.3) than the indeterminate types on which the pods are well spaced along the branches (Lateef and Reed, 1981). The pod bunches offer niches in which pests such as *Helicoverpa* and *Maruca* larvae can conceal themselves, and thus are not exposed to predation when moving from pod to pod.

Screening for Resistance

There are many methods of screening plants for resistance to insect pests (Maxwell and Jennings, 1980). Most depend upon exposing the test plants, and those of a control cultivar, to adequate and equal numbers of the pests, and then comparing the development and/or multiplication of the pests, and the damage caused on the plants. Such testing is easiest in closed facilities such as greenhouses and screenhouses where the pests can be confined and other pests, parasitoids, and predators can be excluded. This method is particularly convenient for screening seedlings, since large numbers can be accommodated in trays, and several batches can be screened in each season.

Unfortunately, such screening methods were not practicable for the requirement to screen

Table 14.3. Pod borer damage on determinate and indeterminate segregants of pigeonpea cultivars of different maturity durations under unsprayed conditions on Alfisols and Vertisols, ICRISAT Center, 1975/76.

		Alfisols		Vertisols	
Parent cultivar (maturity duration)	Growth habit of segregant	Pods on 40 plants	Borer damage (%)	Pods on 40 plants	Borer damage (%)
Pusa Ageti (short)	Determinate	3 017	64.5	5 221	76.2
	Indeterminate	8 953	25.9	8 086	41.9
ICP 7050 (medium)	Determinate	11 259	23.3	5 431	49.0
	Indeterminate	17 582	12.1	13 511	21.1
ICP 6365 (long)	Determinate	3 242	25.4	4 750	42.9
	Indeterminate	8 047	15.5	8 449	27.1
SE (mean)		(±2.00)		(±2.09)	

pigeonpea for resistance to the pests that damage the crop at the flowering and podding stage. At this stage most genotypes are large, so few can be accommodated in a greenhouse, and the vegetative stage takes several months, so few tests could be conducted in each year. In the absence of very large field cages, it was decided to attempt screening large numbers of germplasm accessions in open fields, largely relying upon the natural infestations of the pests, but with some supplementation with laboratory-reared insects when needed.

Open Field Screening

There are two major problems in open field screening. First, patchy spatial distribution of the pests can result in "escapes", where a plant or genotype suffers less damage than others in the field by chance, rather than because of any inherent resistance. The second problem is that pest populations vary over time (Figure 14.10) so screening genotypes that vary in duration will simply lead to the selection of those that happen to be flowering when pest populations are low.

There have been many reports of "resistant" pigeonpeas, selected in open field screening, that on further testing proved to be susceptible and had obviously simply escaped damage in the first tests.

ICRISAT screening has been conducted in a large (>100 ha) pesticide-free area where the major pests, including *Helicoverpa* and podfly, have been common in each year. There were many (>11000) germplasm accessions to be screened and resources were limited, so preliminary testing was of 1000 or more accessions in small unreplicated plots in each year.

To overcome the problem caused by pest populations varying over time, the test accessions were grouped into narrow duration ranges. Thus, within each test group, all plants should be flowering simultaneously. Also, within each group, a commonly used cultivar of the appropriate duration was used as a control. The damage and pest counts on the test accessions, and their yields, were compared with those from the control cultivars. In an attempt to ensure adequate pest populations, rows of susceptible pigeonpeas of mixed durations were sown a few weeks before the test plots, so that a continuous supply of flowers and pods were available on which the pests could multiply in each field.

To overcome the problem of escapes, rather than selecting plants that were apparently resistant,

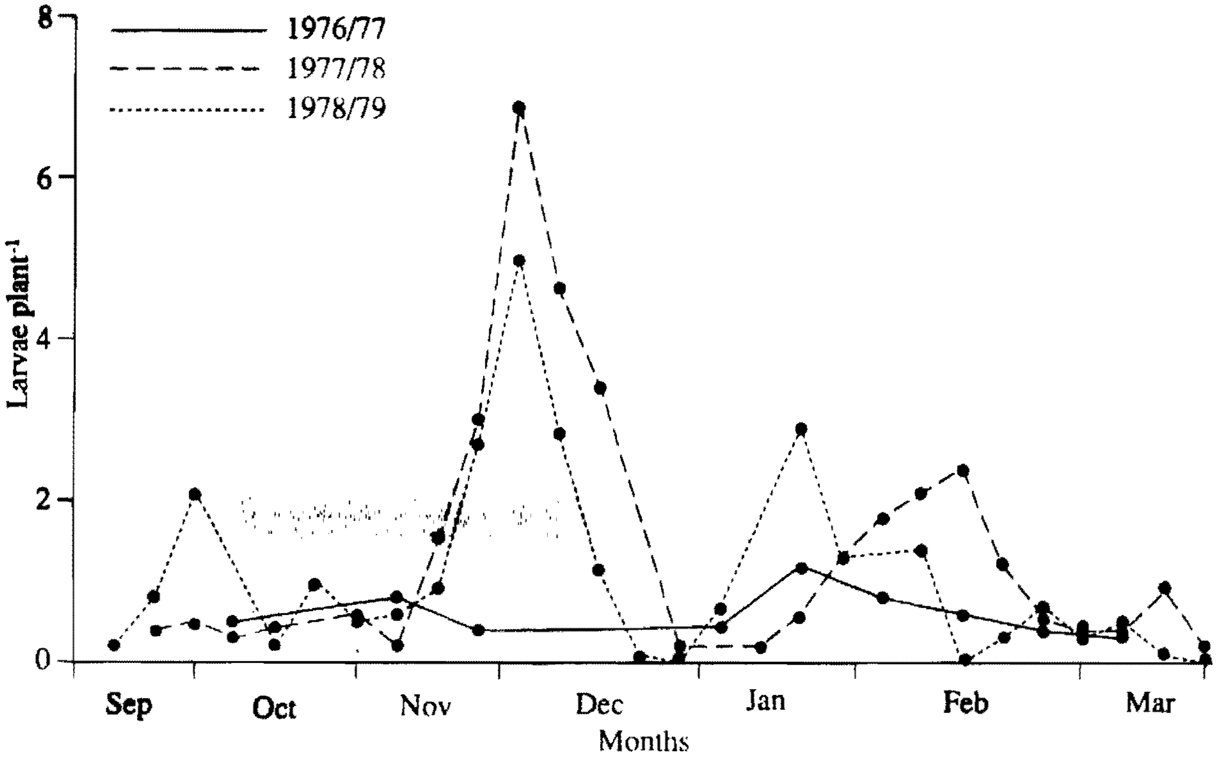


Figure 14.10. *Helicoverpa armigera* larvae (numbers plant^{-1}) on pigeonpea in pesticide-free fields at ICRISAT Center, 1976–1979.

all those that were more susceptible (i.e., those that suffered more damage and had lower yields) than the control were rejected. As most accessions were clearly more susceptible than the control cultivars, it was possible to discard most entries and test the survivors in 2-replicate, augmented-design trials using larger plots in the second year. From these the susceptible entries were again rejected, and the survivors were retested in 3- or 4- replicate trials in the third year. By the fourth year there were few survivors and these could be accommodated in balanced lattice square trials, that gave more precision than randomized-block trials. By this stage ICRISAT scientists were confident that the entries had useful resistance, so they were also grown in pesticide-protected trials to determine their tolerance and yield potential.

Typical results from one of these screening trials are illustrated in Table 14.4. Several genotypes in each duration group that showed some resistance, either to *Helicoverpa*, podfly, or the pest complex were selected; but none had sufficient resistance to ensure high yields in the face of intensive pest attacks.

Single Plant Selection and Selfing

Many of the germplasm accessions tested were not pure genotypes but variable populations, so there could be resistant and susceptible plants in the same plot in the preliminary screening trials. In this case seed from the apparently resistant plants was harvested, and used for subsequent tests.

As pigeonpea is readily cross pollinated, there are problems in keeping genotypes pure, particularly when they are grown in small plots among other genotypes that are flowering at the same time in a pesticide-free field. To avoid the problems that would arise in segregation of the plants in generations following such pollination, one or two plants in each genotype were covered with muslin bags through the flowering stage to prevent cross pollination, and the selfed seed from these was used for subsequent tests.

Table 14.4. Performance of some borer-resistant and control pigeonpea cultivars tested on unsprayed fields, ICRISAT Center, rainy season 1987/88.

Cultivars	Time to 50% flowering (days)	Pod damage (mean %)			Yield (t ha^{-1})
		Pod borer	Podfly	Total	
BDN 1 (control)	123	79.2	2.7	82.6	0.12
ICP 1903-E1-E6-E2	125	21.5	7.1	32.8	1.46
ICPL 87088	132	42.0	11.7	54.1	0.59
ICPL 87089	132	44.1	11.6	56.3	0.86
ICP 1903-E1-E1-E2	134	47.1	8.8	58.8	0.70
ICPL 84060	134	39.1	10.1	50.4	0.71
C 11 (control)	134	86.4	2.7	90.4	0.11
Trial mean (24 entries)		54.8	7.7	63.7	0.59
SE (mean)		±5.60	±1.60	±4.84	±0.588

Transferring Resistance from Wild Species

Some of the *Cajanus* species, the wild relatives of pigeonpea, show strong resistance to some of the major pigeonpea pests, including *Helicoverpa* and podfly, so derivatives of crosses between these species and pigeonpea were screened for pest resistance. Where the plants and seeds largely resembled their wild progenitors *Helicoverpa* resistance was obvious, but those that resembled pigeonpea were almost all at least as susceptible as the common cultivars. A few derivatives, particularly those from a cross involving *C. scarabaeoides* var. *scarabaeoides* showed some promise, and have been retained for further selection, but this screening programme appears to have been less productive than screening the germplasm selections. The major problem in attempting to transfer resistance from the wild species was that there was no surity that it could be usefully transferred. For example, the pods and seeds of *C. scarabaeoides* var. *scarabaeoides* are small, hard, and bitter, and if these characters form the mechanism of resistance there would be little value in breeding pigeonpeas with such resistance.

Mechanisms of Resistance

Having selected pigeonpea genotypes that had some field resistance to the pests, it was necessary to identify the mechanisms of that resistance, both to facilitate its exploitation in breeding programmes and to ensure that there were no toxic factors in the plants that might cause problems for consumers.

Field counts of eggs and larvae indicated that much of the *Helicoverpa* resistance in ICRISAT selections could be attributed to oviposition non-preference, since fewer eggs were laid on resistant than on susceptible plants. Feeding tests in the laboratory showed that *Helicoverpa* larvae grew more slowly when fed on seeds of some of the resistant selections, than those fed on seed from susceptible plants; thus there was evidence that antibiosis was involved in the resistance of some genotypes. No visible characters were identified as being indicative of resistance, but in general the large white-seeded pigeonpea were found to be particularly susceptible. This is unfortunate, as the grain from these types is particularly popular in many markets.

Studies of podfly resistant selections revealed that these all had relatively small seeds and pods, that are regarded as disadvantageous in most markets.

Research to identify the chemicals involved in the resistances is being undertaken at the Max-Planck Institute for Biochemistry, Munich, Federal Republic of Germany. Preliminary results have indicated that the oviposition attractant is located in the sesquiterpenoid fractions of plant extracts. Characteristic varietal differences have been detected in the desired fractions from resistant and susceptible genotypes.

Problems of Non-preference Resistance

Non-preference is generally considered to be of little value, for its effects may only be evident when the pests have a choice. When there is no choice because only the resistant cultivar is available, there may be no diminution of infestation. However, with a polyphagous pest such as *Helicoverpa* there will almost always be a choice, for many cultivated and wild plant species are attractive hosts.

Increased Resistance

The levels of resistance so far discovered are encouraging, and attempts are being made to intensify them. In a cooperative project with ICRISAT plant breeders, many crosses between the more resistant cultivars have been made, and the segregating progenies screened and tested for 5-6 years under unprotected conditions. This borer and podfly resistance breeding program has produced the following:

Borer-resistant lines: ICPX 77303, ICPL 87088, ICPL 84060, and ICPL 87089.

Podfly resistant lines: ICPL 82064-E15-E1, ICPX 81277-E42-E1, ICPX 82056-E4-E1, and ICPX 8211-E4-E1.

Combined Resistances

Unfortunately, most of the *Helicoverpa*-resistant selections available at ICRISAT Center have been found to be very susceptible to fusarium wilt, and are therefore useless in fields that are infested with this pathogen. Crosses between these selections and wilt-resistant genotypes have been made, and their progenies have been screened in a pesticide-free, wilt-sick field. Selections that combine wilt and pod borer resistance with high-yielding characters are bing evaluated for yield performance under unprotected conditions.

INTEGRATED PEST MANAGEMENT (IPM)

The recent indications that *Helicoverpa* in southern India is becoming resistant to insecticides further emphasise the folly of relying upon chemical pest control. There is little doubt that insecticides are needed to ensure a profitable increase in pigeonpea production. But, they must be used judiciously, in combination with other elements of pest management, otherwise we may soon be faced with pests that are impossible to control.

IPM must start with the seed. Understandably, almost all plant breeders insist that their materials and trials are well protected against pests, for the selection of more productive genotypes is very difficult where pests interfere with the normal growth and yields of the plants. However, plants that have been selected in protected environments may be useless in farmers' fields, where the same level of protection is not practicable or profitable. It is obviously desirable that all new cultivars should be highly pest-resistant, but it is equally obvious that this is impossible, at least in the near future. At ICRISAT Center what appears to be a sensible compromise has been reached:- most of the breeders' selection plots and trials are protected by insecticide use, but all of the advanced selections are subjected to tests in a pesticide-free area, where scientists can identify and reject any that are more susceptible than the cultivars that they may replace. This precaution is in addition to the intensive efforts being made to select resistant genotypes. Thus, the new genotypes produced by ICRISAT will either be at least as resistant, or tolerant as the cultivars that they are to replace, or will be high-yielding and/or high quality types that can be profitable when adequate protection is available.

All the farmers in an area should sow simultaneously, so that the pests will be diluted across the crop, rather than building up on the early flowering fields and then migrating to the later ones. There may be a transient problem in areas where the new, highly productive short-duration cultivars are adopted, for pest populations may build up on these and migrate to the later-flowering traditional crops in that area. However, where these new cultivars are successful, they will probably replace the traditional cultivars very rapidly.

Insecticides should only be applied when needed; this will seldom be before the flowering stage, so the natural enemies will have an opportunity to build up. If any means of biological pest control are available, then these should be used to replace or reduce insecticide use.

After harvest, the crop residues should be either removed and used as fuel, or ploughed in to the soil, to reduce the numbers of pests surviving from one season to the next.

REFERENCES

Bhatnagar, V.S. and Davies, J.C. (1979) Arthropod endoparasitoids on insect pests (excluding *Heliothis* spp.) recorded at ICRISAT Center, A.P., India, 1974-79. *Cropping Entomology Progress Report no. 3*. Patancheru A.P., India: Legumes Program, ICRISAT, 17 pp. (Limited distribution).

Bhatnagar, V.S. and Davies, J.C. (1981) Pest management in intercrop subsistence farming. In: *Proceedings of the International Workshop on Intercropping, 10-13 January 1979, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 249-257.

Bhatnagar, V.S., Lateef, S.S., Sithanantham, S., Pawar, C.S. and Reed, W. (1982) Research on *Heliothis* at ICRISAT. In: *Proceedings of the International Workshop on Heliothis Management, 15-20 November 1981, ICRISAT Center, India*. Patancheru, A.P., India: Legumes Program, ICRISAT, pp. 385-396.

ICRISAT (1980) *Pulse Entomology (Pigeonpea) Report of Work, June 1979-May 1980, Departmental Progress Report-5*. Patancheru, A.P., India: Legumes Program, ICRISAT, 88 pp. (Limited distribution).

ICRISAT (1982) *Pulse Entomology (Pigeonpea) Report of Work, June 1981-May 1982, Departmental Progress Report-9*. Patancheru, A.P., India: Legumes Program, ICRISAT, 103 pp. (Limited distribution).

ICRISAT (1988a) *Pulse Entomology (Pigeonpea) Report of Work, June 1986-May 1987, Departmental Progress Report-22*. Patancheru, A.P., India: Legumes Program, ICRISAT, 97 pp. (Limited distribution).

ICRISAT (1988b) *Annual Report 1987*. Patancheru, A.P., India: ICRISAT, pp. 152-155.

Joyce, R.J.V. (1982) A critical review of the role of chemical pesticides in *Heliothis* management. In: *Proceedings of the International Workshop on Heliothis Management, 15-20 November 1981, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 173-188.

King, E.G., Powell, J.E. and Smith, J.W. (1982) Prospects for utilization of parasites and predators for management of *Heliothis* spp. In: *Proceedings of the International Workshop on Heliothis Management, 15-20 November 1981, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 103-122.

Lal, S.S., Yadava, C.P. and Chandra, S. (1986) Suppression of podfly damage through varietal selection. *International Pigeonpea Newsletter* 5, 42-43.

Lateef, S.S. and Reed, W. (1981) Development of a methodology for open-field screening for insect pest resistance in pigeonpea. In: *Proceedings of the International Workshop on Pigeonpeas, volume 2, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 315-322.

Lateef, S.S. and Reed, W. (1983) Review of crop losses caused by insect pests in pigeonpea internationally and in India. In: *Crop Losses Due To Insect Pests, volume-II*. Special Issue, Indian Journal of Entomology. The Entomological Society of India, Hyderabad Branch, India, pp. 284-291.

Lateef, S.S. and Reed, W. (in press) Insect pests on pigeonpea. In: Singh, S.R. (ed), *Insect Pests of Tropical Food Legumes*. IITA and John Wiley and Sons, Chichester.

Lateef, S.S., Reed, W. and LaSalle, J. (1985) *Tanaostigmodes cajaninae* LaSalle sp. n. (Hymenoptera: Tanaostigmatidae), a potential pest of pigeonpea in India. *Bulletin of Entomological Research* 75, 305-313.

Mathews, G.A. (1979) *Pesticide Application Methods*. Longman, London, 334 pp.

Maxwell, F.G. and Jennings, P.R. (1980) *Breeding Plants Resistant to Insects*. John Wiley and Sons, USA, 683 pp.

Pollard, G.V. and Guiseppi-Elie, A. (1981) Studies on the economic importance of the blossom thrips, *Frankliniella insularis* (Thripidae, Thysanoptera) on pigeonpea, *Cajanus cajan*, in Trinidad. *Tropical Agriculture (Trinidad)* 58, 281-286.

Rawat, R.R., Singh, Z. and Jakhmola, S.S. (1969) Effect of infestation of blossom-thrips on pod setting in pigeonpea, *Cajanus cajan* (L.) Millsp. *Indian Journal of Agricultural Sciences* 39, 623-625.

Reed, W., Lateef, S.S., Sithanantham, S. and Pawar, C.S. (1989) *Pigeonpea and Chickpea Insect Identification Handbook. Information Bulletin no. 26*. Patancheru, A.P., India: ICRISAT, 120 pp.

Reynolds, H.T., Adkisson, P.L. and Smith, R.F. (1975) Cotton insect pest management. In: Metcalf, R.L. and Luckmann, W.H. (eds), *Introduction to Insect Pest Management*. John Wiley and Sons, New York, pp. 379-443.

Saunders, J.L., King, A.B.S., Vargas, S.C.L. (1983) *Plagas de cultivos en América Central - Una Lista de Referencia. Boletin Tecnico no. 9*. Departamento de Produción Vegetal, Centro Agronomico Tropical de Investigacion Y Enseñanza, CATIE, Turrialba, Costa Rica.

Sheldrake, A.R. and Narayanan, A. (1977) *Pulse Physiology Annual Report 1976-77, Part I, Pigeonpea Physiology*. Patancheru, A.P., India: Legumes Program, ICRISAT, pp. 39-59 (Limited distribution).

Sheldrake, A.R., Narayanan, A. and Venkataratnam, N. (1979) The effect of flower removal on the seed yield of pigeonpeas (*Cajanus cajan*). *Annals of Applied Biology* 91, 383-390.

Sithanantham, S., Bhatnagar, V.S., Jadhav, D.R. and Reed, W. (1982) Some aspects of *Trichogramma* spp. in eggs of *Heliothis armigera* (Hub.) (Lepidotera : Noctuiidae). Paper presented at the International Symposium on *Trichogramma*, 20-23 April 1982, Antibes, France, 12 pp.

Sithanantham, S., Kumar Rao, J.V.D.K. and Rameshwar Rao, V. (1987) A pot-culture method for infesting pigeonpea root nodules with *Rivellia angulata*. *International Pigeonpea Newsletter* 6, 68-69.

Sithanantham, S., Kumar Rao, J.V.D.K., Reed, W. and Dart, P.J. (1981) Studies on nodule damage in pigeonpea. In: *Proceedings of the International Workshop on Pigeonpeas, volume 2, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 409-415.

Wilson, A.G.L. (1974) Resistance of *Heliothis armigera* to insecticides in the Ord irrigation area, North Western Australia. *Journal of Economic Entomology* 67, 256-258.

Chapter 15

PIGEONPEA: BREEDING

LAXMAN SINGH, S.C. GUPTA, and D.G. FARIS

Principal Agronomist, Eastern African Regional Cereals and Legumes (EARCAL) Network, ICRISAT, C/o OAU/STRC, J.P.31 SAFGRAD, P.O. Box 30786, Nairobi, Kenya, Plant Breeder, and Principal Coordinator Asian Grain Legumes Network, Legumes Program, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Andhra Pradesh 502 324, India.

INTRODUCTION

Pigeonpea is grown under a wide range of cropping systems in many countries. This is because of the diversity of production environments, genotypes available, and the end uses of its products. This wide diversity makes its improvement a dynamic challenge.

For any crop species the nature and magnitude of genetic variation, its reproductive behaviour, adaptation to environments and cropping systems, and usage have a bearing on the objectives and methods chosen for its genetic improvement.

In addition to knowing about pigeonpea's phenology and reproductive system, breeders also need to be aware of its centres of origin, existing genetic variability in the species, and its wild relatives.

Although both Africa (Zeven and Zhukorsky, 1975) and India (De, 1974) have been suggested as the place of origin of pigeonpea, in a recent review van der Maesen (1980) concluded that, "floristic, linguistic, and cytological evidence points to an Indian origin of the pigeonpea, from where it was most probably distributed to Africa at least two millennia BC". He also feels Africa is a definite secondary centre of origin since some pigeonpea characters found in African material are not present in material originating from the Indian sub-continent. Reddy (1973) and De (1974) postulated that the genus *Cajanus* probably originated from an advanced *Atylosia* species through single-gene mutation. *Atylosia cajanifolia (C. cajanifolius)* is presumably the link between the genus *Atylosia* and the genus *Cajanus*. Recently, van der Maesen (1986) revised the taxonomy of the genera *Cajanus* and *Atylosia* and suggested merging them into *Cajanus* (see Chapter 2).

Pigeonpea is botanically a short-lived perennial (Kay, 1979) but is remarkable in that its duration and growth habit form a continuum of short-duration, near-annual types to long-duration perennial types. Based on days to 50% flowering pigeonpea breeders at ICRISAT classified pigeonpea varieties into 10 maturity groups, and grouped them into four photoperiod response groups (Table 3.3). Byth *et al.* (1981) for convenience reduced the diversity of production systems to three classes based on phenology, general similarity of plant growth, and development within a phenological class. These classes were defined as long-season, full-season, and short-season crops. For the sake of uniformity in nomenclature, Gupta *et al.* (1989) classified short-duration pigeonpeas into three groups; extra-short-duration, short-duration A, and short-duration B.

Pigeonpea is a quantitative short-day plant and its phenology is influenced by complex photoperiod and temperature interactions (Byth *et al.*, 1981; Whiteman *et al.*, 1985). Since phenology underlies the development of production systems, knowledge of its effect and control is important in pigeonpea improvement. The constraint of confining a breeding programme to a particular phenological group may result in a narrowing of the genetic base, particularly in the short-duration group. To broaden the genetic base, genetic material from other phenological groups can be introgressed if necessary. There are no complete insensitivities to photoperiod and temperature influences in pigeonpea. Like soybean, short-duration cultivars of pigeonpea are relatively less sensitive to both influences. Because of the crop's photoperiod sensitivity and the influence of temperature on growth and development, sowing date has a marked effect on its phenology and growth. Laxman Singh *et al.* (1971) in India, Spence and Williams (1972) in Trinidad, Abrams and Julia (1973) in Puerto Rico, and Akinola and Whiteman (1975) in Australia all observed that crops sown in the months when daylengths were short flowered sooner, and were shorter, and had fewer branches than crops sown in months when days were long. Photoperiod-sensitive cultivars flower more rapidly when sown after the longest day, i.e., when days start getting shorter (Whiteman *et al.*, 1985).

The flowers of pigeonpea are cleistogamous, a condition that generally favours self pollination. However, unlike other major grain legumes, a considerable degree of natural outcrossing exists in pigeonpea. Howard *et al.* (1919) were the first to report outcrossing in pigeonpea to the extent of 14%. Since then several studies have reported outcrossing to range from 0 to 70%. At a given site the factors that may affect the extent of cross pollination are the flowering habit of the cultivars, the type and number of insect pollinators present in relation to the number of flowers, the location of the field in relation to the habit of pollinating insects or barrier crops, and environmental factors such as temperature, humidity, wind velocity, and direction (Bhatia *et al.*, 1981). Besides environmental and genetic factors and insect pollinators, genetic variation can determinate the magnitude of outcrossing. Prasad *et al.* (1972) reported genetic differences in the extent of natural outcrossing among pigeonpea cultivars. Byth *et al.* (1982) also observed a similar variation in two pigeonpea lines in Australia. They observed that within the same field and same year Prabhat exhibited >40% natural outcrossing while Royes exhibited <2% natural outcrossing. They attributed the reduced natural outcrossing in Royes to the "wrapped petals" modification in its floral morphology, a condition where the overlapping of the standard petal delays the opening of the flower. A cleistogamous flower type which provided a mechanism for almost complete selfing was reported in pigeonpea (ICRISAT, 1979). In this flower type flower opening is delayed, thus reducing the chances of outcrossing.

With the recent development of short-duration cultivars, a significant step towards the evolution of pigeonpea as a field-scale crop has been taken. This improvement means that research is no longer confined to increasing the productivity and stability of the existing production systems that are based on long-duration genotypes, but now includes the challenge of developing new production systems in both traditional and nontraditional areas of adaptation. Hence, in addition to genetic variability, reproductive behaviour, and phenology, a consideration of different production systems has now become a central issue in pigeonpea improvement.

BREEDING OBJECTIVES

Increased yield with acceptable grain quality and stability is the major breeding objective across phenological groups. Stability in production is sought by incorporating resistance or tolerance to such major biotic stresses, such as diseases (sterility mosaic, wilt, phytophthora blight) and pests (pod borer, podfly), and such abiotic stresses as waterlogging, drought, acidity, and salinity.

Pigeonpea is grown in a diverse array of cropping systems and for multiple uses (food, fodder, and fuel). This requires the nomination of clear objectives with respect to general and/or specific adaptation of the crop to the existing or new cropping systems. The adaptation of improved genotypes of different phenological types to such systems as; intercropping, alley cropping, multiple cropping, and multiple harvests (ratoonability), is an important objective in pigeonpea improvement.

Accomplishment of these objectives will depend on scientific knowledge of the plant attributes needed to realize yield gains and stability. These attributes include; appropriate duration, rapid early growth, ratoonability, annuality or perenniality, total biomass production and/or high harvest index, determinate or indeterminate growth habit, and resistances to biotic and abiotic stresses peculiar to the system.

Some objectives will be common across systems but others will be system-specific. A few of the objectives relevant to some existing and potential production systems are given in Table 15.1.

Breeding program also need to be concerned with the suitability for existing end product uses, such as, vegetables fodder, high protein content for the animal feed industry, processing for canning, market preferences (e.g., seed size and colour), milling quality for split peas, and potential new uses such as fermented products and noodles. The effectiveness of selection is greatly advanced when the nature of genetic variation is understood, and rapid and reliable screening techniques are available.

Not all the issues given in Table 15.1 can be tackled simultaneously, nor will some be pursued until stable sources of resistance are identified and screening techniques developed. Resistances to abiotic stresses such as drought, salinity, acidity, and waterlogging, and breeding for efficient nitrogen-fixing ability are likely to be pursued when advances in screening techniques are made, and genetic variation studied further.

GENETIC VARIATION

Pigeonpea grows well in tropical and subtropical environments between latitudes 30°N and 30°S. Even though 90% of the world area is sown in India, in over 50 countries pigeonpea is grown for a variety of uses (food, fodder, fuel wood, rearing lac insects, hedges, windbreaks, soil conservation, green manuring, etc. (see Chapters 1 and 16). It is obvious, therefore, that human and natural selection has resulted in the development of plant and grain types suitable for different uses, environments, and production systems. The great plasticity of the taxon therefore needs careful study if the natural genetic variability is to be effectively used. Systematic efforts to understand and document the variability in the species started in the early 20th Century. Krauss (1927) distinguished the short, yellow-flowered, early type from the tall, red and yellow flowered late-maturing types. In India, the Imperial Economic Botanist in Pusa surveyed the types of pigeonpea in 1928/29.

Table 15.1. Some objectives of pigeonpea improvement for various production systems.

Objective	Relevance to geographic regions, production systems, uses, phenology
Yield enhancement[1]	All production systems and phenological groups
Resistance to fusarium wilt (*Fusarium udum*)	Important in long- and medium-duration groups, multiple harvest system for short-duration, and perennial agroforestry systems
Resistance to sterility mosaic disease	All phenological groups on Indian subcontinent
Resistance to phytophthora blight (*Phytophthora drechsleri* f.sp *cajani*)	All phenological groups
Resistance to alternaria leaf spot (*Alternaria tenuissima*)	Postrainy-season cropping in Northeast plains zone in India
Resistance to dry root rot (*Rhizoctonia bataticola*)	In off-season (spring season, postrainy season), perennial system in eastern Africa
Resistance to leaf spots (*Cercospora* sp)	Eastern Africa
Resistance to powdery mildew (*Oidiopsis taurica*)	Eastern Africa, higher altitudes
Multiple disease resistance	Most geographic regions and all phenological groups
Resistance to pod borer (*Helicoverpa armigera*)	In all phenological groups, but particularly short-duration
Resistance to podfly (*Melanogromyza obtusa*)	In medium- and long-duration groups, and probably in short-duration group
Resistance to leaf webber (*Maruca testulalis*)	Short-duration group
Resistance to pod-sucking bugs (*Clavigralla* spp)	Eastern Africa, in all phenological groups
Shorter duration	For multiple cropping, multiple harvest, high latitudes and altitudes, and year-round production for vegetable purposes.

1. Includes such yield and growth components as plant height, pod number, seed size, seed colour, pod size, growth habit, harvest index, biomass, and acceptable quality wherever necessary.

This variability was documented by Shaw *et al.* (1933). Selections from landraces have resulted in the release of improved cultivars (Pathak, 1970). More recently Reddy *et al.* (1975) reported the variability for some agronomic traits among a collection of 877 lines. Laxman Singh and Shrivastava (1976) made a collection of 900 samples from central India, and reported variability in relation to the adaptation to production systems. Reddy and Rao (1975) and Rao *et al.* (1977) observed that natural variation in pigeonpea was also due to somatic variation, in addition to genetic mutations and outcrossing. The All India Coordinated Pulses Improvement Project (AICPIP) of the Indian Council of Agricultural Research (ICAR) in collaboration with the United States Department of Agriculture (USDA) and the Indian Agricultural Research Institute (IARI) collected 5244 germplasm lines, and in 1969 a mimeographed catalogue was published in New Delhi. In 1973/74 this germplasm material was sent to ICRISAT Center. By June 1989, ICRISAT had a world collection of 11,171 accessions from 52 countries (R.P.S. Pundir, ICRISAT personal communication). This represents a wide range of variability for a large number of agronomic and morphological characters. The range of variability for quantitative characters available in the pigeonpea germplasm at ICRISAT Center is documented in the catalogue published in 1988 (Remanandan *et al.*, 1988).

HISTORY OF BREEDING

Since the beginning of pigeonpea cultivation farmers exercised selection for maturity duration suited to their production system and uses. Plant type, seed coat colour, seed and pod size were also considered when selections were made. As a result, landraces adapted to growing conditions and use preferences were developed, and are still popularly grown.

Early breeding efforts aimed at improving yield and acceptability to specific uses and production systems, and selections were made from landraces. Despite considerable outcrossing in the species, pedigree selection methods applicable to self-pollinated crops were also used.

In India the study of landraces with potential for improvement by selection started early in this Century (Howard *et al.*, 1919; Mahta and Dave, 1931; Shaw *et al.*, 1933; Pal, 1934). Pathak (1970) gave a detailed account of work done on pigeonpea improvement in the 1940s and 1950s under ICAR-sponsored schemes in various Indian states. Several varieties were evolved as a result of this work (Table 15.2). ICAR sponsored the formation of the multidisciplinary AICPIP at the end of 1965. Pigeonpea breeding work by AICPIP has been reported by Ramanujam and Singh (1981). Tunwar and Singh (1985) listed 57 varieties of pigeonpea notified or released in India (Table 15.3), the majority of the varieties listed have been developed by selection from the landraces.

In Kenya, recent pigeonpea improvement work at the University of Nairobi was reviewed by Onim (1981). As a result of this work NPP 670, a relatively short-duration line that matures in 160 days was released. Omanga and Matata (1987) reported the development of early (<150 days) lines 60/8, 50/3, and II RA with yields of 3 t ha^{-1} of dry grain in multiple harvests, and medium- (576/6, 777, and 81/3/3), and long-duration (E9/6, 788, and E31/4) cultivars with higher grain and fodder yields than local landraces.

In Uganda, pigeonpea improvement work started with the collection of landraces in 1968 and a world collection was acquired from India, eastern Africa, South America, and Puerto Rico. Khan and Rachie (1972) have summarized this early work. In Nigeria, the International Institute of Tropical Agriculture (IITA) selected cultivars from elite stocks identified or developed in their breeding programme. These lines have been distributed world-wide for trials by cooperators (IITA, 1976).

Table 15.2. Pigeonpea varieties evolved in different states of India before 1970.

State	Improved cultivars	Maturity duration
Andhra Pradesh	RG 72, RG 37(SA 1), RG 434, RG 476, RG 56	Medium-late (170-190 days)
	RG 97	Late (200-225 days)
Gujarat	Vijaypur 49	Medium-late
Madhya Pradesh	No. 148, Cross 86	Medium-late
	Gwalior 3	Late
Madras	SA 1	Medium-late
Maharashtra	C 11, No. 148, T 84, K 132, Tur Hyderabad	Medium-late
Mysore	C 21	Early (< 160 days)
	C 11 (Thogari 3)	Late
	Thogari 155-016 (Thogari 2), T 136-1, TS 24	Medium and medium-late
Uttar Pradesh	T 17, T 105, T 7	Late
	T 21, T 1	Early
West Bengal	B 7	Medium-late

Source: Pathak, 1970.

Table 15.3. Notified varieties of pigeonpea in India.

Selections from landraces/germplasm	Selections from segregating populations
Short-duration (maturing in < 140 days)[1]	
AL 15, UPAS 120, Hy 5, Co 1 — Co 4	Prabhat, T 21, Manak (H 77 216), Co 5, TAT 10, Vishakha 1 (TT 6)
Medium-duration (maturing in 141-200 days)	
BR 183, BS 1, C 28, GS 1, Hyderabad 185, Hy 1 to Hy 5, Khargone 2, LRG 30, LRG 36, No. 84, No. 290-21, PDM 1, PT 221, PT 301, SA 1, Sharda (S 8)	Laxmi (Kanke 3), S 20, TAT 5 (TT 5), Pusa 74, Pusa 84 (4 84), Pusa Ageti (S 5)
	Alternaria blight resistant
	20 (105) Rabi
Wilt-resistant/tolerant	
BDN 1, BDN 2, C 11, F 52, Mukta (R 60), No. 148, ST 1	
Long-duration (maturing in > 200 days)	
Basant (1234), Chuni (B 517), Gwalior 3, Sweta (B 7), T 7, T 17, T 15–15	JA 3
Sterility mosaic resistant	
Bahar (1258)	
Wilt-resistant	
NP(WR) 15	

1. Co 1 to Co 5, and Vishakha 1 are listed as short-duration but take longer to mature at higher latitudes (>20°N).

Source: Tunwar and Singh, 1985.

In Trinidad and Tobago pigeonpea lines suitable for dhal making were introduced from Pusa, India in 1937. Breeding work was sporadic until 1956, when Gooding (1962) initiated a programme of collection, hybridization, and selection aimed at increased production of immature green pigeonpeas. Further improvement work in the West Indies was reported by Ariyanayagam (1975). The recommended varieties were Code 1, and Chaguarama Pearl. More recently, Ariyanayagam (1981) gave an update on pigeonpea breeding in the Caribbean regional programme, and reported newly developed lines UWI 17 and UWI 26. In the countries of the Caribbean and Central and South America, tall, indeterminate, and photosensitive types are grown by small-holder farmers. A need for early-maturing types that are insensitive to daylength, and/or temperature for year-round production for fresh green peas and dry grain has been suggested. In Puerto Rico pigeonpeas are produced for canning and fresh vegetable green peas. Abrams (1975) summarized the pigeonpea research in Puerto Rico; the main breeding objectives were to develop high-yielding and high quality, indeterminate types in early, medium, and late groups, and semi-dwarf or dwarf determinate types resistant to leaf rust and adapted for mechanical harvesting. Kaki is the most popular variety with the canneries (Aponte Aponte, 1963). 2B-Bushy is an early-maturing, semi-dwarf type. In Guadeloupe, several local and introduced types have been evaluated, and suitable lines identified (Derieux, 1971). In Venezuela, a cultivar called Panameno, selected and released in 1972, has been described by Rivas and Gomez Rivas (1975).

In the USA, a nematode-resistant cultivar called Norman (selected from PI 218066, a strain from Pakistan) was first tried in North Carolina and then in Florida (Killinger, 1968). A breeding programme was started at the University of Hawaii in 1919/20. Pigeonpea's potential as forage led Krauss (1921, 1927) to breed it for this purpose, and a cultivar named New Era was released and extensively cultivated. In 1929 as sugarcane cultivation took over the land sown to pigeonpea, interest shifted to other forage legumes that would grow better than pigeonpea at higher elevations, and today the pigeonpea is seldom sown in Hawaii.

The establishment in India in 1972 of ICRISAT with its world mandate for pigeonpea improvement created a new impetus and interest in research efforts on the crop. ICRISAT has since sent pigeonpea germplasm, breeding lines, and segregating populations to cooperators all over the world in an attempt to develop short-duration pigeonpea lines suitable for mechanized production, and export markets. At the University of Queensland, Australia this work has resulted in the release of three cultivars, Hunt, Quantum, and Quest, that are relatively photoperiod-insensitive, short-duration cultivars suitable for mechanized cultivation. Meekin *et al.* (1988) described the performance of Quantum; it was derived from the ICRISAT cross between T 21 × JA 277, and is a sister line of ICPL 87. It has outyielded Hunt by 34%.

Results of international multilocational trials and breeding lines sent out by ICRISAT to the cooperators in several countries of the world have been summarized (Sharma *et al.*, 1981; ICRISAT, 1989, 1988a). As a result of multilocational cooperative testing, several cultivars have been identified for release; e.g., a mid-late vegetable type, ICP 7035 known as Kamika in Fiji; a long-duration wilt-resistant type, ICP 9145 in Malawi; a wilt-resistant, medium-duration type, ICP 8863 known as Maruti, in Karnataka, India; the short-duration ICPL 87 that has good ratoonability for multiple harvests and is known as Pragati in peninsular and central India; short-duration ICPL 151 with tolerance to sterility mosaic disease for multiple cropping in rotation with wheat, called Jagriti, in north and central India; and a long-duration, sterility mosaic resistant line, ICPL 366, in Nepal. Short-duration cultivars, such as ICPL 87 and ICPL 151 have shown wide adaptation, particularly in Sri Lanka, Myanmar, the Philippines, Zimbabwe, Malawi, and Tanzania; although insect pests remain the major constraint to realizing an optimum production of 2-3 t dry grain ha^{-1}. However, up to 5 t ha^{-1} has been obtained in multiple harvests of ICPL 87 in peninsular India (Chauhan *et al.*, 1984). The cooperative international adaptive testing of new short-duration pigeonpea genotypes by ICRISAT is not confined to traditional pigeonpea-growing areas (between latitudes 30°N and 30°S), it is also conducted in nontraditional growing areas up to latitude 45°N.

Short-duration genotypes such as, ICPLs 85030, 85010, 83015, 83019, and 84023 that are relatively insensitive to photoperiod and temperature interactions when sown in May/June, can be harvested for dry grain production before killing frosts in October at latitudes between 32° and 46°N in the USA and South Korea. The same genotypes when sown in June mature in 90-100 days at latitude 17°N at ICRISAT Center. The area of pigeonpea adaptation could therefore be expanded to higher latitudes, where mechanized commercial production would be possible.

The short-duration pigeonpeas are likely to be considered for the new production systems in situations listed in Table 15.4. These systems are based on observations on adaptation trials and discussions with the scientists who conducted the trials in several countries.

Table 15.4. Suggested new production systems using short-duration pigeonpea.

Country	Latitudes/Altitudes	Existing production systems	Suggested new production systems
Kenya	0-25°S 1000-2000 m	Long-duration (6-9 months) cultivars grown intercropped with maize, sorghum and pearl-millet. Sown in Oct with short rains and harvested after long rains in Sep.	1. Short-duration (4-5 months) sole crops to be sown in rotation with wheat in the Rift Valley. 2. Short-duration crops to follow a rice crop in irrigation project areas, to be sown in Dec. 3. Oct-and Apr-sown sole or intercrops sown with such short-duration legumes as groundnut and cowpea in rainfed dryland areas in Eastern and Coastal provinces.

Table 15.4. continued.

Country	Latitudes/Altitudes	Existing production systems	Suggested new production systems
Tanzania	6°S 500-1200 m	Small plots with tall long-duration varieties mixed with sorghum, maize, and other crops. Sown in Jan-Feb and harvested in Sep-Oct, taking advantage of bimodal rainfall with peaks in Nov-Jan and Mar-May.	1. Sole short-duration (3-4 months) crops sown in Feb-Apr. Multiple harvested genotypes with good ratoonability such as ICPL 87.
Malawi	14°S 600-1100 m	Long-duration cultivars mixed-cropped with maize. Wilt is major disease.	1. Recently released wilt-resistant cultivar ICP 9145 for the existing cropping system. 2. Short-duration types like ICPL 87, ICPL 146 that have potential for sole cropping and multiple harvesting when sown in Dec-Jan.
Zimbabwe	17-21°S 800-1600 m	Similar to Malawi.	1. Sole short-duration crops for mechanized cultivation such as ICPL 87, or 84039 when sown in Nov-Dec.
Philippines	14°N, 50 m	On homesteads, a few tall long-duration types are grown for green peas and dry grain.	1. Northern Philippines – Short-, and medium-duration types sown in Oct-Dec after rice on residual moisture, limited irrigation, or zero tillage. Medium-duration types for intercropping with corn/mung bean sown in Sep on uplands. 2. Southern Philippines – Short-, and medium-duration types sown in Aug-Sep after maize and upland rice. Long-, and medium-duration types sown at the start of the wet season, i.e., Apr-May on contours in 5 to 10-m alleys with maize and rice in between.
Sri Lanka	8°N 50-300 m	On homesteads, a few tall long-duration types are grown.	1. Dry zone – short-duration types with ratoon-ability as sole crops for multiple harvests in the "Maha" season sown in Oct, and "Yala" season sown in Apr-May. 2. Intermediate zone – As above and intercropped with coconut. Medium- and long-duration types as alley crops in agroforestry systems.
Myanmar	19°N sea level-100 m	Medium- and long-duration types grown as sole and intercrops with cotton and sesamum in semi-arid central Myanmar.	1. Short-, and medium-duration types sown in Oct-Dec after rice in transition and delta regions. 2. Short-duration types sown in Apr-May and Aug-Sep in the central region.

BREEDING METHODS

Adaptation

Pigeonpea breeding methods and programmes are influenced by the species - including its specificity of adaptation, photoperiod reactions, outcrossing, and the multiplicity of cropping systems in which it is grown. However, as mentioned earlier, most of the early improvement work was confined to selection and pedigree evaluation from landraces adapted to the region in which such selection was exercised. In India, where 90% of world's pigeonpea is grown in widely diverse environmental conditions and cropping systems, a start was made in 1965 to pool cultivars from different regions of adaptation and to initiate multilocational testing across regions. This resulted in the; identification of widely adapted cultivars, exchange of material from diverse geographic regions, and an understanding of the adaptation patterns of phenological groups to environments and production systems (Ramanujam, 1981). ICRISAT set up breeding programmes for three maturity groups in appropriate environments (Green *et al.*, 1981), and cooperated with AICPIP in multilocational testing of advanced breeding material. Byth *et al.* (1981) emphasized that quantitative pigeonpea improvement should involve identification of major production systems in use, or of potential value, and implementation of breeding specifically within and for the optimal system. While local breeding would specialize in one or more relevant systems, valuable contributions could be made by centralized pigeonpea improvement programmes in three main areas, 1. development of breeding populations and lines specifically adapted to particular systems, 2. introgression of desirable genes among the gene bases of these systems, and 3. the improvement of characters that are transferable across production systems, such as disease and pest resistance (Byth *et al.*, 1981). This broad-based programme may involve; using biotechnological tools, and the introgression of alien genes from incompatible wild relatives such as *Cajanus platycarpus*. It may also include germplasm enhancement for disease and pest resistance and certain abiotic stresses like salinity, using genetic male sterility, and further involve a search for cytoplasmic male sterility.

A separate study of the physiological limitations that may exist in the materials adapted to different systems and phenological groups is needed, so are studies on the expression of genetic variability and heritability of particular characters in different environments. However, shuttle breeding or alternate selection cycles in diverse systems and seasons, could lead to widely adapted genotypes.

Selection and Hybridization

The parents for hybridization should be chosen to comply with breeding objectives and the special attributes of the lines, i.e., maturity, height, growth habit, seed size, seed colour, pod size, number of seeds per pod, branching, disease and insect resistance, and/or yield *per se*. Diallel or line × tester mating schemes should be used to determine the combining ability of parents. Omanga (1983) concluded that array mean and *per se* performance are good indicators of parental combining ability. At ICRISAT Center, most of the crosses are now made in a line × tester mating scheme using three or four well-adapted cultivars as testers.

In pigeonpea, crosses are normally made by hand emasculation and pollination. Pathak (1970), and Sharma and Green (1980) have given detailed descriptions of hybridization technique. Successful hybridization is greatly influenced by weather conditions, particularly temperature, humidity, and sunshine. Single crosses are commonly used by breeders, but Hartwig (1972) suggested one or more backcrosses to the adapted parent to retain productivity, and adaptation to a specific environment. Frey (1972) noticed that triple crosses were superior to single crosses for developing high-yielding progenies. Harlan *et al.* (1940) working with barley suggested multiple crosses and bulk handling of the large variability so created. But, Mackey (1954) commented that using a large number of parents in a multiple cross would force the inclusion of an unduly large number of unadapted strains. He therefore suggested a modified backcrossing programme to obtain parental materials with which to carry out the multiple-crossing programme.

The commonly used breeding methods in pigeonpea are applicable to any self-pollinated crop, even though a considerable amount of outcrossing occurs in the species. As a result, controlled production of self-pollinated seed is necessary for genetic testing and maintenance. Such controlled production is not generally feasible in routine breeding, and the use of open-pollinated seed for progeny tests creates problems. Byth *et al.* (1981) suggested the use of cleistogamy or "wrapped flower" modifications to enforce self pollination, and thus allow the use of simpler and more rigorous breeding methods, and efficient pure seed production. They argued that the "wrapped flower" character appears to be simply inherited and dominant and can be recovered in all phenological groups. Thus, it can be used to establish the simple, classical breeding systems for self-pollinated plants, directed towards pure-line cultivars, and would have great impact on breeding methods. Green *et al.* (1981) observed that pedigree selection has been useful in breeding for highly heritable traits such as sterility mosaic disease resistance, seed size, seed colour, growth habit, and seed number per pod. Selections based on single-plant yield in early segregating generations has been found to be ineffective (Byth *et al.*, 1980). In view of the minimum efforts of selfing required, and the apparent ineffectiveness of pedigree selection for breeding for yield *per se*, bulk hybrid advance by single-pod descent appears to be a better procedure for breeding high-yielding lines (Green *et al.*, 1979). Onim (1981) in Kenya used stratified mass selection (SMS) and mass selection with progeny testing (MSPT) for yield gains in pigeonpea. He made progress per cycle of selection of 2.3% under SMS, and 4.3% under MSPT. Nerkar (1981) suggested early generation (F_3) testing and selection in intercropping with sorghum to improve for yield in that system. However, Byth *et al.* (1981) argued against this, and suggested screening of advanced lines under intercropping. Information on the potential of crosses at an early stage in a breeding programme helps in efficient utilization of resources. Saxena and Sharma (1983) from a study involving eight crosses concluded that low-yielding crosses can be rejected on their F_1 performance. They further suggested that the F_2 performance was consistently related to cross performance in succeeding generations.

Handling of segregating populations of biparental or multiple crosses as bulk populations before pure lines are extracted has become a favoured practice. Natural selection in a target environment may cause evolutionary changes in the mean expression of a trait in a bulk population of segregates in a self-pollinating species, e.g., Suneson (1956) found this in a favourable direction in barley populations, whereas Frey (1967) found no significant changes for some traits in oat populations.

Grafius (1965) and Brim (1966) proposed a modification of the bulk population method, which has become known as "single-seed descent". In this method, one or two random seeds are harvested from each plant in the population to form the seed source for the next generation, in order to ensure the preservation of genetic variation and minimize the effects of natural selection. At ICRISAT Center, segregating populations of pigeonpea have been handled by bulk, and/or single-seed decent methods, and pure lines extracted as the end product. No evidence of the superiority of bulk methods in realizing significant gains in yield has been observed over the traditional pedigree or bulk pedigree systems. However, bulk methods were more useful in handling a large number of populations. The final products in both cases were pure lines. Studies are therefore necessary to determine the usefulness of phenotypically homogeneous bulk populations retaining genetic heterogenity (e.g., composites) as final products rather than pure lines, given the nature of the pollination behaviour of pigeonpea.

Breeding for Disease Resistance

Surveys conducted in India revealed sterility mosaic and fusarium wilt as major diseases of pigeonpea. In Africa, wilt is the most important disease causing estimated annual losses of US$ 5 million (ICRISAT, 1983). Other diseases considered important in Africa are cercospora leaf spot and powdery mildew (see Chapter 13).

Wilt

Inheritance of wilt resistance is not fully understood. Pal (1934) reported that resistance to wilt in pigeonpea was controlled by multiple genes, while Shaw (1936) and Pathak (1970) suggested that it was governed by two complementary genes.

Breeding wilt-resistant genotypes was of interest as early as 1906 (Butler, 1906, 1908, 1910). Subsequently, selection of resistant plants in wilt-sick plots was carried out at several locations in India. Mathur (1954), Vaheeduddin (1956), and Pathak (1970) listed several wilt-resistant cultivars in India. Nene *et al.* (1981) reviewed the sources of resistance to wilt and observed that cultivars NP(WR)15, 15-3-3, BDN 1, and 20-1 had consistently low disease levels. They also listed several sources of recently identified resistance. Breeding for wilt resistance is usually done by pedigree or mass-pedigree selection, although in some cases backcrossing has also been successful. Some resistant varieties are listed in Table 15.5.

Sterility Mosaic (SM)

Sharma *et al.* (1984) reported that susceptibility to sterility mosaic disease was dominant over resistance and tolerance, and that the tolerant reaction was dominant over the resistance of certain lines. Two loci and more than two alleles at each locus were the suggested explanation for the reaction in the F_1 and F_2 generations in different cross combinations.

With the availability of an effective screening method, breeding for resistant genotypes started with the identification of resistant germplasm accessions (Nene and Reddy, 1976). Nene *et al.* (1981) listed several sources of resistance, and some of these have been utilized in developing high-yielding, disease-resistant lines at ICRISAT Center (Table 15.5).

Phytophthora Blight (PB)

The inheritance of resistance to phytophthora blight (P2 isolate of *Phytophthora drechsleri* f. sp.*cajani*) was reported by Sharma *et al.* (1982). It was found to be governed by a single dominant gene, and all the seven diverse resistant parents used in the study carried the same gene.

Resistance to the virulent isolate (P3) has yet to be achieved (see Chapter 13). Induced mutagenesis is being used in an attempt to create sources of resistance. Genetic male sterility has been transferred to disease-resistant genotypes with a view to producing resistant hybrids and lines that can be used for population enhancement to accumulate favorable genes that will confer stable resistance.

Multiple Disease Resistance

At ICRISAT Center, a multiple disease screening nursery for wilt, SM, and PB has been established. Some sources of combined resistances have been identified (Nene *et al.*, 1981) and varieties combining resistances to wilt and SM have been developed (Table 15.5).

Table 15.5. Performance of sterility mosaic and wilt-resistant pigeonpea lines, ICRISAT Center 1982/83 – 1985/86.

Lines	Sterility mosaic[1] (%)	Wilt[1] (%)	Grain yield[2] (t ha^{-1})
ICPL 335	8.2 (4)[3]	0.0 (2)	1.97 (4)
ICPL 227	7.3 (4)	1.6 (2)	2.05 (4)
ICPL 8363	5.8 (4)	0.9 (2)	1.88 (4)
ICPL 8362	7.5 (4)	0.0 (2)	1.86 (4)
ICPL 343	99.0 (2)	2.4 (4)	2.44 (3)
ICPL 8357	6.8 (4)	100.0 (2)	2.22 (4)
ICPL 345	67.0 (2)	0.0 (4)	2.16 (3)
C 11 (control)	100.0	60.0	2.13 (4)

1. Disease incidence recorded in sick plot.
2. Grain yield under disease-free conditions.
3. Numbers in parentheses indicate number of years tested.

Insect Pest Resistance

Under favourable growing conditions insect damage caused to the foliage, floral buds, and flowers can be fully compensated by extended crop growth (Reed *et al.*, 1981). The field screening technique for tolerance to the pod borer, *Helicoverpa armigera* in use at ICRISAT Center has been described by Reed *et al.* (1981). Selecting single plants under pesticide-free conditions, subsequent progeny evaluation, and continued selection and selfing have resulted in the identification of relatively stable differences among genotypes to damage caused by *Helicoverpa*, or compensation in yield after damage, particularly in the medium-duration group. Breeders have used these sources to incorporate low susceptibility into good agronomic backgrounds using the pedigree method of breeding. ICPL 87088 and ICPL 87089 are two lines developed in this way that produced some yield, even during the heavy pod borer epidemic that devastated pigeonpea and cotton in peninsular India in 1987 (Table 15.6).

ICRISAT entomologists are screening for differences in damage caused by the podfly, *Melanagromyza obtusa* at the ICRISAT Cooperative Research Station at Gwalior. After 5-6 years' observation genetic differences have been noticed. With the availability of this material, and other lines selected by the Directorate of Pulses Research entomologists at Kanpur, differences in long-duration genotypes for podfly damage (S.S. Lal, Directorate of Pulses Research, Kanpur, personal communication), have been established (Table 15.7).

Population improvement using genetic male sterility has been suggested as a method of accumulating genes that will confer low susceptibility to this pest.

Lal *et al.* (1986) also observed that by reducing the duration of long-duration pigeonpea in northern Indian conditions, and selecting for shorter reproductive duration (less time from flowering to maturity) podfly damage can be escaped. Variation for this trait has yet to be thoroughly quantified and exploited.

In Kenya, Omanga and Matata (1987) observed genotypic differences to pod-sucking bugs. Selections 423/85 and 423/20 from landraces seem to have resistance to pod-sucking bugs, but this resistance needs to be stabilized.

Table 15.6. Performance of medium-duration *Helicoverpa*-tolerant pigeonpea lines, ICRISAT Center, rainy season 1987/88.

	MPAY[1] trial (sprayed)	Intercropping trial[2] (sprayed)				PIRY[3] trial		
		Sole crop		Intercrop		Yield (t ha^{-1})		Borer damage (%)
Lines	Yield (t ha^{-1})	Yield (t ha^{-1})	Borer damage (%)	Yield (t ha^{-1})	Borer damage (%)	Sprayed	Unsprayed	
ICPL 87088	1.95	0.85	44	0.75	43	1.71	0.47	58
ICPL 87089	1.73	0.82	41	0.84	46	2.04	0.46	67
Controls								
C 11	1.43	0.09	95	0.17	68	1.88	0.04	99
BDN 1	0.33	0.14	81	0.19	78	1.54	0.04	94
SE	±0.28	-	-	-	-	±0.27	-	±7.7
Trial mean	1.21	-	-	-	-	1.91	-	71
CV %	46	-	-	-	-	28	-	22

1. MPAY = Medium-duration Pigeonpea Adaptation Yield trial.
2. Of 16 entries tested in the trial, only 5 produced grain and 11 did not; hence the statistical analysis was not relevant.
3. PIRY = Pigeonpea Insect Resistant Lines Yield trial.

Source: ICRISAT, 1989.

Most of the genotypes that are tolerant to pod borer are highly susceptible to wilt. A combined screening nursery for wilt and pod borer tolerance has been established at ICRISAT Center, but combined resistances have yet to be identified.

Table 15.7. Reaction of long-duration pigeonpea genotypes to podfly (*Melanagromyza obtusa*) damage at Kanpur, India[1].

Reaction to podfly	Genotypes
Resistant (5-10% damage)	110 12/2, MA 2/3, SL 12/2, SL 42/3, GP 3/3, SL 21/2, ICP 7151, ICP 8102
Tolerant (11-20% damage)	SL 11/6, SL 20/2, PDA 84/B, AC 314/314, ICP 3615, ICP 4745
Susceptible (>21-50% damage)	Code 3, JM 2412, ICP 7050

1. Results are means of 6-8 years' trials.

Drought

Even though pigeonpea is considered a drought-tolerant crop by virtue of its deep root system and indeterminate growth habit, it often suffers drought stress in the semi-arid tropics – an environment subject to large variations in moisture availability under rainfed conditions. In limiting moisture situations, pigeonpea remains alive when all other crops dessicate, but pod production commences only with the availability of required moisture in the form of rain or irrigation.

Breeders have attempted to alleviate this constraint to productivity and stability by reducing crop duration to escape terminal drought stress. Agronomists at ICRISAT Center are screening genotypes for resistance/tolerance to drought stress, and to assess the exploitable genetic variation. Medium-duration genotypes; BDN 5, ICPL 8340, ICP 3233, PBN/A 53, and ICP 4865 have been classified as drought tolerant (ICRISAT, 1987).

Although longer-duration types have a comparatively increased tolerance to drought stress because of their well developed root system, short-duration pigeonpea can escape stress in regions where terminal drought stress reduces yields of medium- or long-duration genotypes. Yet, short-duration genotypes are subjected to intermittent water deficit on light soils during the rainy season. Genotypic differences in response to drought stress have been reported (ICRISAT, 1988a,). Hybrids ICPH 8 and ICPH 9 performed better at all moisture levels than their respective male parents, ICPL 161 and ICPL 87. Generally, yields of the indeterminate group were relatively less affected by drought stress than those of the determinate group.

A specific breeding programme for this character has yet to be undertaken. However, the developments in screening techniques and in the understanding of the nature of genetic variation for drought response will pave the way for improvement in this character.

Salinity

Soil salinity in the arid and semi-arid tropics has become one of the factors limiting crop production in pigeonpea. Genetic variation in salinity tolerance has been reported. ICPL 227 proved to be most tolerant to salt stress with respect to nodulation and growth (ICRISAT, 1986). Among pigeonpea's wild relatives *Cajanus platycarpus*, *C. albicans*, *C. cajanifolius*, and *Dunbaria ferruginea* were found to be more tolerant to salinity than cultivated pigeonpea ICPL 227 (ICRISAT, 1988a). The screening procedure for salinity tolerance is being standardized at ICRISAT Center.

Breeding for Production Systems

Short- and extra-short-duration, short-statured pigeonpeas with comparatively low sensitivity to photoperiod and temperature interactions have been bred. These are relatively stable in phenology and agronomic performance over a range of environments, and are amenable to mechanized cultivation as sole crops in multiple-cropping systems (Wallis *et al.*, 1983; Gupta *et al.*, 1988). Short-duration lines with fast ratoonability, like ICPL 87, are suitable for multiple harvests in environments with warm winters. Chauhan *et al.* (1984) reported yields of 5.2 t ha^{-1} grain from ICPL 87 in three harvests within a year (September, November, and March). This system provides stability and gives much higher grain yields than traditional medium-duration genotypes in the same environment over a similar time period (Chauhan *et al.*, 1987). Ratoonability is also important in situations where the first flush of flowers may be lost due to overcast skies, rain, or insect damage. Wider adaptation to higher altitudes and latitudes is achieved by using extra-shortduration genotypes. Short-duration genotypes produce more dry grains per day per unit area than medium- and long-duration genotypes. In replicated yield trials, advanced short-duration lines yielded <39 kg day^{-1} ha^{-1} dry grains at Hisar (Gupta *et al.*, 1988) as against <16 kg day^{-1} ha^{-1} by advanced medium-duration lines at ICRISAT Center (Jain *et al.*, 1987), and long-duration lines at Gwalior (ICRISAT, 1988b).

Medium- and long-duration pigeonpeas are principally grown as intercrops with tall cereals (maize, sorghum, millets), and a variety of other crops. Breeding and selecting for competitiveness and high productivity in such systems from early generations is not practical. Green *et al.* (1979) reported the absence of significant genotype × cropping systems interactions in a test where medium- and long-duration cultivars were evaluated in both sole and intercropping situations. In another experiment, medium-duration pigeonpea germplasm selections were tested in sole and intercropping systems with sorghum for 4 years (1976/77 to 1979/80). It was found that, on an average over 4 years, selection in sole crops would have been 41% effective at 20% selection intensity, and 55% effective at 33% selection intensity for selecting the top 20 and 33% lines in intercropping performance (Green *et al.*, 1981).

For alley cropping in agroforestry systems, genotypes with resistances to SMD and wilt have been identified. One such genotype, ICP 8094 has been selected for on-farm testing (C.K. Ong, ICRISAT, personal communication).

Breeding for Special Traits

Vegetable Purposes

In selecting for vegetable purposes (for use as immature green peas), the main criteria used at ICRISAT Center are; large white seeds (100-seed mass >12g), and large pods with 5-6 or more seeds per pod. Cultivars with these traits plus wilt and SM resistance have been developed in the medium-duration group (ICRISAT, 1988a). However, short-duration types with relative insensitivity to photoperiod are still being sought for year-round vegetable production. Variation for quality parameters such as sugar and fibre content have yet to be quantified and exploited. The pedigree method of breeding has been effective in selecting for such highly heritable characters as seed size and number of seeds per pod (Jain *et al.*, 1981). However, selection of individual plants for yield in the F_2 has not been effective (Green *et al.*, 1979).

Dwarfs

Several genetic dwarf plant types have been identified and are being maintained at ICRISAT. The inheritance of this trait is governed by a single recessive gene. Incorporation of this trait in different phenological groups is in progress, but its utility in production systems and environments needs further studies.

POPULATION BREEDING

Recurrent selection and population improvement methods have been suggested as ways to accumulate desirable genes and facilitate the breaking of linkages (Doggett and Eberhart, 1968 in sorghum; Compton, 1968 in self-pollinated species; Khan, 1973 in pigeonpea). Jensen (1970) suggested diallel selective mating, and Rachie and Gardner (1975) suggested a dual-population system. Both of these methods have been successfully used at ICRISAT Center (Green *et al.*, 1981) and have achieved limited yield gains.

Populations involving genetic male sterility have also been developed at ICRISAT Center since 1976 (Faris, 1985a) in the hope that they can be used to increase recombination by intermating large numbers of genotypes with desirable characters. These populations will serve as source material from which to draw desirable parents for use in breeding programmes.

HYBRID PIGEONPEA

Most of the methods mentioned above are designed to exploit additive genetic variance to develop high-yielding pure lines. However, pigeonpea has a substantial amount of non-additive genetic variance (Sharma *et al.*, 1973; Reddy *et al.*, 1981; Saxena *et al.*, 1981), and hybrid vigour for yield (Solomon *et al.*, 1957). The discovery of stable genetic male sterility (Reddy *et al.*, 1978), coupled with its outcrossing nature, has opened the possibility of commercial utilization of the heterosis in pigeonpea.

Genetic male steriles in pigeonpea are identifiable by their translucent anthers. This genetic male sterility requires roguing 50% of the normal fertile plants from the female rows in hybrid seed production blocks at flowering, and the identification and collection of seeds from male-sterile plants in the maintenance block. The identification of genetic male sterility, coupled with the high level of natural outcrossing by insects in pigeonpea, enabled the economic production of hybrid seed. To date it has been demonstrated that full seed set is obtained if one fertile pollinator parent is sown after every six male-sterile rows (Saxena *et al.*, 1986).

These additional operations represent the primary additional expense involved in the production of hybrid seed. However, in conducive environments, pigeonpea plants (especially those in the short-duration group) produce multiple harvests during a single year. To date only two sources of genetic male sterility are available; one is characterized by translucent anthers (Reddy *et al.*, 1978), and the other by dark brown, arrow-head shaped anthers (Wallis *et al.*, 1981). These sources have been transferred to several genetic backgrounds in different phenological groups that have resistances to various diseases (Saxena *et al.*, 1986).

Successful hybrids are produced from those combinations where specific combining ability effects result in considerable heterosis in the F_1 generation. To find these combinations and develop a successful hybrid programme, it will be necessary to test a large number of hybrids. In order to do this ICRISAT has developed a cooperative programme with Indian national agriculture research centres. The joint hybrid programme involves the production and testing of a large number of experimental hybrids, the maintenance of male-sterile lines, and the transference of male sterility to elite genotypes. Promising hybrids will be mass produced and evaluated in different production systems (Saxena *et al.*, 1989). Among the short-duration hybrids developed at ICRISAT Center, ICPH 8 has been found to be the most promising. This is an indeterminate hybrid developed by crossing a male-sterile line, MS Prabhat (DT) and an indeterminate advanced breeding line, ICPL 161 (Gupta *et al.*, 1983).

MUTATION BREEDING

A number of mutants, both induced and spontaneous, for various qualitative characters have been reported in pigeonpea (Rao and Reddy, 1986; Murthi and van der Maesen, 1979). A few pigeonpea cultivars have been developed through the utilization of induced quantitative variability. Pawar *et al.* (1984) irradiated seeds of T 21 with gamma rays at Bhabha Atomic Research Centre, Trombay, Bombay, India, and selected a new induced mutant, T 6. This has been released for cultivation because it has larger seeds and higher yield potential than T 21. A cultivar Co 2 has been developed at Coimbatore through mutation breeding. Veeraswamy *et al.* (1975) reported that this cultivar is suitable for both rainfed and irrigated conditions. At ICRISAT Center wilt-resistant mutants from the irradiated population of a highly wilt-susceptible cultivar LRG 30 have been isolated (S. Dwivedi, personal communication).

INTERSPECIFIC HYBRIDIZATION

Attempts have been made at ICRISAT Center to transfer some desirable traits from wild species of *Cajanus* to pigeonpea. Reddy *et al.* (1981) reported that six species of *Cajanus (C. lineatus, C. sericeus, C. scarabaeoides* var. *scarabaeoides, C. albicans, C. trinervius,* and *C. cajanifolius)* cross with pigeonpea cultivars. However, *C. crassus* var. *crassus* and *C. platycarpus* can not be crossed. Later attempts to introgress *C. platycarpus,* using bridge crosses and tissue culture to rescue the hybrid embryo before it aborted, were not successful (I.S. Dundas, University of Adelaide, personal communication). Several other workers have reported hybridization of pigeonpea with other *Cajanus* spp (Reddy, 1981; Reddy and De, 1983; Kumar *et al.*, 1985; Pundir and Singh, 1985). The genetic diversity of the wild relatives of pigeonpea has been discussed by Remanandan (1981), van der Maesen (1986), and Dundas *et al.* (1986).

Reddy *et al.* (1981) mentioned traits obtained in wild *Cajanus* species, that are of potential value for pigeonpea improvement. For instance, *C. scarabaeoides* var. *scarabaeoides* possesses both the physical and antibiosis types of resistance to *Helicoverpa armigera,* while *C. sericeus* and *C. albicans* are rich in protein, and *C. reticulatus* var. *grandifolius* is hardy and fire-tolerant (Akinola *et al.*, 1975). As mentioned earlier *C. albicans* also has tolerance to soil salinity. Singh *et al.* (in press) reported that the amino acid composition of lines with a high percentage of seed protein derived from *Cajanus cajan* × *Cajanus* spp crosses was comparable to the protein in normal lines, and that the utilizable protein values were considerably higher in high-protein genotypes, suggesting that they were nutritionally superior.

Frey (1985) suggested that the grain yield in short-duration pigeonpea could be increased by improving its harvest index and growth rate (biomass productivity). It is necessary to determine whether genetic variability exists for biomass productivity within the short-duration gene pool. Growth rate seems to have two phases for pigeonpea; 1. early growth rate (germination to 6 weeks) is slow when compared to other crops, and 2. growth rate after 6 weeks is at a comparatively faster rate. The exact patterns of growth rate and their genetic variability have not been subjects of pigeonpea research. Interspecific introgresion is an additional source of genes that would improve growth rate. The F_1s of crosses between *Cajanus cajan* and other *Cajanus* species show considerable vigour in growth. Whether the vigour noted in F_1 can be retained in later backcross generations, together with associations with desirable plant characteristics needs to be researched in a planned interspecific hybridization programme.

GENETIC PURITY CONSIDERATIONS IN BREEDING AND SEED PRODUCTION

The pollination behaviour of pigeonpea creates difficulties in improvement programmes. The long-duration and photoperiod sensivity of certain genotypes restrict generation turnover. Genetic variation for the self-pollinating mechanism leads to considerable outcrossing, and creates ambiguities in the choice of appropriate breeding methods, problems in the maintenance of genetic constitution during pedigree selections, and in that of the final product. Landraces as evolved by natural selection, and subsequently improved upon by human selection, tend to retain considerable heterogeniety. Whether phenotypically homogenous pure lines or populations with certain genetic heterogeniety are desirable is generally ignored. Because, in the latter case, the established system of seed certification then creates problems for breeders and seed certification agencies. To resolve this, breeders go along with the system suggesting single-plant selection, selfing, progeny testing, and bulking such pure lines to produce breeders' seed of established cultivars (Gupta *et al.*, 1981; Faris 1985b). This procedure is unique at ICRISAT and some Indian national programme centres.

Other centres resort to growing the crop for seed stock in isolation of 100-200 m and roguing out apparent off-types. During the breeding process selfing is not practical, hence early generation testing usually is made from open-pollinated seed, and only in advanced stages is some selfing done (Gupta *et al.*, 1981). Byth *et al.* (1981) suggested modification of the mating system itself as a valid objective in breeding. Consequently, efforts are being made at ICRISAT Center to transfer the cleistogamous flower character to established cultivars through backcrossing to maintain genetic purity. This trait is governed by a single recessive gene, and restricts outcrossing to less than 2%. At the other extreme, the presence of genetic male sterility, and the outcrossing ability of pigeonpea allows the utilization of breeding methods often applicable to cross-pollinated species. This characteristic is also being utilized to produce hybrids, and in population breeding programmes.

FUTURE

In pigeonpea and in several self-pollinated species, varietal improvement methods based on pedigree, bulk pedigree, backcross- and multiple-crossing techniques have been useful in recombining simply inherited characters such as disease resistance, seed size and colour, and maturity duration. However, these varietal improvement methods have not been very efficient in improving quantitatively inherited traits like seed yield. Selection among lines derived from advanced bulk populations seems to be more effecient than the pedigree method in breeding for seed yield. Local landraces should be utilized to derive adapted lines for use in breeding programmes. Single plant selection is generally ineffective for yield, hence, selection must be done on a progeny basis. More studies are needed to determine the usefulness of phenotypically homogeneous composite populations rather than pure lines as final products.

The discovery of stable genetic male sterility, coupled with its often-outcrossing nature, has opened the possibility of commercial utilization of heterosis in pigeonpea. Future progress will depend on collaborative efforts of national agricultural research centres, private seed companies, and ICRISAT in cooperative research on efficient methods of hybrid seed production, transferring genetic male sterility to different genetic backgrounds, and the search for cytoplasmic male sterility.

Effective use needs to be made in the future of cleistogamous flower morphology to ensure near-complete self pollination to maintain the purity of lines.

The major limitations in multilocational testing of advanced material are the high coefficient of variability, high genotypic × environment interactions, and the adaptability to different production systems. Selection of suitable sites and production systems, and characterization of test environments are vital for precise testing. Future progress will be enhanced by streamlining procedures to ensure precise testing and efficiency in selection. Zonalization of production environments on some agroclimatic parameters have been attempted in India, and several other pigeonpea-growing countries. But more work is needed to quantify existing production systems and identify niches of cropping systems and environments where new short-duration plant types can be used. It is in these environments and cropping systems that the testing of appropriate genotypes needs to be done.

Traditionally medium- and long-duration pigeonpeas are grown as mixed or intercrops with tall cereals such as sorghum, millet and maize. For commercial production as a sole crop in multiple cropping systems a new plant type has been developed with a short (3 - 5 month) duration type amenable to mechanized cultivation. This type includes the new extra-short and short-duration genotypes. These very early and early-maturing genotypes are more amenable to fitting certain environmental windows, and they have a shorter growing season during which to interact with environmental elements. These genotypes are relatively less sensitive to photoperiod and temperature interactions. Such genotypes will permit "general adaptation" to a wide range of latitudes. Presently cultivation of pigeonpea is restricted to latitudes 30°N and 30°S. New short-duration determinate plant types (Figure 15.1) developed at ICRISAT have recently been successfully grown

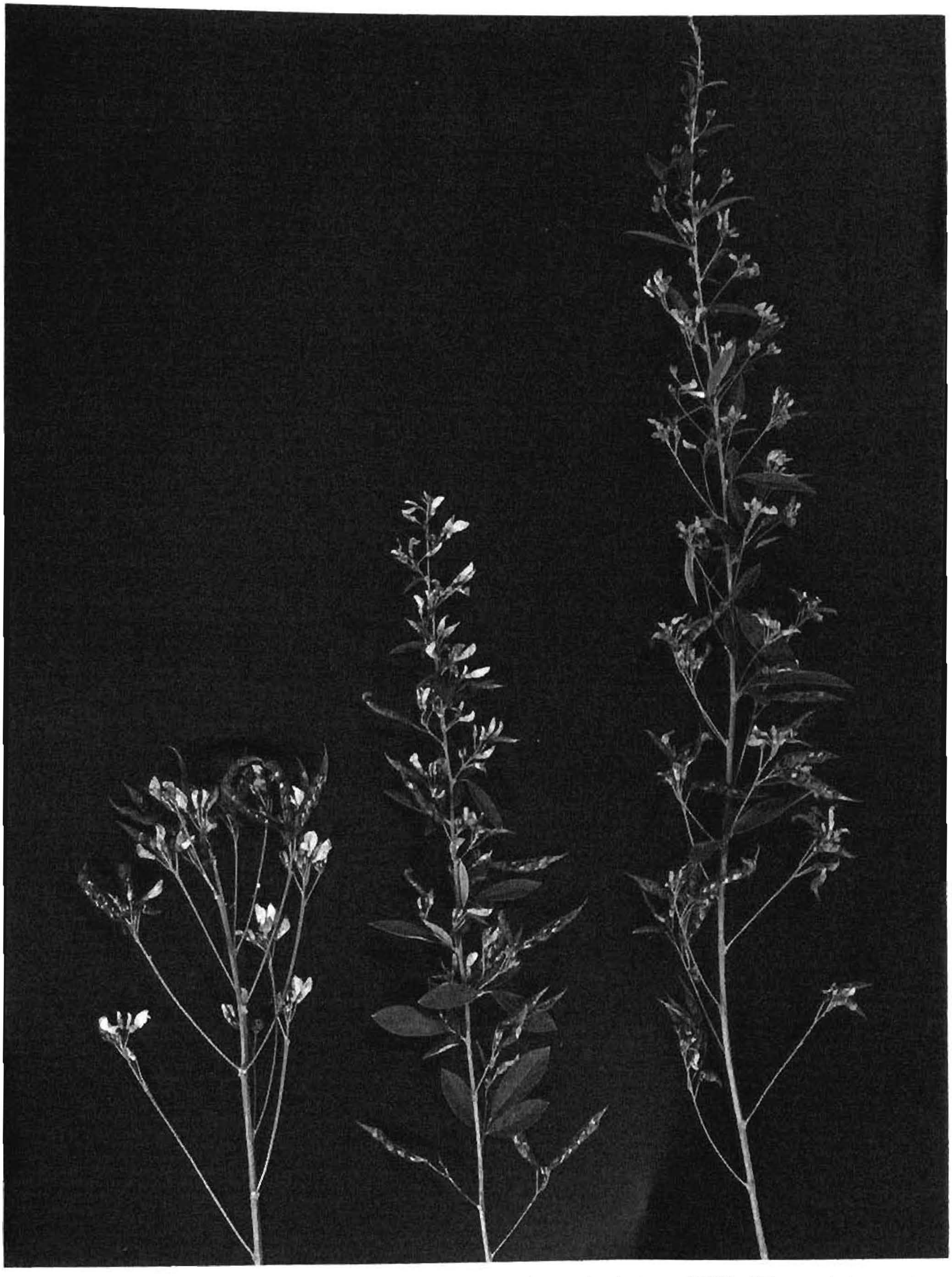


Figure 15.1. Flowering habit in pigeonpea (left to right): determinate type (ICPL 87); semi-determinate type (ICPL 269); and indeterminate type (ICPL 161).
Photo: ICRISAT.

up to latitude 45°N. These short-statured determinate cultivars are suitable for mechanized commercial cultivation.

Improvement in harvest index and growth rate will contribute to increased grain yield within a maturity duration (Takeda and Frey, 1976) in any crop. In short-duration pigeonpea introgression from wild *Cajanus* species for rapid growth rate, salinity tolerance, etc. should be future research considerations.

A new ideotype is then visualized that would be of short-duration, photoperiod-insensitive, short-statured, and determinate in growth habit, with an elevated harvest index and faster growth rate. Modifications of this ideotype could then be used for different purposes and in different environments.

REFERENCES

Abrams, R. (1975) Status of research on pigeonpeas in Puerto Rico. In: *International Workshop on Grain Legumes, 13-16 January 1975, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 141-147.

Abrams, R. and Julia, F.J. (1973) Effect of planting time, plant population and row spacing on yield and other characteristics of pigeonpeas, *Cajanus cajan* (L.) Millsp. *Journal of Agriculture of the University of Puerto Rico* 57, 275-285.

Akinola, J.O. and Whiteman, P.C. (1975) Agronomic studies on pigeonpea (*Cajanus cajan* (L.) Millsp.). II. Responses to sowing density. *Australian Journal of Agricultural Research* 26, 57-66.

Akinola, J.O., Whiteman, P.C. and Wallis, E.S. (1975) *The Agronomy of Pigeonpea (Cajanus cajan). Review Series no. 1/1975*. CAB, UK, 57 pp.

Aponte Aponte, F. (1963) El cultivo de gandules en Puerto Rico. *Caribbean Agriculture* 1, 191-197 (in Spanish).

Ariyanayagam, R.P. (1975) Status of research on pigeonpeas in Trinidad. In: *International Workshop on Grain Legumes, 13-16 January 1975, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 131-139.

Ariyanayagam, R.P. (1981) Pigeonpea breeding in the Caribbean Regional Programme. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 415-426.

Bhatia, G.K., Gupta, S.C., Green, J.M. and Sharma, D. (1981) Estimates of natural cross-pollination in *Cajanus cajan* (L.). Millsp.: several experimental approaches. In: *Proceedings of the International Workshop on Pigeonpeas, volume 2, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 129-136.

Brim, C.A. (1966) A modified pedigree method of selection in soybeans. *Crop Science* 6, 220.

Butler, E.J. (1906) The wilt disease of pigeonpea and pepper. *Agricultural Journal of India* 1, 25-36.

Butler, E.J. (1908) Selection of pigeonpea for wilt disease. *Agricultural Journal of India* 3, 182-183.

Butler, E.J. (1910) The wilt disease of pigeonpea and the parasitism of *Neocosmospora vasinfecta* Smith. *Memoirs of the Department of Agriculture in India, Botanical Series* 2, 1-64.

Byth, D.E., Green, J.M. and Hawtin, G.C. (1980) ICRISAT/ICARDA chickpea breeding strategies. In: *Proceedings of the International Workshop on Chickpea Improvement, 28 February-2 March 1979, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 11-27.

Byth, D.E., Saxena, K.B. and Wallis, E.S. (1982) A mechanism for inhibiting cross-fertilization in pigeonpea (*Cajanus cajan* (L.) Millsp.). *Euphytica* 31, 405-408.

Byth, D. E., Wallis, E.S. and Saxena, K.B. (1981) Adaptation and breeding strategies for pigeonpea. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 460-465.

Chauhan, Y.S., Venkataratnam, N. and Sheldrake, A.R. (1984) The high-yield potential of extra-early pigeonpeas in peninsular India. *International Pigeonpea Newsletter* 3, 28-31.

Chauhan, Y.S., Venkataratnam, N. and Sheldrake, A.R. (1987) Factors affecting growth and yield of short-duration pigeonpea and its potential for multiple harvests. *Journal of Agricultural Science, Cambridge* 109, 519-529.

Compton, W.A. (1968) Recurrent selection in self-pollinated crops without extensive crossing. *Crop Science* 8, 773.

De, D.N. (1974) Pigeonpea. In: Hutchinson, J. (ed), *Evolutionary Studies in World Crops: Diversity and Change in the Indian Subcontinent*. Cambridge University Press, London, pp. 79-87.

Derieux, M. (1971) Quelques données sur le comportment du pois d'Angole en Guadeloupe (Antilles Francais). *Annales de l'Amelioration des Plantes* 21, 373-407.

Doggett, H. and Eberhart, S.A. (1968) Recurrent selection in sorghum. *Crop Science* 8, 119-221.

Dundas, I.S., Britten, E.J., Byth, D.E. and Gordon, G.H. (1986) Australian *Atylosia* species - a new gene source for pigeonpea breeders. In: Napompeth, B. and Subhadrabandhu, S. (eds), *New Frontiers in Breeding Research. Proceedings of the Fifth International Congress Society for the Advancement of Breeding Researches in Asia and Oceania (SABRAO)*. Kasetsart University, Bangkok, Thailand, pp. 389-395.

Faris, D.G. (1985a) Pigeonpea population breeding at ICRISAT. Paper presented at AICPIP kharif pulses workshop, 16-19 May 1985, Tamil Nadu Agricultural University, Coimbatore, India.

Faris, D.G. (1985b) Production of quality breeder's seed. Paper presented at AICPIP kharif pulses workshop, 16-19 May 1985, Tamil Nadu Agricultural University, Coimbatore, India.

Frey, K.J. (1967) Mass selection for seed width in oat populations. *Euphytica* 16, 341-349.

Frey, K.J. (1972) Stability indexes for isolines of oats (*Avena sativa* L.). *Crop Science* 12, 809-812.

Frey, K.J. (1985) *Breeding High Yielding Cultivars of Pigeonpea. Consultancy Report, Pigeonpea Breeding*. Patancheru, A.P., India: Legumes Program, ICRISAT, 20 pp. (Limited distribution).

Gooding, H.J. (1962) The agronomic aspects of pigeonpeas. *Field Crop Abstracts* 15, 1-5.

Grafius, J.E. (1965) Short cuts in plant breeding. *Crop Science* 5, 377.

Green, J.M., Sharma, D., Reddy, L.J., Saxena, K.B., Gupta, S.C., Jain, K.C., Reddy, B.V.S. and Rao, M.R. (1981) Methodology and progress in the ICRISAT Pigeonpea Breeding Program. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 437-449.

Green, J.M., Sharma, D., Saxena, K.B., Reddy, L.J. and Gupta, S.C. (1979) Pigeonpea breeding at ICRISAT. Paper presented at the Regional Workshop on Tropical Grain Legumes, 18-22 June 1979, University of West Indies, St. Augustine, Trinidad.

Gupta, S.C., Johansen, C. and Laxman Singh (1989) Uniformity of nomenclature in short-duration pigeonpeas. *International Pigeonpea Newsletter* 10, 3-6.

Gupta, S.C., Laxman Singh, Kapoor, R.K. and Rao, A.N. (1988) *Report of Work, June 1987-May 1988. Pigeonpea Breeding Progress Report* 23. Patancheru, A.P., India: Legumes Program, ICRISAT, 144 pp. (Limited distribution).

Gupta, S.C., Reddy, L.J. and Faris, D.G. (1983) Early-maturing pigeonpea hybrids. *International Pigeonpea Newsletter* 2, 19-20.

Gupta, S.C., Reddy, L.J., Sharma, D., Green, J.M., Murthi, A.N. and Saxena, K.B. (1981) Maintenance of pigeonpea cultivars. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 295-302.

Harlan, H.V., Martini, M.L. and Stevens Harland (1940) A study of methods in barley breeding. *USDA Technical Bulletin* 720, 1-26.

Hartwig, E.E. (1972) Utilization of soybean germplasm strains in a soybean improvement program. *Crop Science* 12, 856-859.

Howard, A., Howard, G.L.C. and Khan, A.R. (1919) Studies in the pollination of Indian crops-I. *Memoirs of the Department of Agriculture in India, Botanical Series* 10, 195-200.

ICRISAT (1979) *Pigeonpea Breeding, Report of Work, June 1978-May 1979. Pigeonpea Breeding Progress Report* 3. Patancheru, A.P., India: Legumes Program, ICRISAT, 359 pp. (Limited distribution).

ICRISAT (1983) *Annual Report 1982*. Patancheru, A.P., India: ICRISAT, p. 131.

ICRISAT (1986) *Annual Report 1985*. Patancheru, A.P., India: ICRISAT, p. 182.

ICRISAT (1987) *Annual Report 1986*. Patancheru, A.P., India: ICRISAT, pp. 176-177.

ICRISAT (1988a) *Annual Report 1987.* Patancheru, A.P., India: ICRISAT, pp. 181-222.

ICRISAT (1988b) *Report of Work, June 1986-May 1987. Pigeonpea Breeding Progress Report 13.* Patancheru, A.P., India: Legumes Program, ICRISAT 36 pp. (Limited distribution).

ICRISAT (1989) *Annual Report 1988*. Patancheru, A.P., India: ICRISAT, pp. 106-109.

IITA (1976) *Recommendations for Pigeonpea Uniform Cultivar Trial*. Grain Legume Improvement Program, International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria, pp. 2-6 (Limited distribution).

Jain, K.C., Reddy, M.C. and Laxman Singh (1987) *Pigeonpea Breeding, Report of Work, June 1986-May 1987. Pigeonpea Breeding Progress Report 17.* Patancheru, A.P., India: Legumes Program, ICRISAT, 68 pp. (Limited distribution).

Jain, K.C., Sharma, D., Gupta, S.C., Reddy, L.J. and Singh, U. (1981) Breeding for vegetable-type pigeonpeas. In: *Proceedings of the International Workshop on Pigeonpeas, volume 2, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 165-172.

Jensen, N.F. (1970) A diallel selective mating system for cereal breeding. *Crop Science* 10, 629-635.

Kay, D.E. (1979) *Crop and Product Digest no. 3–Food Legumes*. Tropical Products Institute, London, pp. 322-347.

Khan, T.N. (1973) A new approach to the breeding of pigeonpea (*Cajanus cajan* (L.) Millsp.): formation of composites. *Euphytica* 22, 373-377.

Khan, T.N. and Rachie, K.O. (1972) Preliminary evaluation and utilization of pigeonpea germplasm in Uganda. *East African Agricultural and Forestry Journal* 38, 78-82.

Killinger, G.B. (1968) Pigeonpea (*Cajanus cajan* (L.) Druce), a useful crop for Florida. *Proceedings of the Soil Crop Science Society of Florida* 28, 162-167.

Krauss, F.G. (1921) The pigeonpea– its culture and utilization in Hawaii. *Hawaii Agricultural Experiment Station Bulletin* 46, 1-23.

Krauss, F.G. (1927) Improvement of the pigeonpea, genetic analysis of *Cajanus indicus* and creation of new varieties through hybridization and selection. *Journal of Heredity* 18, 227-232.

Kumar, P.S., Subrahmanyam, N.C. and Faris, D.G. (1985) Intergeneric hybridization in pigeonpea. I. Effect of hormone treatments. *Field Crops Research* 10, 315-322.

Lal, S.S., Yadava, C.P. and S. Chandra (1986) Suppression of podfly damage through varietal selection. *International Pigeonpea Newsletter* 5, 42-43.

Laxman Singh, Maheshwari, S.K. and Sharma, D. (1971) Effect of date of planting and plant population on growth, yield, yield components and protein content of pigeonpea (*Cajanus cajan* (L.) Millsp.). *Indian Journal of Agricultural Sciences* 41, 535-538.

Laxman Singh and Shrivastava, M.P. (1976) Cultivation systems and varietal adaptations of pigeonpea in Madhya Pradesh. *Indian Journal of Genetics and Plant Breeding* 36, 293-300.

Mackey, J. 1954. Breeding of oats. *Handbuch der Pflanzenzuchtung* 2, 512-517.

Mahta, D.N. and Dave, B.B. (1931) Studies in *Cajanus indicus*. *Memoirs of the Department of Agriculture in India, Botanical Series* 19, 1-25.

Mathur, R.S. (1954) Diseases of pulse crops in Uttar Pradesh. *Agriculture and Animal Husbandry in India* 5, 24-28.

Meekin, S., Troedson, R.J., Byth, D.E. and Wallis, E.S. (1988) Release of Quantum in Queensland, Australia. *International Pigeonpea Newsletter* 7, 6-8.

Murthi, A.N. and van der Maesen, L.J.G. (1979) Leaf variants in pigeonpea *Cajanus cajan* (L.) Millsp. *Tropical Agriculture (Trinidad)* 56, 81-83.

Nene, Y.L., Kannaiyan, J. and Reddy, M.V. (1981) Resistance to major pigeonpea diseases. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 121-128.

Nene, Y.L. and Reddy, M.V. (1976) A new technique to screen pigeonpea for resistance to sterility mosaic. *Tropical Grain Legume Bulletin* 5, 23.

Nerkar, Y.S. (1981) Performance of early generation lines under different cropping systems and its bearing on the selection procedure in pigeonpea breeding. In: *Proceedings of the International Workshop on Pigeonpeas, volume 2, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 159-163.

Omanga, P.A. (1983) Studies on the magnitude and nature of hybrid vigour utilizing male sterile and fertile lines in pigeonpea (*Cajanus cajan* (L.) Millsp.). MSc thesis, Andhra Pradesh Agricultural University, Hyderabad, India, 123 pp.

Omanga, P.A. and Matata, J.B.W. (1987) Grain legume production in Kenya. In: *Research on Grain Legumes in Eastern and Central Africa. Summary Proceedings of the Consultative Group Meeting for Eastern and Central African Regional Research on Grain Legumes (Groundnut, Chickpea, and Pigeonpea), 8-10 December 1986, International Livestock Centre for Africa (ILCA), Addis Ababa, Ethiopia*. Patancheru, A.P., India: ICRISAT, pp. 51-56.

Onim, J.F.M. (1981) Pigeonpea improvement research in Kenya. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 427-436.

Pal, B.P. 1934. Recent progress in plant breeding at Pusa. *Agriculture and Livestock in India* 4, 505-515.

Pathak, G.N. (1970) Red gram. In: *Pulse Crops of India*. Indian Council of Agricultural Research, New Delhi, India, pp. 14-53.

Pawar, S.E., Thakare, R.G., Mitra, R., Krishna, T.G. and Bhatia, C.R. (1984) Induced mutations for the genetic improvement of pulse crops. In: Srivastava, H.C., Bhaskaran, S., Menon, K.K.G., Ramanujam, S. and Rao, M.V. (eds), *Pulse Production –Constraints and Opportunities*. Oxford and IBH Publishing Co., New Delhi, India, pp. 361-367.

Prasad, S., Prakash, R. and Hassan, M.A. (1972) Natural crossing in pigeonpea [*Cajanus cajan* (L.) Millsp.]. *Mysore Journal of Agricultural Sciences* 6, 426-429.

Pundir, R.P.S. and Singh, R.B. (1985) Biosystematic relationships among *Cajanus*, *Atylosia*, and *Rhynchosia* species and evolution of pigeonpea (*Cajanus cajan* (L.) Millsp.). *Theoretical and Applied Genetics* 69, 531-534.

Rachie, K.O. and Gardner, C.O. (1975) Increasing efficiency in breeding partially outcrossing grain legumes. In: *International Workshop on Grain Legumes, 13-16 January 1975, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 285-297.

Ramanujam, S. (1981) Varietal adaptation to production systems. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 82-93.

Ramanujam, S. and Singh, S.P. (1981) Pigeonpea breeding in the All India Coordinated Programme. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 403-414.

Rao, D.M. and Reddy, T.P. (1986) Induced polygenic variability in *Cajanus cajan* L. In: Manna, G.K. and Sinha, U. (eds), *Perspectives in Cytology and Genetics, volume 5*. All India Congress of Cytology and Genetics, Kalyani, India, pp. 303-309.

Rao, N.G.P., Reddy, R.P. and Harinarayana, G. (1977) Somatic variation in grain legumes. *Indian Journal of Genetics and Plant Breeding* 37, 457-459.

Reddy, B.V.S., Green, J.M. and Bisen, S.S. (1978) Genetic male sterility in pigeonpea. *Crop Science* 18, 362-364.

Reddy, L.J. (1973) Interrelationship of *Cajanus* and *Atylosia* species as revealed by hybridization and pachytene analysis. PhD thesis, Indian Institute of Technology, Kharagpur, India.

Reddy, L.J. (1981) Pachytene analyses in *Cajanus cajan*, *Atylosia lineata* and their hybrid. *Cytologia* 46, 397-412.

Reddy, L.J. and De, D.N. (1983) Cytomorphological studies in *Cajanus cajan* × *Atylosia lineata*. *Indian Journal of Genetics and Plant Breeding* 43, 96-103.

Reddy, L.J., Green, J.M. and Sharma, D. (1981) Genetics of *Cajanus cajan* (L.) Millsp. × *Atylosia* spp. In: *Proceedings of the International Workshop on Pigeonpeas, volume 2, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 39-50.

Reddy, R.P. and Rao, N.G.P. (1975) Somatic variation in *Cajanus cajan*. *Current Science* 44, 816-817.

Reddy, R.P., Singh, D. and Rao, N.G.P. (1975) Character association in pigeonpea. *Indian Journal of Genetics and Plant Breeding* 35, 119-122.

Reed, W., Lateef, S.S. and Sithanantham, S. (1981) Pest management in low-input pigeonpea. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 99-105.

Remanandan, P. (1981) The wild gene pool of *Cajanus* at ICRISAT, present and future. In: *Proceedings of the International Workshop on Pigeonpeas, volume 2, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 29-38.

Remanandan, P., Sastry, D.V.S.S.R. and Mengesha, M.H. (1988) *ICRISAT Pigeonpea Germplasm Catalog: Evaluation and Analysis*. Patancheru, A.P., India: ICRISAT, 90 pp.

Rivas, N. and Gomez Rivas, E. (1975) Study of the canning quality of the pigeonpeas *(Cajanus cajan)* var. Panameno. *Revta de la Facultad de Agronomica (Maracay)* 83(3), 77-81 (in Spanish).

Saxena, K.B., Byth, D.E., Wallis, E.S. and De Lacy, I.H. (1981) Genetic analysis of a diallel cross of early-flowering pigeonpea lines. In: *Proceedings of the International Workshop on Pigeonpeas, volume 2, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 81-92.

Saxena, K.B., Faris, D.G., Reddy, L.J., Sharma, D., Reddy, B.V.S., Gupta, S.C. and Green, J.M. (1986) Prospects for hybrid pigeonpeas. In: Napompeth, B. and Subhadrabandhu, S. (eds), *New Frontiers in Breeding Researches. Proceedings of the Fifth International Congress Society for the Advancement of Breeding Researches in Asia and Oceania (SABRAO)*. Kasetsart University, Bangkok, Thailand, pp. 379-388.

Saxena, K.B., Laxman Singh, Gupta, S.C., Chauhan, Y.S. and Reddy, M.V. (1989) Hybrid pigeonpea development and prospects. Paper presented at the seminar on Strategies for Increasing Pulses Production, 3-4 January, 1989, Agricultural Research Station, Badnapur, Maharashtra, India.

Saxena, K.B. and Sharma, D. (1983) Early generation testing in pigeonpea (*Cajanus cajan* (L.) Millsp.). *Tropical Plant Science Research* 1(4), 309-313.

Sharma, D. and Green, J.M. (1980) Pigeonpea. In: Fehr, W.R. and Hadley, H.H. (eds), *Hybridization of Crop Plants*. Madison, ASA, pp. 471-481.

Sharma, D., Gupta, S.C., Rai, G.S. and Reddy, M.V. (1984) Inheritance of resistance to sterility mosaic disease in pigeonpea–I. *Indian Journal of Genetics and Plant Breeding* 44, 84-90.

Sharma, D., Kannaiyan, J. and Reddy, L.J. (1982) Inheritance of resistance to blight in pigeonpeas. *Plant Disease* 66, 22-25.

Sharma, D., Reddy, L.J., Green, J.M. and Jain, K.C. (1981) International adaptation of pigeonpeas. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 77-81.

Sharma, H.K., Laxman Singh and Sharma, D. (1973) Genetic analysis of flower initiation in pigeonpea. *Indian Journal of Genetics and Plant Breeding* 33, 393-397.

Shaw, F.J.F. (1936) Studies in Indian pulses: the inheritance of morphological characters and wilt resistance in *rahar (Cajanus indicus* Spreng.). *Indian Journal of Agricultural Sciences* 6, 139-187.

Shaw, F.J.F., Khan, A.R. and Singh, H. (1933) Studies in Indian pulses. 3. The types of *Cajanus indicus* Spreng. *Indian Journal of Agricultural Sciences* 3, 1-36.

Singh, U., Jambunathan, R., Saxena, K.B. and Subrahmanyam, N. (in press) Nutritional quality evaluation of newly developed high protein genotypes of pigeonpea (*Cajanus cajan* (L.). *Journal of the Science of Food and Agriculture*.

Solomon, S., Argikar, G.P., Salanki, M.S. and Morbad, I.R. (1957) A study of heterosis in *Cajanus cajan* (L.) Millsp. *Indian Journal of Genetics and Plant Breeding* 17, 90-95.

Spence, J.A. and Williams, S.J.A. (1972) Use of photoperiod response to change plant design. *Crop Science* 12, 121-122.

Suneson, C.A. (1956) An evolutionary plant breeding method. *Agronomy Journal* 48, 188-191.

Takeda, K. and Frey, K.J. (1976) Contributions of vegetative growth rate and harvest index to grain yield of progenies from *Avena sativa* × *A. sterilis* crosses. *Crop Science* 16, 817-821.

Tunwar, N.S. and Singh, S.V. (1985) *Handbook on Cultivars*. Central Seed Committee, Ministry of Agriculture and Rural Development, New Delhi, India, pp. 217-226.

Vaheeduddin, S. (1956) Selection of tur (*Cajanus cajan* L.) resistant varieties against wilt (*Fusarium udum* Butler). *Agricultural College Journal, Osmania University* 3, 12-13.

van der Maesen, L.J.G. (1980) India is the native home of the pigeonpea. In: Arends, J.C., Boelema, G., de Groot, C.T. and Leeuwenberg, A.J.M. (eds), *Libergratulatorius in honorem H.C.D. de Wit. Landbouwhogeschool Miscellaneous Paper no. 19*. Wageningen, Netherlands: H. Veenman and B.V. Zonen, pp. 257-262.

van der Maesen, L.J.G. (1986) *Cajanus DC. and Atylosia W. & A. (Leguminosae). Agricultural University Wageningen Papers 85-4 (1985)*. Agricultural University, Wageningen, the Netherlands, 225 pp.

Veeraswamy, R., Rangasamy, P. and Sheriff, N.M. (1975) CO 2 redgram–a new strain with early maturity and improved plant type. *Madras Agricultural Journal* 62, 541-543.

Wallis, E.S., Byth, D.E., Whiteman, P.C. and Saxena, K.B. (1983) Adaptation of pigeonpea (*Cajanus cajan*) to mechanized culture. In: Driscoll, C.J. (ed), *Proceedings, Australian Plant Breeding Conference, Adelaide, South Australia, 14-18 February, 1983*. University of Adelaide, South Australia, pp. 142-145.

Wallis, E.S., Saxena, K.B. and Byth, D.E. (1981) A new source of genetic male sterility in pigeonpea. In: *Proceedings of the International Workshop on Pigeonpeas, volume 2, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 105-108.

Whiteman, P.C., Byth, D.E. and Wallis, E.S. (1985) Pigeonpea [*Cajanus cajan* (L.) Millsp.]. In: Summerfield, R.J. and Roberts, E.H. (eds), *Grain Legume Crops*. Collins Professional and Technical Books, London, pp. 658-698.

Zeven, A.C. and Zhukorsky, P.M. (1975) Dictionary of cultivated plants. In: Huxby, J. (ed), *The New Systematics*. Oxford University, London, pp. 549-566.

Chapter 16

PIGEONPEA: NUTRITION AND PRODUCTS

D.G. FARIS and U. SINGH

Principal Coordinator, Asian Grain Legumes Network, Legumes Program, and Biochemist, Grain Quality and Biochemistry Unit, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Andhra Pradesh 502 324, India.

INTRODUCTION

Pigeonpea is an unusual and versatile crop; this versatility is reflected in a wide array of pigeonpea products. The most important products come from the seed, and dominant among these products is dhal made by dehulling the dry seed. Although exact figures are not available it is widely accepted that most of India's crop, which represents about 90% of the total world production, is made into dhal (Kurien, 1981). The next most important product of pigeonpea is probably the wood left after the crop has been threshed that is used as fuel for cooking. Two other important products are feed and forage for animals. The amount of pigeonpea used in this way is difficult to measure since with the exception of the by-products from dhal mills very little enters commercial channels. However, there is great potential for using pigeonpea as animal feed as can be seen from the extensive literature on this topic. Next in importance after animal feed is vegetable pigeonpea from green pods and green seeds. There are many other minor products including lac and various medicines.

This chapter covers nutrition, human food, animal feed, other products, and medicinal uses.

NUTRITION

Chemical Constituents

Pigeonpea cotyledons contribute about 85%, the embryo about 1%, and the seed coat 14% to the total seed mass (Table 16.1). The chemical constituents of pigeonpea seed govern its nutritive value. There is wide variability in the reported chemical constituents of pigeonpea (Tripathi *et al.*, 1975; Sharma *et al.*, 1977; Narasimha and Desikachar, 1978; Manimekalai *et al.*, 1979; Singh *et al.*, 1984c); most of this variability can be attributed to differences in analytical methods, and to the origin of samples. Variations in sample origin include differences in sampling time after harvest, the cultivar used, and the environment where the crop was grown.

Table 16.1. Distribution of some dietary nutrients in different parts of mature pigeonpea seed.

Constituents	Whole seed	Cotyledons	Embryo	Seed coat	Reference
Part of seed (%)	100	85.3	0.7	14.3	Singh and Jambunathan, 1982
Protein (%)	20.5	22.2	49.6	4.9	Singh and Jambunathan, 1982
Lysine[1]	6.8	7.1	7.0	3.9	Singh and Jambunathan, 1982
Threonine[1]	3.8	4.3	4.7	2.5	Singh and Jambunathan, 1982
Methionine[1]	1.0	1.2	1.4	0.7	Singh and Jambunathan, 1982
Cystine[1]	1.2	1.3	1.7	-	Singh and Jambunathan, 1982
Carbohydrates (%)	64.2	66.7	31.0	58.7	Singh *et al.*, 1968
Fat (%)	3.8	4.4	13.5	0.3	Singh *et al.*, 1968
Fibre (%)	5.0	0.4	1.4	31.9	Singh *et al.*, 1968
Ash (%)	4.2	4.2	6.0	3.5	Singh *et al.*, 1968
Calcium[2]	296	176	400	917	Singh *et al.*, 1968
Iron[2]	6.7	6.1	13.0	9.5	Singh *et al.*, 1968
Thiamine[2]	0.63[3]	0.40[4]	-	-	
Riboflavin[2]	0.16[3]	0.25[4]	-	-	
Niacin[2]	3.1[3]	2.2[4]	-	-	

1. $g\ 100g^{-1}$ protein
2. $mg\ 100g^{-1}$ dry matter
3. Salunkhe *et al.*, 1986
4. Geervani and Theophilus, 1980.

Starch

Starch and protein are the principal constituents of pigeonpea seed (Table 16.1). Singh *et al.* (1984c) showed that the starch content of the cotyledons of several cultivars belonging to different maturity groups ranged between 51.4 and 58.8%, with a mean of 54.7%; i.e., a relatively small variation among the cultivars tested (Table 16.2). There was no consistent difference among the three maturity groups. These values were higher than those reported by Sharma *et al.* (1977), who reported that the cotyledon starch percentage of 22 cultivars showed a larger variation, ranging between 39.0 and 55.9% with a mean of 47.7%.

Protein

Protein quality is of prime importance in the pigeonpea products used for human food (Salunkhe *et al.*, 1986). The protein quality of pigeonpea seed is a function of the amount of its protein, the

Table 16.2. Chemical composition (%) of dhal made from different pigeonpea cultivars.

Cultivar	Maturity group	Protein	Starch	Soluble sugars	Fat	Crude fibre	Ash
Pant A2	Early	24.0	51.4	5.2	2.1	1.6	4.0
UPAS 120	Early	21.4	54.5	4.8	2.2	1.5	3.5
Prabhat	Early	20.1	54.9	4.5	1.8	2.0	3.7
C 11	Medium	23.7	57.6	4.6	2.0	1.6	3.5
No.148	Medium	22.7	54.2	4.3	1.7	1.8	3.2
Hy 3C	Medium	20.3	58.8	5.0	1.8	1.9	3.5
Gwalior 3	Late	24.8	51.5	5.5	2.0	1.8	4.1
T 17	Late	22.0	54.5	5.0	1.9	1.3	3.8

Source: Singh *et al.*, 1984c.

essential amino acids in that protein, and the protein's digestibility (Singh and Eggum, 1984). Hulse (1977), found that the protein content of pigeonpea seed samples ranged between 18.5 and 26.3% with a mean of 21.5%. Singh and Jambunathan (1981a) found that the protein content of 43 commonly cultivated varieties of pigeonpea ranged between 17.9 and 24.3% for whole seed, and between 21.1 and 28.1% for dhal samples; indicating only a small variation. Dahiya *et al.*, 1977, reported a high environmental influence on protein content, and a negative correlation between yield and percentage seed protein.

Because many of the protein contents quoted in the literature are based on a wide variety of sources and various methods of analysis, they are not all readily comparable, and may prove to be of little practical value to the plant breeder. Yet the genetic variability in protein content is an important factor that affects the improvement of protein quality by selection and breeding. Fortunately, the protein content of dhal samples of cultivated and wild species of pigeonpea have shown wide variation, and systematic efforts have been made to use this genetic variability to develop high protein lines of pigeonpea with acceptable seed size (Saxena *et al.*, 1987).

Seed Protein Fractions

Protein fractions play an important role in determining the overall amino acid composition of the seed proteins. Storage proteins; i.e., globulins constitute about 65% of the total seed protein of pigeonpea cotyledons (Table 16.3, Singh and Jambunathan, 1982). These globulins have fewer

Table 16.3. Distribution of protein fractions in different components of **pigeonpea seed.**

Component	Non-protein nitrogen[1] (%)	Protein fractions[1] (%)					
		Albumin	Globulin	Glutelin	Prolamin	Residue	Total
Embryo	6.2	17.0	52.7	21.3	2.7	2.1	95.8
Cotyledons	9.5	11.4	64.5	18.2	3.5	1.8	99.4
Seed coat	27.4	2.6	26.3	32.8	4.2	23.0	88.9
Whole seed	12.8	10.2	59.9	17.4	3.0	5.3	95.8

1. Values are averages of two determinations and expressed as percentage of total protein (N × 6.25)

Source: Singh and Jambunathan, 1982.

sulphur amino acids than other seed proteins, and thus limit the nutritive value of pigeonpea protein. Albumin fractions, although representing a small proportion of the total proteins, are a very rich source of methionine and cystine. The glutelin fraction is a better source of sulphur amino acid than the globulin fraction.

Amino Acids

So far as the amino acids are concerned, there is less methionine, cystine, and tryptophan in pigeonpea than in other legumes. Unfortunately, pigeonpea had the lowest values for these amino acids among several legumes examined by Eggum and Beames (1983). A negative relationship is usually found in legumes between protein percentage and methionine content per unit of protein (Bliss and Hall, 1977). However, this negative relationship was not found to be strong in pigeonpea, indicating that both protein and methionine contents could be improved by breeding for protein quality (Singh and Eggum, 1984).

Digestibility

The true protein digestibility (TD) of pigeonpea significantly increases with cooking (Singh *et al.*, in press). Interestingly the biological value (BV) of cooked samples decreases in both whole seed and dhal, whereas the net protein utilization (NPU) of cooked samples increases. This may be due to an increase in protein digestibility (Table 16.4). The BV of cooked samples of both whole seed and dhal probably decreases because heat causes considerable nutritional damage to methionine, the most important amino acid in grain legumes (Shemer and Perkins, 1975). A comparison of the TD of raw whole seed (nearly 60%) and dhal samples (over 70%) indicated a large increase in TD when pigeonpea seed is made into dhal (Singh *et al.*, in press). The lower TD of whole seed may be due to its higher fibre content, as a majority of this fibre is concentrated in the seed coat (Table 16.1).

High Protein Lines

As mentioned earlier high-protein (HP) pigeonpea lines containing over 25% protein with acceptable seed size have been bred. The protein digestibility, BV, NPU, and utilizable protein (UP) of

Table 16.4. Biological evaluation of cooked and raw samples of dhal made from high- and normal-protein pigeonpea genotypes[1].

	Raw					Cooked				
Genotype	Protein[2]	TD	BV	NPU	UP	Protein[2]	TD	BV	NPU	UP
High-protein										
HPL 8	28.7	71.5	75.8	54.2	15.6	27.6	83.7	67.0	56.1	15.5
HPL 40	31.1	69.8	73.6	51.4	16.0	30.8	82.9	65.3	54.1	16.7
Normal-protein										
C 11	24.8	72.3	73.6	53.2	13.2	23.9	84.3	66.7	56.2	13.5
ICPL 211	23.1	70.8	76.4	54.1	12.5	22.8	85.7	62.9	53.9	12.3
SE	±0.28	±0.98	±1.14	±1.23	±0.34	±0.26	±2.14	±1.68	±1.06	±0.25

1. TD = true protein digestibility, BV = biological value, NPU = net protein utilization (TD × BV/100), UP = utilizable protein (protein × NPU/100).
2. Protein = N × 6.25 (dry mass basis).

Source: Singh *et al.*, in press.

raw and cooked whole seed and dhal samples of these HP genotypes have been compared with normal protein (NP) genotypes using rat feeding trials (Table 16.4, Singh *et al.*, in press). The protein digestibility of raw samples ranged between 69.8 and 72.3%, and of cooked samples between 82.9 and 85.7% indicating a small variation among the genotypes. Pigeonpea's coefficient of digestibility ranged between 59 and 90% showing a large variation (Hulse, in press). Although BV and NPU values have shown some differences among genotypes (Table 16.4), no noticeable differences between HP and NP genotypes as a group were observed. More importantly, the values for UP were considerably higher in HP than in NP pigeonpea genotypes. This indicates that HP genotypes are nutritionally better than NP genotypes since they contain more utilizable protein (Singh *et al.*, in press).

Antinutritional Factors

Pigeonpea contains considerable amounts of polyphenolic compounds that inhibit the activity of the digestive enzymes trypsin, chymotrypsin, and amylase. These are much higher in pigeonpea cultivars with dark seed coats (Table 16.5; Singh, 1984).

Of the antinutritional factors found in grain legumes, trypsin, chymotrypsin, amylase inhibitors, polyphenols (commonly known as tannins), and oligosaccharides are very important in pigeonpea (Table 16.6; Singh, 1988). Pigeonpea also contains considerable amounts of unavailable carbohydrates that are known to reduce the bioavailability of some nutrients (Kamath and Belavady, 1980).

A large variation exists in the trypsin and chymotrypsin inhibitor contents of cultivated and wild species of pigeonpea (Table 16.7). In comparison with soybeans, peas, and common beans, these antinutritional factors are less of a problem in pigeonpea. Although it contains less protease inhibitors than soybean, pigeonpea contains higher levels than the other commonly consumed pulses in India (Sumathi and Pattabiraman, 1976). Phytolectins are toxic factors that interact with glycoprotein on the surface of red blood cells, causing them to agglutinate. Pigeonpea contains phytolectins, but they are highly sensitive to heat treatment and hence may be of little significance. Pigeonpea also contains traces of glycosides but not at a toxic level (Singh, 1988).

Food legumes are known to cause flatulence when consumed in large amounts. This is because they contain high levels of the oligosaccharides; stachyose, raffinose, and verbascose. These three sugars together constitute about 53% of the total soluble sugars in pigeonpea, although there is a two- to four-fold variation in the content of these sugars among cultivars (Singh, 1988).

Table 16.5. Polyphenol contents and varietal differences in the enzyme-inhibitory property of pigeonpea polyphenols.

			Enzyme inhibition[1] (%)			
Cultivar	**Testa colour**	Polyphenols (mg g^{-1} sample)	Trypsin	Chymotrypsin	Human saliva	Hog pancreas
Hy 3C	White	3.7	37.9	36.0	34.5	21.8
NP(WR) 15	White	6.0	40.5	38.6	32.7	19.7
C 11	Light brown	14.2	91.5	90.3	86.0	80.9
BDN 1	Brown	15.2	90.3	91.6	79.4	69.3
No. 148	Brown	14.9	88.0	85.9	75.8	68.5
Mean		10.8	69.7	68.5	61.7	52.0
SE		±0.2	±2.1	±1.7	±1.4	±1.3

1. Based on assay using 200 mg polyphenols for trypsin and chymoptrypsin, and 250 μg polyphenols for amylase inhibitions.

Source: Singh, 1984.

Table 16.6. Antinutritional factors and toxic substances in pigeonpea seed.

Constituent	Cultivars tested	Range	Mean
Protease inhibitors (units mg^{-1})			
Trypsin	9	8.1-12.1	9.9
Chymotrypsin	9	2.1-3.6	3.0
Amylase inhibitor (units g^{-1})	9	22.5-34.2	26.9
Oligosaccharides (g 100g^{-1})			
Raffinose	10	0.24-1.05	0.47
Stachyose	9	0.35-0.86	0.49
Stachyose + verbascose	4	1.60-2.30	2.0
Polyphenols (mg g^{-1})			
Total phenols	14	3.0-18.30	10.67
Tannins	10	0.0-0.2	0.03
Phytolectins (units g^{-1})	1	400	400
Cyanogens (glycosides)	1	traces	-
Mycotoxins	1	traces	-

Source: Singh, 1988.

Table 16.7. Protein contents, trypsin and chymotrypsin inhibition, and protein digestibilities in cultivars of pigeonpea and its wild relatives.

Cultivars/species	Protein N × 6.25 (%)	Trypsin inhibition		Chymotrypsin inhibition		*In vitro* protein digestibility (%)
		(Units mg^{-1} meal)	(Units mg^{-1} protein)	(Units mg^{-1} meal)	(Units mg^{-1} protein)	
Cajanus cajan cultivars						
Pant A-2	24.4	12.5	69.7	5.0	27.8	57.8
UPAS 120	23.1	12.9	71.3	4.2	23.1	59.5
Baigani	26.2	15.1	67.1	3.5	15.3	64.1
Mean	24.6	13.5	69.4	4.2	22.1	60.5
Wild species						
C. scarabaeoides var. *scarabaeoides*	27.8	14.2	60.4	14.2	60.9	67.8
C. sericeus	28.4	17.9	76.4	20.1	85.3	68.1
C. albicans	28.5	19.4	81.9	22.0	92.4	62.6
C. crassus var. *crassus*	27.1	25.8	121.4	11.5	47.1	59.3
C. platycarpus	29.3	13.3	54.5	11.5	47.1	59.3
C. cajanifolius	29.1	14.9	61.3	5.9	24.2	56.0
Rhynchosia rothii	27.6	82.4	445.7	20.9	113.2	40.9
Mean	28.3	26.6	127.6	15.2	69.1	58.2
SE	±0.3	±0.5	±2.0	±0.2	±1.3	±1.6

Source : Singh and Jambunathan, 1981b.

Other Factors

The crude fibre, ash, and fat contents of pigeonpea cultivars (Table 16.2) do not show a large variation (Singh *et al.*, 1984c). Differences in the mineral composition (except for calcium) of whole grain and dhal have only a marginal effect on human nutrition (Sankara Rao and Deosthale, 1981). These workers also indicate that pigeonpea, either as whole grain or dhal, appears to be a significant contributor to the daily requirements of magnesium, manganese, and copper in the diet. Narasimha and Desikachar (1978) reported a large variation in the calcium (118 to 198 mg 100g^{-1}) and magnesium (76 to 152 mg 100g^{-1}) contents of the cotyledons of 10 pigeonpea cultivars, and noticed that these minerals were positively correlated with the cooking time of the cotyledons. When compared with other pulses (chickpea, urd bean, and mung bean), the mineral composition of pigeonpea seed showed little variation (Shobhana *et al.*, 1976). In this study, the calcium content of pigeonpea seed was higher than that of chickpea, urd bean, and mung bean, but the reverse was true for their iron content. Like other legumes, pigeonpea is a relatively good source of water-soluble vitamins especially thiamin, riboflavin, and niacin (Salunkhe *et al.*, 1986). According to Miller *et al.* (1956), pigeonpea contained the highest amount of B vitamins, carotene, and ascorbic acid of 285 food items used in Hawaii, USA.

Supplementation Value of Pigeonpea in Cereal-based Diets

Legumes as a supplement bring to cereal-based diets a variety of tastes and textures. They supplement cereals for minerals and vitamins of the B complex (Aykroyd and Doughty, 1982) but most importantly they complement the essential amino acids in cereals (Hulse, in press). Cereals like rice, wheat, maize, and finger millet, which form the basic ingredients of the diet in a majority of developing countries, are generally deficient in lysine and threonine. Their protein quality greatly improves by supplementation with the essential amino acids deficient in these cereals. Pigeonpea protein is a rich source of lysine, but is usually deficient in the sulphur-containing amino acids, methionine and cystine (Table 16.8). It thus provides a good means of supplementing the essential amino acids in cereals.

Table 16.8. Protein content and essential amino acid score of pigeonpea alone and in combination with rice and wheat in different proportions[1].

	Amino acid score[2]								
		Rice:pigeonpea (w/w)				Wheat:pigeonpea (w/w)			
Essential amino acid	Pigeonpea	a	b	c	d	a	b	c	d
Lysine	140	67	74	82	89	49	58	68	76
Threonine	80	92	91	90	89	72	73	74	75
Methionie + cystine	55	110	104	97	93	105	100	95	90
Tryptophan	64	128	121	115	109	112	107	103	97
Valine	83	122	118	114	110	90	89	88	88
Leucine	103	114	113	112	111	94	95	96	96
Isoleucine	100	120	118	116	114	88	89	91	92
Tyrosine + phenylalanine	157	152	153	153	154	123	126	130	133
Protein (%)	**22.3**	6.8	8.4	9.9	11.5	11.8	12.8	13.9	15.0

1. Calculated on the basis of amino acid and protein values of pigeonpea dhal, whole wheat, and raw milled rice reported by Gopalan *et al.*, 1971.
2. Cereal:pigeonpea ratio; a = 100:0, b = 90:10, c = 80:20, and d = 70:30

The supplementary value of legumes is generally estimated by comparing the amino acid composition of mixed diets with standard reference proteins (FAO/WHO, 1973). By applying this calculation, an amino acid score is calculated, and the lowest score indicates the first limiting amino acid of the proteins in cereal-legume mixed diets. The lowest score obtained for any essential amino acid may be taken as a first approximation of the probable efficiency of utilization of the test protein by children (FAO/WHO, 1973). According to Hulse (1977) the ratio of cereal protein to legume protein is 70:30 in Latin America, 75:25 in Africa and the Near East, and 90:10 in Southeast Asia. The mutual compensation is closest to ideal when the ratio by weight of cereal to legume is roughly 70:30, in which proportion each provides above equal parts by weight of protein (Hulse, in press). The protein contents and amino acid scores of pigeonpea, wheat, rice alone and mixed in different proportions as shown in Table 16.8 indicate that methionine and cystine followed by tryptophan and threonine are the limiting essential amino acids in pigeonpea, whereas lysine is the first limiting amino acid of rice and wheat. It is apparent that pigeonpea improves the amino acid score for lysine in rice- and wheat-based diets; and for threonine, leucine, and isoleucine in wheat-based diets if the proportion of pigeonpea in the diet is increased to 70:30 cereal:pigeonpea (Table 16.8).

Daniel *et al.* (1970) assessed the effect of supplementing rice and finger millet diets with 8.5%, 16.7%, and 25% pigeonpea with and without vitamins and minerals on the overall nutritive value of the diet. They found that supplementation with pigeonpea brought about a significant increase in the nutritive value of mixed diets (Table 16.9). Results of this study suggested that incorporation of 8.5% pigeonpea dhal in a rice diet, and 16.7% in a finger millet diet would markedly improve the diet's nutritive value. In the subsequent year, Kurien *et al.* (1971) reported that the nutritive value of the kaffir corn (maize) and wheat-based diets was considerably improved when supplemented with pigeonpea.

Table 16.9. Effect of supplementary rice diets with varying levels of pigeonpea on the growth of young rats[1].

Diet	Protein (%)	Gain in mass (%)	Protein intake	Protein efficiency ratio
Rice	7.2	25.5	11.8	1.78
Rice + 8.5% pigeonpea	8.7	32.8	15.5	2.13
Rice + 16.7% pigeonpea	10.0	45.2	19.6	2.32
Rice + 25.0% pigeonpea	11.4	48.9	21.8	2.25

1. Based on an experimental period of 4 weeks.

Source: Daniel *et al.*, 1970.

Nutritional Quality of Vegetable Pigeonpea

Green seeds of pigeonpea are consumed as a vegetable. This green seed is more nutritious than the dry seed because it contains more protein, sugar, and fat than the mature seed (Table 16.10). In addition, the protein and starch digestibilities of green seed are higher than those of the mature seed. Also the green seed contains lower quantities of flatulence-causing sugars, and of trypsin and amylase inhibitors (Singh *et al.*, 1984a). Green pigeonpea is a good source of iron (Singh *et al.*, 1984b) and a better source of calcium than dhal. Studies on the bioavailability of important dietary nutrients of whole and green pigeonpea seed are not available. These are needed to understand the relative nutritional qualities of green and mature seed.

Table 16.10. Comparison of nutritional constituents on the basis of dry mass, and cooking times of pigeonpea seed.

Constituent/cooking time	Green seed	Mature seed	Dhal[1]
Protein (%)	21.0	18.8	24.6
Protein digestibility (%)	66.8	58.5	60.5
Trypsin inhibitor (units mg^{-1})	2.8	9.9	13.5
Starch content (%)	48.4	53.0	57.6
Starch digestibility (%)	53.0	36.2	-
Amylase inhibitor (units mg^{-1})	17.3	26.9	-
Soluble sugars (%)	5.1	3.1	5.2
Flatulence factors (g $100g^{-1}$ soluble sugar)	10.3	53.5	-
Crude fibre (%)	8.2	6.6	1.2
Fat (%)	2.3	1.9	1.6
Minerals and trace elements (mg $100g^{-1}$)			
Calcium	94.6	120.8	16.3
Magnesium	113.7	122.0	78.9
Copper	1.4	1.3	1.3
Iron	4.6	3.9	2.9
Zinc	2.5	2.3	3.0
Cooking time (min)	13	53	18

1. Split seed with seed coat removed.

Source: Faris *et al.*, 1987 taken from various reports and publications available from ICRISAT.

Cooking Quality

Pigeonpea dhal and whole seed are consumed as human food after cooking to a desirable softness by boiling in water. Housewives prefer pigeonpea dhal that cooks fast and increases in volume when cooked (Manimekalai *et al.*, 1979). Therefore cooking quality is primarily defined in terms of cooking time. Sharma *et al.* (1977) reported that the cooking time of dhal from 22 genotypes ranged between 20 and 44 min, and of whole seed between 45 and 67 min indicating a large variation. This study attributed longer cooking time to the presence of the seed coat in whole seed. No significant differences in taste and flavour of cooked dhal were found among pigeonpea varieties whose cooking time ranged from 40 to 60 min (Manimekalai *et al.*, 1979). In some African countries, pigeonpea is consumed as whole seeds cooked to a soft consistency, but pigeonpea is less popular than cowpea because the former takes longer to cook. A comparison of the cooking time of pigeonpea and cowpeas, with and without 16-h presoaking treatments, and using either water or a sodium bicarbonate solution (1% w/v), indicated that the pigeonpea genotypes tested took longer to cook than cowpea when the seed had not been presoaked but that this was reversed after presoaking (ICRISAT, 1987). This means that the beneficial effect of soaking on cooking time is more pronounced in pigeonpea than in cowpea. The test also showed that soaking in sodium bicarbonate solution reduced cooking time more in pigeonpea than in cowpea.

Several physical and chemical factors influence the cooking quality of pigeonpea. The amounts of water absorbed and the solids dispersed during cooking were found to be highly correlated with the cooking time of pigeonpea dhal (Singh *et al.*, 1984c). This suggests that these two parameters can be objective indicators of the cooking quality of pigeonpea dhal (Narasimha and Desikachar, 1978; Singh *et al.*, 1984c). Calcium and magnesium contents were significantly and positively correlated with the cooking time of pigeonpea dhal, though in some cultivars the magnitude of this correlation was low (Narsimha and Desikachar 1978; and Singh *et al.*, 1984c; Sharma *et al.*, 1977). Further work to study the role that these constituents play in influencing the cooking time of pigeonpea would be useful. Although no clear cut differences in cooking time, water absorption, solids dispersion, and texture of pigeonpea cultivars of different maturity groups were observed, the cooking quality of early cultivars appeared to be better than those of the medium and late maturity groups (Singh *et al.*, 1984c). These studies also indicated that seasonal variations must be taken into consideration when pigeonpea cultivars are compared for cooking quality.

Effect of Processing on Nutritive Value

Pigeonpea is traditionally processed into consumable forms by methods which can be broadly divided into two categories: primary processing or "dehulling" to form dhal; and secondary processing that involves three major treatments – cooking, germination, and fermentation. Dehulling pigeonpea reduces its cooking time and improves palatability and digestibility (see Chapter 17). Dehulling usually removes the germ along with the husk, thus important dietary nutrients such as protein, calcium, iron, and zinc are lost (Singh *et al.*, 1989a). Efforts should be made to develop dehulling methods that reduce these nutritional losses.

Cooking

Of the various secondary processing practices, cooking improves the bioavailability of nutrients and also partially or wholly destroys some of the antinutritional factors (Salunkhe, 1982). Starch digestibility is improved by moist heat treatment. Although cooking improves nutritional quality, prolonged cooking results in a decrease in protein quality and a loss of vitamins and minerals. In this context, pigeonpea cultivars that require less time to cook are preferable as cooking them requires less fuel. A major beneficial effect of cooking on pigeonpeas is the destruction of the protease inhibitors that interfere in protein digestibility. These inhibitors are completely destroyed when heated under acidic conditions (Sumathi and Pattabiraman, 1976). Preliminary soaking followed by dry heat treatment only partially inactivates the trypsin inhibitors (Contreras and Tagle, 1974). The essential amino acids of pigeonpea do not change noticeably during cooking, except for a possible slight decrease in lysine (Singh *et al.*, 1989a).

Germination

Soaking followed by germination considerably reduces the activity of the trypsin inhibitors in pigeonpea. Phytic acid forms insoluble compounds with essential minerals such as calcium, iron, magnesium, and zinc. Germination can reduce or eliminate appreciable amounts of phytic acid in pigeonpea, thus improving the bioavailability of its minerals (Salunkhe, 1982). Germination followed by cooking can reduce the levels of oligosaccharides in pigeonpea by about 70% (Iyengar and Kulkarni, 1977). Germination and cooking also significantly enhance the digestibility of pigeonpea starches (Jyothi and Reddy, 1981). These workers reported that in raw samples, digestibility was highest in cowpea, followed by mung bean, chickpea, urd bean, and pigeonpea. This ranking was also observed in germinated and cooked samples of these legumes. The differences were attributed to differences in the amylose and amylopectin contents of the legume starches. Pigeonpea contained the highest amount of amylose resistant to enzyme action, and as a result had the lowest starch digestibility values (Jyothi and Reddy, 1981).

Fermentation

The nutritive values of legume-based fermented foods are higher than their raw components. Fermentation increases the levels of soluble nitrogen and soluble sugars in pigeonpea. This implies that fermentation may improve the digestibility of pigeonpea protein and starch. Trypsin and chymotrypsin inhibitor activity of pigeonpea were decreased significantly as a result of fermentation (Rajalakshmi and Vanaja, 1967); and Buckle and Iskandar (in press) observed no significant difference in the amino acid composition after fermentation of pigeonpea seeds.

HUMAN FOOD

Whole Dry Seed

Pigeonpea seed has a relatively tough seed coat and as a result takes a long time to cook (Morton *et al.*, 1982, Table 16.10). The seed coat also tends to have a slightly acrid taste but is free from the lipoxidase that causes off-flavours in soybean and some other legumes (Rachie and Roberts, 1974). The pigeonpea seed coat has been reported to contain an essential oil (Morton, 1976). From this essential oil selinenes, copaene, and a mixture of eudesmols that have the aroma of fresh butter have been isolated (Gupta *et al.*, 1969). The seed coat also contains tannins and other antinutritional factors as well as high levels of minerals and fibre.

Since cooking time, cookability, and palatability are major determinants in the utilization of legumes (Gomez, in press), this may explain why relatively little dry pigeonpea seed is cooked and eaten whole. However, it is eaten in eastern Africa, the West Indies, and Indonesia where it is used to make traditional foods. In general these are the same regions where the technology to produce split seed is not well developed. Also many of the varieties grown in these regions tend to be more suitable for cooking whole, often having a white, relatively thin seed coat. Traditional foods made from whole grain are popular in central Java and are well accepted as secondary foods. They include bongko and brubus, and the side dishes and snacks rempeyek, serundeng, and gandasturi (Damardjati and Widowati, in press).

Dhal

Dhal is made by dehulling and splitting pulse seed using various processes to loosen the hull, and then milling or lightly pounding to remove the seed coat and separate the cotyledons (Figure 16.1). This process will be examined in detail in Chapter 17; it is a very old practice that probably started in the kitchen, then expanded to the village level, and is now a large-scale industry. There are presently about 10,000 pulse milling units in India alone (Kurien, 1981); they are next in importance to rice and wheat mills. Mills capable of making dhal are scattered throughout the world and there are indications of an increased interest in making dhal at locations outside India; e.g., the West Indies (Birla, in press), Malawi (Faris, 1981), and Fiji (Faris and Wallis, 1980).

Dhal is popular because dehulling pigeonpea greatly reduces its cooking time and improves the appearance, texture, palatability, and digestibility of the grain (Morton *et al.*, 1982). It also improves the nutritional quality.

Other Products from Dry Seed

There are many other products made from whole dry pigeonpea seed (Aykroyd and Doughty, 1982); some are listed below. Although most of the processes used to make these products are at present not widely used, or are only experimental all have potential.

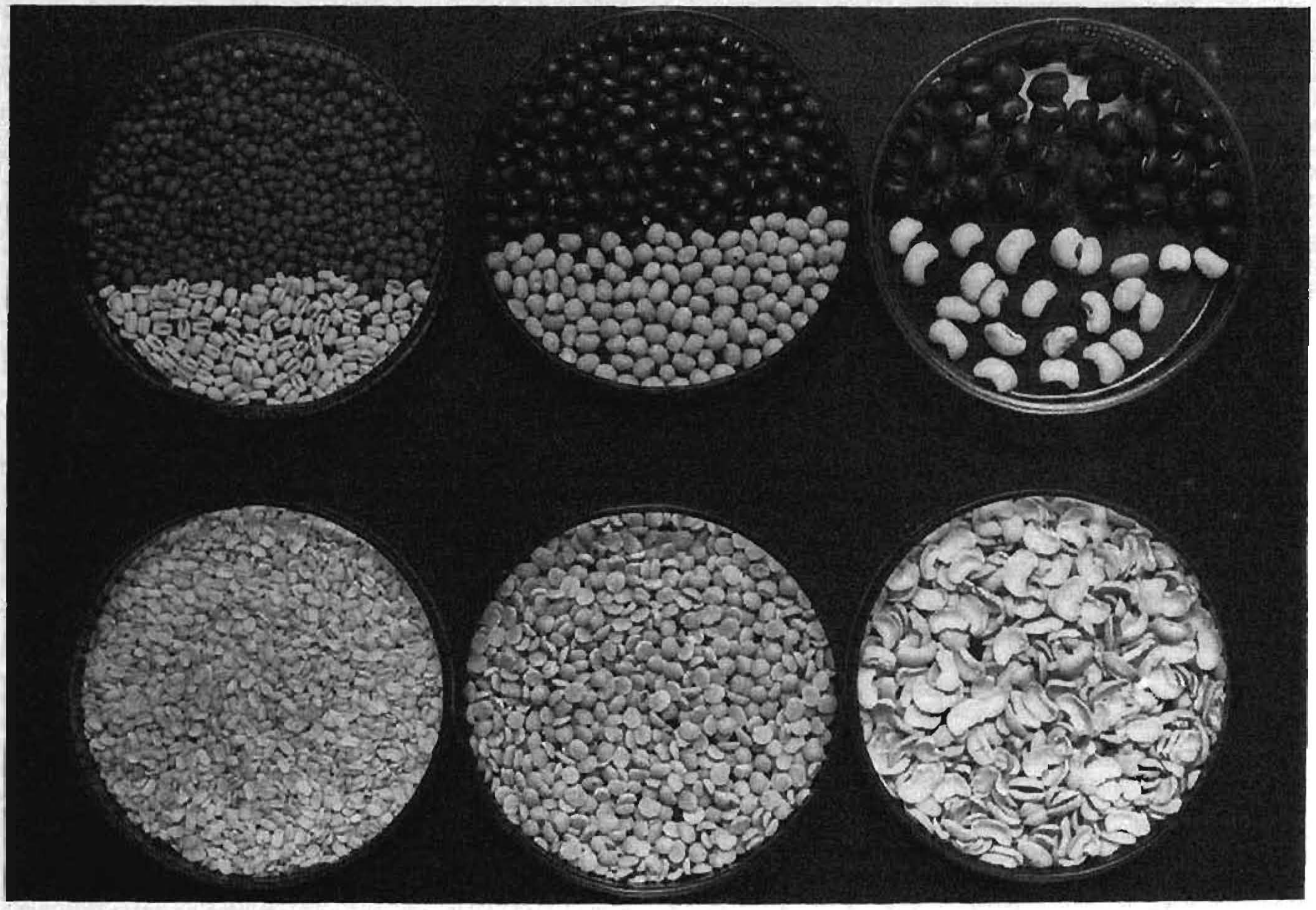


Figure 16.1. Seed of (left to right) mung bean, pigeonpea, and cowpea. Showing (top to bottom) whole seed, dehulled seed, and split cotyledons, i.e., dhal.
Photo: ICRISAT.

- Freshly sprouted seed eaten raw or cooked when the sprouts are about 2-cm long (Aykroyd and Doughty, 1982; Morton, 1976). Sprouting improves the nutritional composition of the seed, and reduces the flatulence suffered by consumers (Savitri and Desikachar, 1985).
- Tempe made with a combination of pigeonpea and soybean. Tempe is a traditional Indonesian food that is prepared by fermenting soaked, dehulled, and cooked legume seed with a *Rhizopus* mould (Buckle and Iskandar, in press). The seed is spread on a mesh, and the mould is allowed to grow on the surface and through the seed forming a compact cake. The tempe cake is cut into pieces for sale and is usually fried before being eaten (Figure 16.2). During soaking, bacterial fermentation takes place and this, along with the subsequent mould fermentation, synthesizes enzymes that decompose proteins, carbohydrates, and lipids, thus improving the digestibility, nutritional value, and palatability of the legume seed (Buckle and Iskandar, in press). Soybean is generally considered to make the best tempe, but because it is expensive it is usually mixed with cheaper legume seed. Tests have shown that tempe prepared from a 2:1 soybean:pigeonpea mixture was not significantly different from soybean tempe in colour, appearance, or texture, raw or fried. Attempts to use a 50:50 mixture produced a significantly poorer product than pure soybean tempe, that while not so good as the pure soybean tempe, was still acceptable. Presently mixed soybean:pigeonpea tempe is under extensive market trials and the subject of an economic study in Indonesia.

- Pigeonpea sauce (ketchup) is a replacement product for soysauce in Indonesia. It is made by fermenting pigeonpea with *Aspergillus oryzae*, *A. niger*, and *Rhizopus* sp. The fermentation is continued in a salt solution, and the sauce is then cooked. Although the protein content of this sauce is less than 2% compared with the 3% protein in soysauce it is still accepted by the consumers (Damardjati and Widowati, in press).
- Canned whole dried seed is a popular product in parts of the Caribbean as it reduces the amount of fuel housewives need to cook pigeonpea. The canning process involves soaking the seed for 24 h and then pressure-cooking it in brine in the can. For this product the processors normally use seed with a white seed coat (Faris, 1982).
- Pigeonpea flour can be used, after mixing it with wheat or rice flour, to improve the protein level of baked products. Tests in Indonesia with rice:pigeonpea flour has shown that up to 30% pigeonpea is acceptable to consumers mainly because the texture is improved although the colour, taste, flavour, and appearance are not so good as pure rice flour when made into cookies (Damardjati, 1989).
- Extruded food is prepared by passing material through a screw device under very high pressure while grinding it at the same time. In principle the process is similar to the hand-turned meat grinder used by some housewives. The low-moisture, high-extrusion systems used in industrial processes are relatively cheap, and are capable of continuously processing pigeonpea/cereal blends. They generate heat by friction and are capable of simultaneous cooking, partial sterilization, expansion, partial dehydration, enzyme inactivation, and (to some extent) shaping the product. Dry extrusion of cereal/pigeonpea blends in appropriate proportions produces convenience foods for high nutritional diets (Wijeratne and Nelson, in press). The addition of up to 30% pigeonpea flour to extrusion foods was acceptable to panelists in organoleptic trials in Indonesia (Damardjati and Widowati, in press).

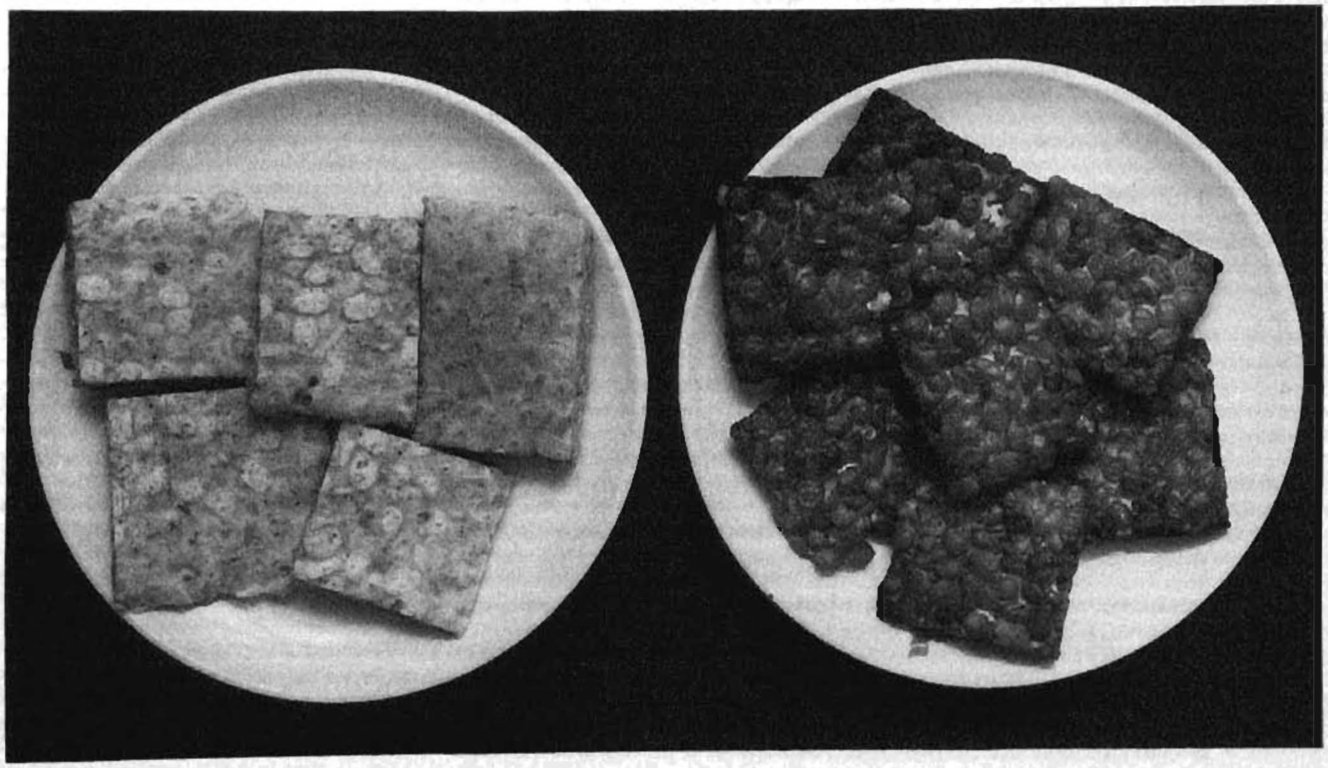


Figure 16.2. Tempe made from pigeonpea, uncooked (left) and fried (right).
Photo: ICRISAT.

- Clear noodles (Figure 16.3) of a quality higher than those made from mung bean have been made using dehulled pigeonpea seed (Singh *et al.*, 1989b).

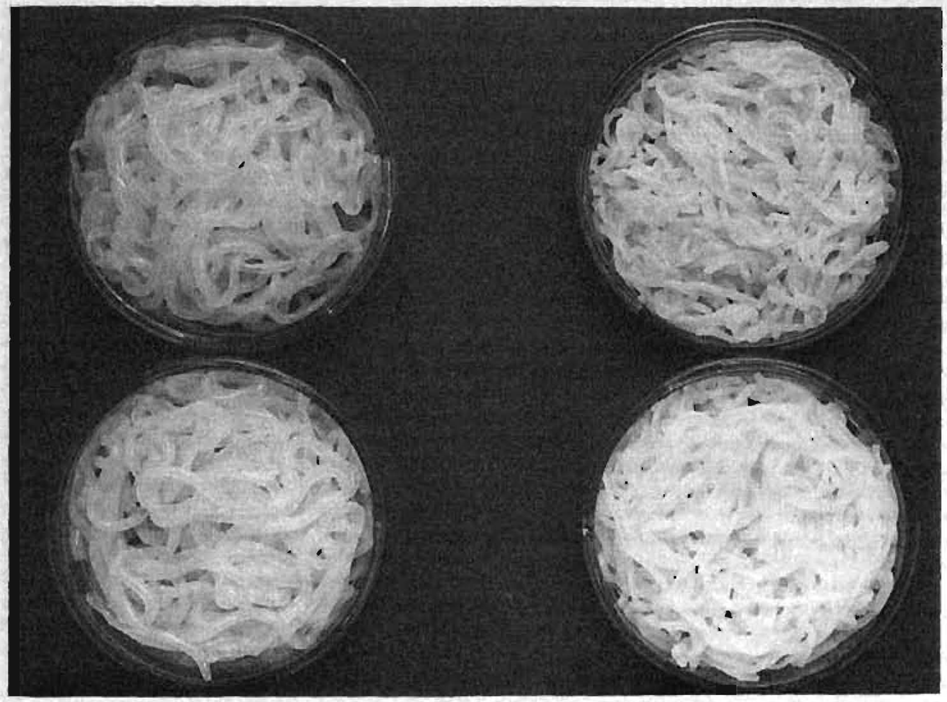


Figure 16.3. Noodles made from whole seed (above) and dhal (below) of mung bean (left), and pigeonpea (right).
Photo: ICRISAT.

Vegetable

Green Seed

The seed of pigeonpea can be used immature or green as a vegetable. For this purpose the pods are usually picked when the seed has reached physiological maturity and is just starting to loose its bright green colour. At this stage it has accumulated most or all of its dry matter, but has not completed converting sugar to starch and is still somewhat tender. Harvesting the seed at the right maturity is the most important step in obtaining a high-quality product (Sánchez-Nieva *et al.*, 1963). The pods are usually hand-picked, and yields of around 15 t ha^{-1} (35% dry matter) have been reported (Sállette and Courbois, 1968).

In most countries where pigeonpea is grown, vegetable pigeonpea plants are grown near houses; e.g., in many countries of Asia, Africa, and the Caribbean, sometimes one or two plants, a hedge, or a small plot. Some observations suggest that when pigeonpea is grown near a house there tend to be fewer insect problems on the pods than when the crop is grown in a field, possibly because of smoke from cooking fires or the movement of people (Faris, 1981).

In many countries in the Caribbean region, in eastern and southern Africa, and in parts of India, e.g., Gujarat, green pigeonpea is an important product in its own right (Faris *et al.*, 1987; Mansfield, 1981; Faris, 1982). In the English-speaking countries of the Caribbean, green pigeonpea is considered an important vegetable component of Christmas dinner, much as cranberries are in North America, or plum pudding in England. In these countries the pigeonpea comes to market as pods and is bought that way for shelling at home. In some markets the vendors will shell the pods while they are waiting for customers and then sell the green seed. In certain countries of the Caribbean, such as the Dominican Republic (Mansfield, 1981) and Puerto Rico (Sánchez-Nieva *et al.*, 1961b) the green seed is canned, partly for local consumption, but mainly for export to markets in North America and Europe for sale to West Indian immigrants. Some of the green pigeonpea is also frozen (Sánchez-Nieva *et al.*, 1961a) and dehydrated for sale (Rahman, 1961; Mansfield, 1981).

The high cost of hand harvesting is an important consideration when producing green pigeonpea for market. The problem is caused because of the variation in the stage of development of pods even within the same branch. This variation means that pods cannot all be harvested at once, but must be selected as they reach the right stage in order to get the best quality and highest yield (Mansfield, 1981; Sammy, 1971; Sánchez-Nieva, 1961). For hand harvesting, varieties such as Kaki with long branches bearing a heavy load of pods have been developed. These are easily harvested by stripping the pods off into a sack (Faris, 1982). Because of the cost of labour for repeated pickings, the higher yield associated with multiple pickings is seldom justified, and picking only once has been recommended (Sánchez-Nieva and Colom Covas, 1964). More recently determinate varieties that bear their pods at the top of the canopy have been close-planted to force synchrony of flowering and maturity, so that the whole crop can be mechanically harvested in one pass. For this purpose green bean picking machines are being modified, or special machines developed that can harvest the pods from this type of crop (Faris, 1982).

Green pigeonpea is often compared with green garden peas (*Pisum sativum*), because in the tropics pigeonpea is often used in place of garden peas. In a sense the two crops complement each other, with the garden pea growing in relatively cool temperate conditions (around 20°C) and pigeonpea growing in warm conditions (around 30°C). In recipes the two products can readily substitute for each other although they have a somewhat different flavour. So as not to disappoint consumers it is important that a sweet vegetable variety of pigeonpea be used (Figure 16.4).

As a group, vegetable pigeonpea varieties have large seeds and large pods. This type of variety has probably been selected to reduce the amount of labour required to pick the crop and shell it. The labour required for depodding is particularly important as it is more difficult to remove the green seeds from the pods of pigeonpea than from garden peas. This requirement is less important in commercial canneries where mechanical depodders are used (Mansfield, 1981). The local varieties that have been identified for use as vegetables also tend to be sweeter than those selected for grain production. Plant breeders at ICRISAT Center are still searching for a good way to efficiently identify sweet and tender genotypes that meet the requirement of consumers in different regions.

Green Pods

In parts of Java and India, very young pods are harvested before the seeds are distinct, and cooked like french beans in curries or used to make relishes (Heynes, 1919; Morton, 1976). In west Java these pods are mixed with fresh seed to make a vegetable dish called pencok hiris (Damardjati and Widowati, in press). In Indonesia very young pods are sometimes used raw in salads. In some areas of Indonesia pigeonpea is only used as a vegetable and local people do not know how to use the mature seed for food (Damardjati and Widowati, in press). It would be interesting to find out if special pigeonpea varieties are required to provide green pods as a vegetable, or whether any pigeonpea variety can be used for this purpose.

ANIMAL FEED

Pigeonpea plants and grain have been used as animal feed for centuries by Indian farmers (Pathak, 1970; Wallis *et al.*, 1986). Even today plants are left in the field to be browsed by animals after the seed has been picked and all other crops have been harvested. Watt (1908) reported that in India

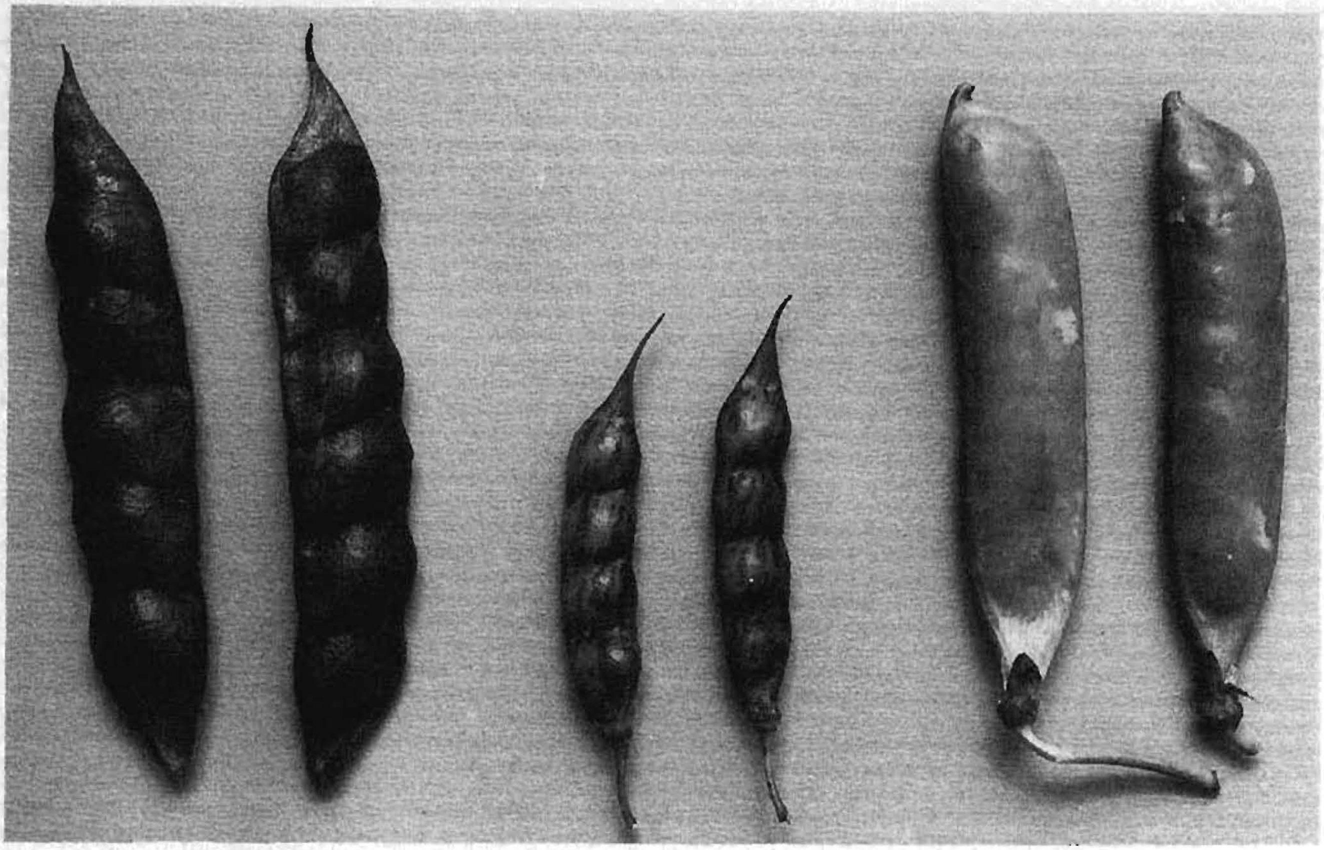


Figure 16.4. Pods of vegetable pigeonpea (left), field pigeonpea (centre), and green garden peas (right).
Photo: ICRISAT.

dry pigeonpea leaves were valued as fodder and the threshings from the crop used as food for milch cows. The by-product of seed coats, broken bits, and powder from dhal mills, collectively called chuni, forms a valuable food for milch cows (Anonymous, 1950; Pathak, 1970). Pigeonpea has also attracted attention in many other countries as a crop capable of providing feed for animals (Whyte *et al.*, 1953), because of its perennial nature, large potential biomass production, and the relatively high nitrogen level of the plant (Whiteman and Norton, 1981). Because high yields of grain can be obtained under relatively adverse conditions interest has been focused on using pigeonpea seed as a feed supplement. This practice can be particularly attractive in areas where soybean does not grow well and soybean meal is imported as animal feed (Wallis *et al.*, 1988).

Plants

Forage

The potential of pigeonpea to produce a very high biomass is demonstrated by the 40 t ha^{-1} of dry matter obtained in one cutting of late-maturing pigeonpea at Kanpur in northern India (Singh and Kush, 1981). Further documentation of this high biomass potential is provided by Akinola *et al.* (1975) and Whiteman and Norton (1981). One example they give is the 57.6 t ha^{-1} dry matter obtained by Herrera *et al.* (1966) in Colombia. A similar yield was obtained by Parbery (1967) who harvested 51 ha^{-1} dry matter in Western Australia with two harvests at 220 and 352 days after sowing. These yields are the highest recorded for a forage legume; higher than those of *Leucaena leucocephala*, and equivalent to high-yielding tropical grasses provided with adequate nitrogen fertilizer. However, the actual yield of edible forage is probably about 50% of these amounts because of pigeonpea's woody stems (Whiteman and Norton, 1981).

It is important to understand how pigeonpea plants respond to the removal of their leaves and branches to know their value as cut fodder or for grazing. In general, the more green leaves that are left on the plants the better the plants seem to respond. If the plant is cut at ground level there is very little, if any, crop re-growth compared to when 1.5 m plants are cut at heights of 0.15 or 0.3 m from ground level (Akinola *et al.*, 1975). Three cuttings to 0.05 m during the first year produced 15.8 t dry matter ha^{-1}, but the subsequent growth was poor.

Forage yields increase as intervals between harvests increase, although stem percentage also increases with harvests. For example, stem percentage increased from 34% at 4-week cutting intervals to 43% at 8 and 12 weeks, and 51% at 16 weeks. The optimum was considered 8-12 weeks (Akinola and Whiteman, 1975). The same authors also found that longer-duration varieties were better adapted to cutting so long as the lower leaves remained on the stubble.

Krauss (1932) also recognized the importance of cutting the crop high. He obtained 10-20 t ha^{-1} green matter when he cut the upper one-third to one-half of the crop for hay when a large proportion of the pods were mature. Handled this way the crop remained healthy for 4 or 5 years. However, the variety, sowing density, sowing date, and growing conditions all influence the yield of dry matter (Akinola *et al.*, 1975), and these must also be taken into consideration. For instance, the total dry matter yield of the long-duration pigeonpea varieties grown by Singh and Kush (1981) varied from 1.7 to 3.4 t ha^{-1} and when density was considered, the yield of one variety varied from 1.5 to 3.3 t ha^{-1}.

Grazing

There are two main methods of grazing pigeonpea, either by regular grazing the vegetative growth at intervals, or by using this grown as stand-over forage for the dry season. As a stand-over crop pigeonpea provides fodder at a time in the season when there is a deficit of energy and protein for the animals (Whiteman and Norton, 1981).

In Hawaii the stock-carrying capacities of good pigeonpea stands ranged from 1.2 to 3.7 head ha^{-1} with average stocking rates of 2.5 animals ha^{-1} year $^{-1}$. Average liveweight gains were 0.7 to 1.25 kg head^{-1} day^{-1}. There are authentic records showing liveweight gains for beef animals in Hawaii in excess of 1120 kg ha^{-1} year $^{-1}$ (Krauss, 1932). This is the second highest level of beef production recorded on tropical legume pastures. The high rate of gain head $^{-1}$ day $^{-1}$ indicates the good nutritive value of pigeonpeas, while the high production ha^{-1} shows their potential for dry-matter production under the excellent growing conditions in Hawai (Whiteman and Norton, 1981). Tests by Henke *et al.* (1940) also in Hawaii, suggested that pigeonpea forage was superior to grass in gain head^{-1}, indicating the pigeonpea forage had a higher nutritive value index and could carry a higher stocking rate than the grass tested (Whiteman and Norton, 1981).

Although productive stands have been maintained for up to 5 years, loss of yield in the second and subsequent seasons in several grazing trials suggest that pigeonpea is best used as an annual forage crop (Norman *et al.*, 1980; Whiteman and Norton, 1981). Trials seem to indicate that pigeonpea can perform well for several years if the plant is not stressed by over-grazing or by adverse climatic conditions. When stressed the crops may show high plant mortality in the second and subsequent years (Wijnberg and Whiteman, 1985). Pigeonpea is definitely an annual forage crop in areas where there are frosts in the winter, as it is a tropical crop and cannot withstand any frost (Bahar and Prine, 1980; Norman *et al.*, 1980).

In recent years the area originally sown to pigeonpea in the lowlands of Hawaii has been replaced by sugarcane, and pigeonpea has moved to higher elevations. In the cooler temperatures at higher elevations pigeonpea has not performed well, so that now little pigeonpea is grown in Hawaii for cattle feed (El Swaify, personal communication). On the other hand, in the highlands of Florida twice-yearly yields of 10-15 t ha^{-1} have been recorded on cleared pineapple land (Stambaugh, 1942, 1943). It is probable that sometimes pigeonpea may not be adopted as a forage crop despite its high potential, because given a choice, cattle usually prefer other more traditional forages (Ahmed, 1987). However, animals will eat it if there is no choice. Krauss (1921) indicated that while certain animals showed reluctance to consume pigeonpea feed, all classes of livestock readily learn to eat it when it is the only available food, especially when they have access to the growing crop.

Pigeonpea has mainly been grown for forage as a sole crop since it generally does not perform well in mixed pastures because of its slow initial growth. It has been successfully sown as hedgerow strips in grass pastures in Zimbabwe (Gooding, 1962) and Brazil (Schaaffhausen, 1965). Results again showed that where the forage is adequate, pigeonpea is capable of giving high liveweight gains (Whiteman and Norton, 1981).

Pigeonpea is used as a forage mainly to provide a protein supplement when pasture quality is low. The leaf is the main component in the vegetative phase but the nutritive value of the crop can be higher when pods and seeds become available. The highest nitrogen content is found in the leaf fraction, and the nutritive value of the fodder drops as the stems grow, although nitrogen increases in the stems as they mature. Ultimately, however, a reasonable amount of seed and pod material in the forage seems to be required to maintain high levels of animal production (Henke, 1943).

Fodder

In general pigeonpea fodder alone may be a bit low in energy (Patel *et al.*, 1972). The leaves can provide a good substitute for alfafa in animal feed formulations, particularly in areas that are not suitable for growing alfalfa. Results in Hawaii suggested that pigeonpea could give 10 times the yield of alfalfa (Krauss, 1921; Embong and Ravoof, 1978). Pigeonpea has been found to be particularly useful as a replacement for alfalfa as a source of carotene and other essential nutrients in baby chick rations (Squibb *et al.*, 1950).

Pods

The dry matter yield of pigeonpea pods is approximately equal to seed yield. The pod's feed value is limited by its low protein and high fibre contents. Trials have indicated that the digestibility of dry pods is low, and they were found inadequate to maintain sheep as a sole diet. The inclusion of a small amount of high-quality forage improves their nutritive value considerably (Whiteman and Norton, 1981). Pods have been recommended for use as a roughage source for cattle when supplemented with herbage and minerals (Jayal *et al.*, 1970; Kumar *et al.*,1978). In the Caribbean, where the hulls represent 60% of the price paid to farmers for green peas in the pod by weight, these hulls can be considered a valuable source of animal feed (Morton, 1976).

Trash from the crop after the seed is removed by threshing is widely used to feed cattle (Figure 16.5). Tests have shown that while the trash is better utilized by ruminants than pods alone, possibly because of their higher digestible crude protein content, a ration of trash alone is insufficient to maintain liveweight gain. It has been suggested that the major deficiency in a trash ration is the low availability of digestible energy, and possibly such minerals as sulphur (Whiteman and Norton, 1981).

Dhal Mill By-products

In India almost all pigeonpea is milled to produce dhal. In this process the recovery of dhal varies from around 65 to 75%; the remainder being the by-product known locally as chuni. At 25% of

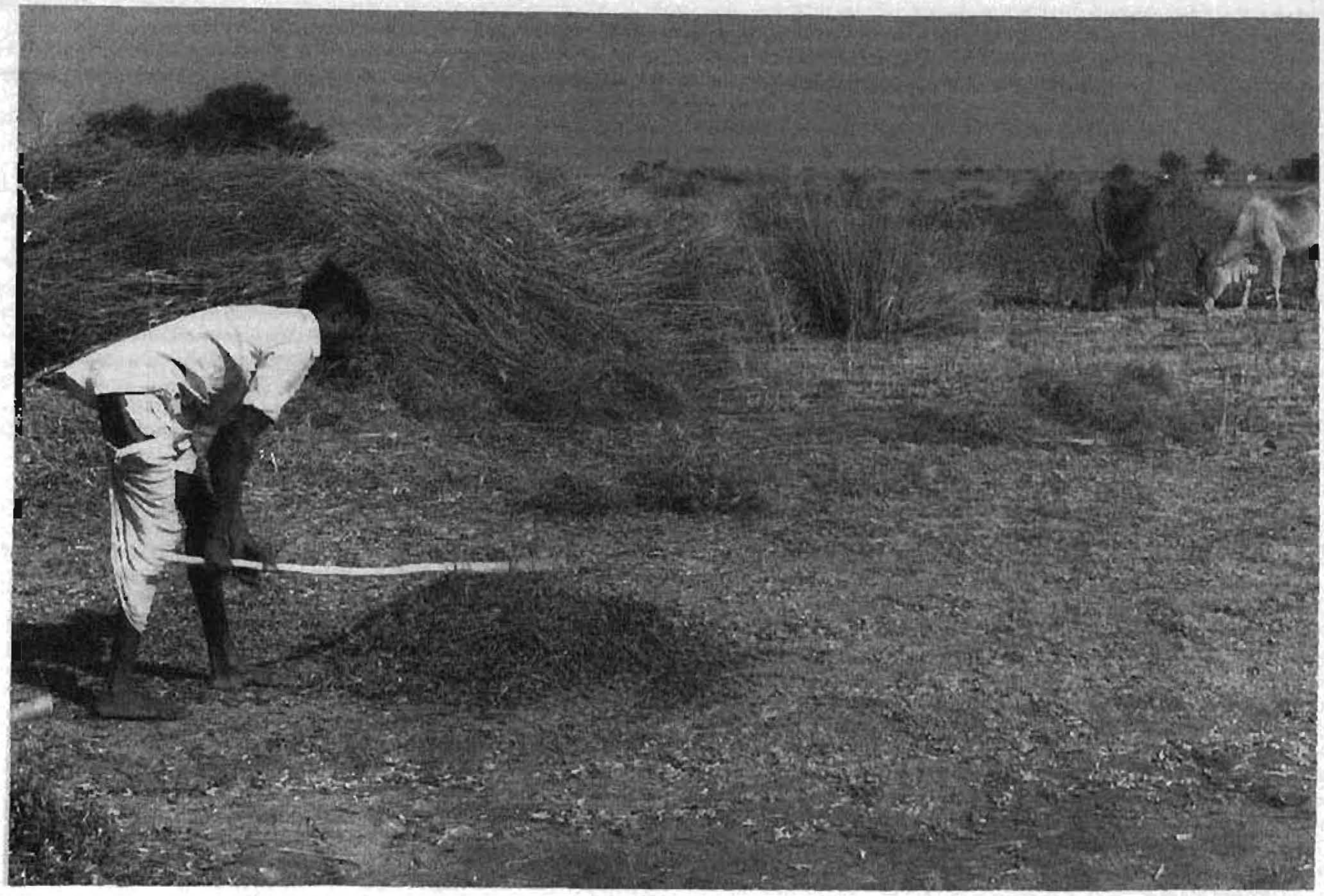


Figure 16.5. Cattle browsing pigeonpea trash. Note threshing by the traditional method using a bamboo, and large piles of sticks, that are used as fuel.
Photo: ICRISAT.

the total amount of seed that passes through India's dhal mills the amount of by-product is approximately 500,000 t year^{-1}. This by-product consists of about 3-8% brokens, 15% powder, and 10% husks. Chuni is usually sold to dairy producers or feed mills. The husks can be aspirated off and sold at a lower price for cattle feed. The powder and brokens are a valuable source of protein for cattle feed and are sold at a higher price (Kurien and Parpia, 1968). They are a favoured food of milk cattle (Pathak, 1970; Jain *et al.*, 1980).

Grain

By far the greatest use of pigeonpea grain is for human food. However, cracked and shrivelled seed and chuni from dhal mills form an important source of protein for feeding animals. The grain is also being considered as a replacement for soybean, particularly in countries such as Thailand and Indonesia where soybean is relatively difficult to produce, and it has been demonstrated that pigeonpea has a high yield potential but has little or no market as human food (Wallis *et al.*, 1988). Pigeonpea is particularly attractive for animal feed in countries where it is too dry and hot to produce other grain legumes. Most consideration has been given to using the grain for non-ruminant animals such as poultry and pigs.

Poultry

Wild pheasants, doves, quail, and domestic fowl feed extensively on pigeonpea seed opening pods without difficulty (Pathak, 1970). Poultry jump as high as 3 feet to get at the pods and they are very fond of the flowers (Krauss, 1921). Observation of green pod damage by birds showed that it was usually less than 3%, although one field with 25% damage was noted (Lateef and Bhagwat, 1985). It does not seem to be a preferred food of birds since damage is most severe when other food is not available. Damage also seems worse in parts of fields closest to trees or wires where the birds roost.

Pigeonpea grain has been successfully used for poultry feed. Krauss (1921) reported that an equal mixture of cracked pigeonpea and cracked maize was the best Hawaiian-grown grain ration for poultry at that time. The ration required occasional supplementation with a little oilseed to supply the necessary fat. Thus pigeonpea was extensively used in feeding poultry in Hawaii (Krauss, 1932). The general consensus of feeding trials seems to be that raw, hammer-milled pigeonpea grain provides a useful protein source for poultry diets with adequate supplementation (Tangtaweewipat and Elliott, in press; Whiteman and Norton, 1981). However, there are certain advantages and deficiencies shown through feeding trials which must be taken into consideration when using it.

Details on nutritional quality have been given earlier in this chapter. High-yielding lines are now available with protein levels approaching 30% (Saxena *et al.*, 1987; Singh *et al.*, in press). This may help enhance pigeonpea's value as a substitute for soybean. In general, pigeonpea has been considered an acceptable protein source for all classes of poultry rations (Draper, 1944; Springhall *et al.*, 1974; Wallis *et al.*, 1986; Tangtaweewipat and Elliott, in press).

Heat treatment (120°C for 20 min) to reduce the antinutritional factors appeared to have little significant effect on growth rates, feed intakes, and feed conversion efficiencies in rations fed to chicks (George and Elliott in Wallis *et al.*, 1986). However, this was at a relatively high level of pigeonpea in the diet, and it is possible that other heat-stable antinutritional factors may have affected the nutritive value of the grain (Wallis *et al.*, 1986). Results of other feeding trials indicated a significant increase in the apparent metabolizable energy content of pigeonpea meal due to heat treatment (Nwokolo and Oji, 1985).

A major limitation to using pigeonpea meal to substitute for soybean formulated in a "best cost program" is the need to provide increasing amounts of supplementary lipid to provide an adequate concentration of metabolizable energy as the level of pigeonpea inclusion increases (Tangtaweewipat and Elliott, in press). In general, lipid supplements are costly, and present problems in handling and storage particularly under tropical conditions. These lipids may be supplied by including seeds rich in oil, e.g., sunflower or groundnut (Krauss, 1921) and rice bran (Tangtaweewipat and Elliott, in press). The cost can be reduced by using screenings from oilseed crops, provided these are not contaminated with aflatoxin.

It appears that with adequate supplementation raw pigeonpea can be included up to a level of 300g kg^{-1} in broiler diets without adversely affecting the health and productivity of the birds, but that the productivity of layers can be adversely affected by levels above 100g kg^{-1}. This depression might be overcome by providing more essential amino acids such as methionine.

Factors affecting the use of pigeonpea in poultry rations are not yet fully understood. These factors include the variations in protein and antinutritional factors among varieties and samples, and differences in the other components used in the diets.

Pigs

Pigeonpea grain is much less useful as a feed for pigs than for poultry judging from results of trials that indicate that pigs are more susceptible than poultry to the antinutritional factors in raw pigeonpea (Wallis *et al.*, 1988). Feeding trials using pigeonpea for pig rations in Thailand showed that including 30% ground pigeonpea increased liveweight gain from 25g day^{-1} to 159g day^{-1} in the local basal feed of chopped banana stalk, rice bran, and maize. By boiling the pigeonpea meal the liveweight gain was increased to 205g day^{-1} (Falvey and Visitpanich, 1980). In a later trial it was determined that when pigeonpea was autoclaved for 15 min at 110°, 124°, or 140°C the trypsin-inhibitor activity was reduced from 11.2 units mg^{-1} to 0.7 units mg^{-1}. Compared to pigs fed unheated pigeonpea meal, pigs fed heated meal had higher ($P<0.05$) growth rates and improved feed conversion ratios. The improved growth responses were similar to those from feeding soybean meal (Visitpanich *et al.*, 1985). These results suggest that to be effective as a feed for pigs pigeonpea must either be ground and boiled, or the whole seed heated to at least 110°C for 15 minutes. This latter treatment makes pigeonpea equivalent to soybean in pig rations.

OTHER PLANT PRODUCTS

Wood

As mentioned in the section on forages pigeonpea has the potential to rapidly produce a huge biomass if it is provided with ample water and nutrients, and a relatively high temperature (over 30°C). Mention was made of the massive dry matter yields of 57.6 t ha^{-1} in Colombia and 51 t ha^{-1} in Western Australia in two cuttings within one year (Whiteman and Norton, 1981). An actual wood yield of 32 t ha^{-1} (air-dried stalks) was obtained in one cutting after 8 months of growth at Hisar in northern India (ICRISAT, 1985). This same crop also produced 2.5 t ha^{-1} of grain. The yields of wood that might be expected under good conditions from short-duration pigeonpea sown in northern India is 6-10 t ha^{-1} (ICRISAT, 1984), and 3-6 t ha^{-1} from medium-duration pigeonpea in central and southern India (Jain *et al.*, 1987).

A considerable proportion of this biomass will be in the form of relatively thin branches, that have been used in several ways:

- As fuel for cooking, by far the most important product (Figure 16.6). The heat value of this wood is about one half that of the same weight of coal (Panikkar, 1950). Pigeonpea has several advantages over traditional trees including its rapid growth potential, the possibility of producing other crops on the same land, and the production of a seed crop. These factors make it very suitable for village use (Khandiya, 1987). Farmers often sow pigeonpea because of the wood it produces rather than for its grain. In the Punjab in India labourers employed to harvest the crop are sometimes paid by giving them half the wood it produces.
- To make light constructions from the thin straight branches i.e., for roofing, wattling on carts, tubular wicker-work lining for wells, and baskets (Watt, 1908; Pathak, 1970). The author has also seen branches used for temporary fencing, and hut construction (Figure 16.7).
- For paper, on an experimental basis pigeonpea was found to produce a pulp yield similar to other hardwoods, and this pulp might be suitable for making good-quality writing and printing papers (Akhtaruzzaman *et al.*, 1986).

Products of the Plant

Pigeonpea can be used to produce silk and lac. Its leaves have been reported to have been used to feed a special silkworm *Boroceras cajani* at Betsileo in Southern Madagascar. This silkworm was grown in the open, and given tufts of grass near the pigeonpea plant on which to lay its eggs (Watt, 1908).

Lac is produced by a scale insect (*Laccifera lacca* Kerr) that lives on small tree branches in clusters, and produces a hard exudate to protect itself. The clusters are harvested and the hard exudate extracted and used to make shellac and lacquer products. For centuries in Asia lac has been harvested from various trees growing wild in the forest. As the forests are cut down this source of lac has become less abundant, so alternate lac hosts are being sought. One of these hosts is pigeonpea (Sreenivasaya *et al.*, 1924), that has several advantages, and also forms a convenient

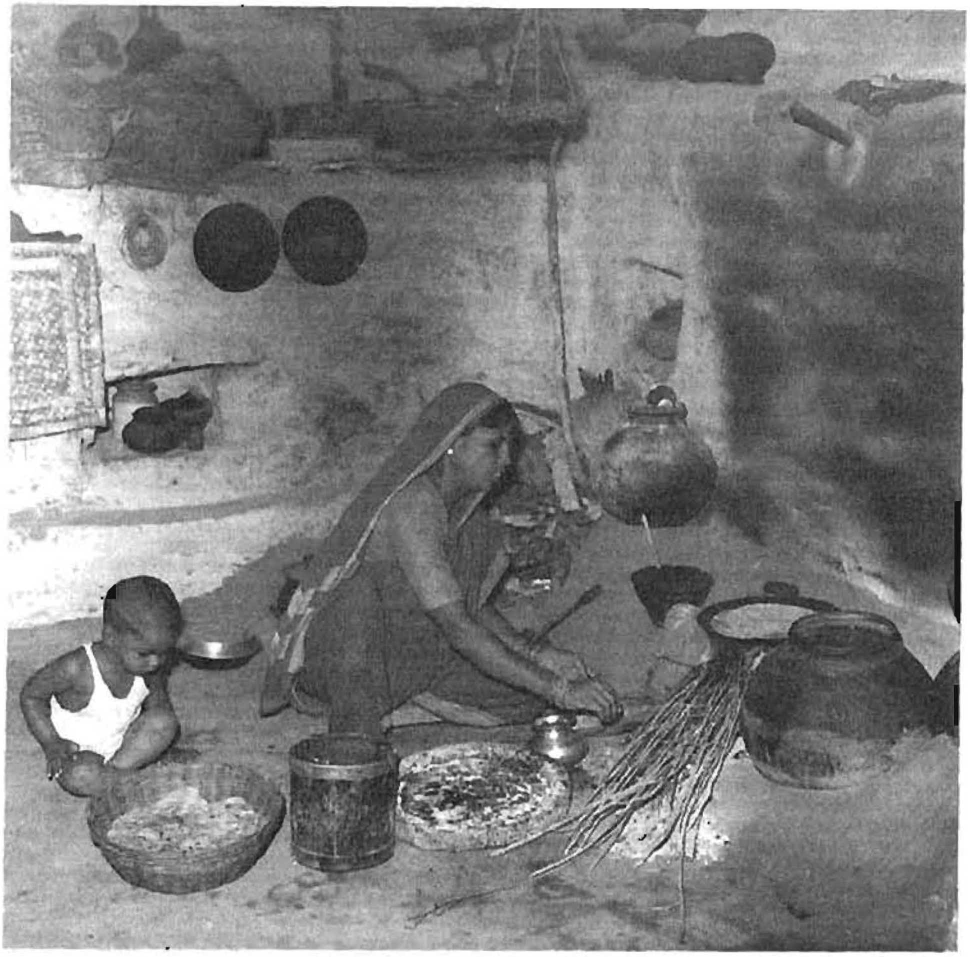


Figure 16.6. Cooking over a fire of pigeonpea sticks, Taddanpalli village, India.
Photo: ICRISAT.

host (Lal *et al.*, 1976). Among its advantages are that; it can be grown as a crop to produce seed as well as lac, thus reducing the loss of crop land for lac production, it can be sown on sloping poor land to check erosion, it reduces the farmers' risks through diversification, and minimal labour is needed to grow the crop with the labour requirement coming largely in the dry season when there are few, if any, alternative employment opportunities. These findings were the result of a study on 400 farms over 2 years in Thailand where the average gross profit margin was about \$135 ha^{-1} $year^{-1}$ (Subpamong *et al.*, 1986). Pigeonpea has the added advantage of being a suitable host for the two lac strains Rangeeni and Kusumi which normally thrive only on one host or another (Chowdhury and Bhattacharya, 1973).

The use of pigeonpea as a lac host is not a recent practice as it was extensively used in north Bengal and Assam in India before 1900 (Watt, 1908). Besides northern Thailand the author has received reports of pigeonpea being used for lac production in northern Vietnam, and has seen it being used in Guandong Province in the southern part of the People's Republic of China (Faris, 1985; Figure 16.8). It is probable that the practice extends throughout the hills separating China from Indo-China, Thailand, and Myanmar as well as in the low hills in northeast India (Krishnaswami and Saikia, 1959). Its use has even been reported from the USSR (Belosludceva, 1962). There is a continuing interest in India to identify superior pigeonpea cultivars that can fill the dual purpose of producing seed and lac (Kumar and Chauhan, 1976). Pigeonpea has the advantage of having a much shorter life cycle than most of the other lac host plants that can require many years for each life cycle. There is one report that lac from pigeonpea is inferior because it does not bleach well (Macmillan, 1946).

Figure 16.7. Fencing and a hut made from pigeonpea stems, thatched with sorghum straw.
Photo: ICRISAT.

Figure 16.8. A Chinese scientist observes lac-forming insects on local pigeonpea growing in Guangdong Province in southern China.
Photo: ICRISAT.

Table 16.11. Medicinal and cosmetic uses of parts of the pigeonpea plant[1].

Use	Whole plant	Leaf		Flowers	Young pods	Seeds	Seed		Roots
		Juice	Decoction				Decoction	Ground (poultice)	
External									
Improves complexion			Argentina(7)						
Disinfects skin			Antilles(7)				India(6)		
Stop bleeding		Malagasy Rep.(6) India(4) Cuba(7) W. Africa(7) Guyana(6) Java(7)							
Cure sores and wounds			India(6) W. Africa(7)					India(6)	China(7)
Smallpox								W. Africa(7) W. Indies(7)	
Cures leprosy							India(6)		
Reduces swelling								W. Africa(7)	
Reduces tumours								W. Indies(7)	
Hair wash						India(3)		Malagasy Rep.(6)	
Internal									
Mouth									
Wash			Gabon(7) India(6)						
Sores		India(7)					India(6)		
Gums			Gabon(6)						
Toothache			Gabon(6)			India(7)			
Teeth			India(6)						
Restore taste						India(6)			
Alimentary tract									
Sore throat			W. Africa(7)						
Vomiting						India(6)			
Laxative	Malagasy Rep.(6)	Malagasy Rep.(6)				India(6)			
Antidysenteric	Malagasy Rep.(6)		W. Africa(7)			India(6)			
Kills worms						India(6)			China(7)
Cures piles		India(6)				India(6)			
Helps liver					Colombia(7)	India(6)			
Jaundice			Cuba(7)						
Diuretic	India(6)	W. Africa(7)							
Incontinence						Vietnam(7)			
Bladder stone			Indonesia(7)						

Table 16.11. continued.

Use	Whole plant	Leaf		Flowers	Young pods	Seeds	Seed		Roots
		Juice	Decoction				Decoction	Ground (poultice)	
Respiratory system									
Chest disease	Cuba(7)		Cuba(7)	Malagasy Rep.(6) Cuba(7) Guyana(6)					
Expectorant						India(6)			China(7)
Bronchitis				Argentina(7)		India(6)			
Pneumonia				Argentina(7)					
Coughs	Malagasy Rep.(6)			Argentina(7) Malagasy Rep.(6)		India(6)			
Colds			W. Indies(7)						
Circulatory system									
Heart						India(6)			
Blood						W. Africa(8)			
Gynecological									
Eases delivery			Antilles(7)						
Soothes female genital region			Argentina(7)						
Checks excess milk secretion								India(6)	
Sedative						Java(2)			China(7)
Overcomes headache						Curacao(7)			

1. Numbers in parentheses refer to the following references:

1. Watt, 1908	5. Prema and Kurup, 1973
2. Ochse, 1931	6. Kirtikar and Basu, 1975
3. Biswas, 1943	7. Morton, 1976
4. Pathak, 1970	8. Ekeke and Shode, 1985.

MEDICINAL USES

There is a considerable folk medicine and ayurvedic listing of the curative effects of various parts of the pigeonpea plant. These reports are worldwide, with similar effects reported from areas as widely separated as India, Indonesia, Madagascar, West Africa, the Caribbean region, and China (Table 16.11). Most of the reports use a special vocabulary for the actions of medicines such as the term "volerant" for medicines that have a general healing effect on wounds and sores, "astringent" for medicines that constrict tissue and stop bleeding, "pectoral" for medicines that relieve or cure diseases of the lungs or chest, and "antihelmintic" for medicines that destroy internal worms. Table 16.11 depends heavily on the listing in Kirtikar and Basu's (1975) descriptions of Indian medicinal plants and Morton's (1976) review. The countries reported are either actually identified by the author(s) or the country or region where the original report they refer to came from. More recently there have been a limited number of experiments to investigate the specific medicinal effects of pigeonpea. These tend to support some of the effects traditionally listed. For example, Prema and Kurup (1973) report that pigeonpea protein intake in rats on a high fat-cholesterol diet had a marked decrease in total and free cholesterol, phospholipid, and triglyceride contents in their blood serum. There is also a recent report that pigeonpea caused reversion of sickled cells in patients suffering from sickle-cell anaemia (Ekeke and Shode, 1985).

FUTURE

The nutritional quality of pigeonpea in terms of its chemical constituents, amino acids, and digestibility has received increasing attention in the past. Although there appears to be a small variation in chemical composition among cultivars, few efforts have been made to show the effect of environment on such constituents. More efforts are needed to study the effects of genotype and environment, and their interaction on the chemical constituents of pigeonpea. The effects of improved agronomic practices should also be more carefully studied, particularly with reference to vitamins and mineral contents. Antinutritional factors such as tryspin and chymoptryspin inhibitors, oligosaccharides, and polyphenols have been extensively studied. Studies are needed on other antinutritional and toxic factors such as haemagglutenins, cyanogenic-glucosides, antivitamins, esterogenic factors, metal-binding constituents, and toxic amino acids, if these constituents are present in pigeonpea seeds.

Pigeonpea is consumed in various food forms and thus receives various types of treatments for such food preparations. A knowledge of the nutritional changes that occur due to various types of heat and other treatments; e.g., fermentation and germination would be very useful. Several physical and chemical factors influence the cooking quality of pigeonpea. It is suggested that seasonal variations must be taken into consideration when pigeonpea cultivars are compared for cooking quality. A variety of food products are made from pigeonpea. These are freshly sprouted seed, tempe, sauce (ketchup), extrusion products, and noodles. Although these products have been studied to a certain extent, depending on the regions of their consumption, detailed studies on the physiochemical properties and consumer acceptance of such foods are required. Green pigeonpea is often compared with garden peas because in the tropics green pigeonpea seeds are often used as a replacement vegetable. Development of suitable vegetable cultivars i.e., with bolder, sweeter tasting seeds would be useful for this purpose.

As an animal feed, green plants for forage, leaves, pod walls, and the soft sticks of mature plants, grains, and by-products of dhal mills are commonly used. While the use of pigeonpea meal in monogastric animal diets seems to be technicaly feasible, its use will ultimately depend on the price of pigeonpea in relation to alternative proteins and energy sources.

Although the various medicinal uses of pigeonpea have been described, the value of most of them is very difficult to substantiate. The fact that in several cases similar reports come from so many different regions of the world suggests that it would be worthwhile to scientifically examine these reports. The reports of the reduction in cholesterol and reversion of sickle-cell anaemia are examples of these. The reasons for the value of various parts of the pigeonpea plant in curing wounds and chest problems might give useful information if pursued in more detail.

REFERENCES

Ahmed, N.U. (1987) Agronomic management and comparative performance of short duration post-rainy season pigeonpea in rice-based cropping patterns. PhD thesis, University of Florida, USA, 143 pp.

Akhtaruzzaman, A.F.M., Siddique, A.B. and Chowdhury, A.R. (1986) Potentiality of pigeonpea (arhar) plant for pulping. *Bano Biggyan Patrika* 15(1-2), 31-36.

Akinola, J.O. and Whiteman, P.C. (1975) Agronomic studies on pigeonpea (*Cajanus cajan* (L.) Millsp.). 3. Responses to defoliation. *Australian Journal of Agricultural Research* 26, 67-79.

Akinola, J.O., Whiteman, P.C. and Wallis, E.S. (1975) *The Agronomy of Pigeonpea (Cajanus cajan). Review Series no. 1/1975.* CAB, UK, 57 pp.

Anonymous (1950) *The Wealth of India, Raw Materials–volume II.* Council of Scientific and Industrial Research, Delhi, India.

Aykroyd, W.R. and Doughty, J. (1982) *Legumes in Human Nutrition. FAO Food and Nutrition Paper 20.* Food and Agriculture Organization of the United Nations, Rome, 152 pp.

Bahar, F.A. and Prine, G.M. (1980) Pigeonpea (*Cajanus cajan* L.) as forage and legume crop. In: *Abstracts of the 72nd Annual Meeting of the American Society of Agronomy.* p. 96.

Belosludceva, N.G. (1962) Pigeonpea - a new plant material for obtaining native shellac. *Trudy Prikladnoi Botanike Genetikei Selektsei, Leningrad (USSR)* 34(1), 197-203.

Birla, S.C. (in press) Potential of pigeonpea as split dhal in the West Indies. In: *Uses of Grain Legumes: Proceedings of a Consultants' Meeting, 27-30 March 1989, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT.

Biswas, H.C. (1943) Investigations on the saponin content of the Indian pulses. *Science and Culture* 9, 165.

Bliss, F.A. and Hall, T.C. (1977) Food Legumes–compositional and nutritional changes induced by breeding. *Cereal Foods World* 22, 106-113.

Buckle, K.A. and Iskandar, D.H. (in press) Composition and quality of tempe prepared from pigeonpea seeds, and pigeonpea seed/soybean mixtures. Uses of legumes. In: *Uses of Grain Legumes: Proceedings of a Consultants' Meeting, 27-30 March 1989, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT.

Chowdhury, M.K. and Bhattacharya, A. (1973) Survival of lac insects on different hosts. In: *Abstracts of the Seminar on Lac Productions, Indian Lac Research Institute, Nankum 9-10 November 1973.* p. 21.

Contreras, S. and Tagle, M.A. (1974) Toxic factors in Chilean legumes. *Archives Latinoamer Nutrition* 24, 191-199.

Dahiya, B.S., Brar, J.S. and Bhullar, B.S. (1977) Inheritance of protein content and its correlation with grain yield in pigeonpea (*Cajanus cajan* (L.) Millsp.). ***Qualitas Plantarum/Plant Foods for*** *Human Nutrition* 27, 327-334.

Damardjati, D.S. (1989) Progress report: study on utilization of pigeonpea at SURIF 1984-1988. Paper presented at the AARS/ACIAR Peanut and Pigeonpea Improvement Project Meeting, 24-25 January 1989, Bogor, Indonesia, 15 pp. (Mimeo).

Damardjati, D.S. and Widowati, S. (in press) Utilization of pigeonpea and other legumes in Indonesia. In: *Uses of Grain Legumes: Proceedings of a Consultants' Meeting, 27-30 March 1989, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT.

Daniel, V.A., Narayanaswamy, D., Desai, B.L.M., Kurien, S., Swaminathan, M. and Parpia H.A.B. (1970) Supplementary value of varying levels of redgram *(Cajanus cajan)* to poor diets based on rice and ragi. *Indian Journal of Nutrition and Dietetics* 7, 358-362.

Draper, C.I. (1944) Algaroba beans, pigeonpeas and processed garbage in the laying mash. *Hawaii Agricultural Experiment Station Progress Reorts 44*. University of Hawaii, Honolulu, Hawaii, USA.

Eggum, B.O. and Beames, R.M. (1983) The nutritive value of seed proteins. In: Gottschalk, W. and Müller, H.P. (eds), *Seed Protein: Biochemisry, Genetics, and Nutritive Value*. Martinus Nijhoff/Dr W. Junk Publishers, The Hague, the Netherlands, pp. 499-531.

Ekeke, G.I. and Shode, F.O. (1985) The reversion of sickled cells by *Cajanus cajan*. *Planta Medica* December 1985, 504-507.

Embong, W.M.W. and Ravoof, A.A. (1978) Investigations on pigeon pea *(Cajanus cajan)* as a legume forage. In: Devendra, C. and Hetagalung, R.I. (eds), *Proceedings of the Symposium on Feedingstuffs for Livestock in South East Asia, 17-19 October 1977, National University of Malaysia, Kuala Lumpur.* pp. 75-85.

Falvey, L. and Visitpanich, T. (1980) Nutrition of highland swine. 2. Preparation of pigeonpea seed fed in conjunction with rice bran and banana stalk. *Thai Journal of Agricultural Science* 13, 29-34.

FAO/WHO (1973) *Energy and Protein Requirements: Report of a Joint FAO/WHO Ad Hoc Expert Committee.* United Nations Food and Agriculture Organization, Rome, and World Health Organization, Geneva, 118 pp.

Faris, D.G. (1981) Tour of pigeonpea areas in eastern and southern Africa (Kenya, Malawi, Zambia and Tanzania), 8-26 July 1981. Patancheru, A.P., India: Legumes Program, ICRISAT, 18 pp. (Limited distribution).

Faris, D.G. (1982) Tour of the Caribbean Islands and Mexico, 19 November-14 December 1982. Patancheru, A.P., India: Legumes Program, ICRISAT, 47 pp. (Limited distribution).

Faris, D.G. (1985) Notes on trip to Florida, Hawaii and China, 7-11 July and 3-20 August 1985. Patancheru, A.P., India: Legumes Program, ICRISAT, pp. 17-28 (Limited distribution).

Faris, D.G., Saxena, K.B., Mazumdar, S. and Singh, U. (1987) *Vegetable Pigeonpea: A Promising Crop for India*. Patancheru, A.P., India: ICRISAT, 13 pp.

Faris, D.G. and Wallis, E.S. (1980) Report on trip to Australia, New Zealand and Fiji, 4-15 November 1980. Patancheru, A.P., India: Legumes Program, ICRISAT, 40 pp. (Limited distribution).

Geervani, P. and Theophilus, F. (1980) Effect of home processing on the nutrient composition of certain high yielding legume varieties. *Indian Journal of Nutrition and Dietetics* 17, 443-446.

Gomez, M.I. (in press) Legume quality factors affecting processing and utilization. In: *Uses of Grain Legumes: Proceedings of a Consultants' Meeting, 27-30 March 1989, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT.

Gooding, H.J. (1962) The agronomic aspects of pigeonpeas. *Field Crop Abstracts* 15, 1-5.

Gopalan, C., Rama Sastri, B.V. and Balasubramanian, S.C. (1971) *Nutritive Value of Indian Foods*. National Institute of Nutrition, Hyderabad, India, 204 pp. (reprinted).

Gupta, G.L., Nigam, S.S., Sastry, S.D. and Chakravarti, R.L. (1969) Investigations on the essential oil from *Cajanus cajan* (Linn.) Millsp. *Perfumes and Essential Oils Research* 60 (11-12), 329.

Henke, L.A. (1943) Roughages for dairy cattle in Hawaii. *Hawaii Agricultural Experiment Station Bulletin 92*. University of Hawaii, Honolulu, Hawaii, U.S.A.

Henke, L.A., Work, S.H. and Burt, A.W. (1940) Beef cattle feeding trials in Hawaii. *Hawaii Agricultural Experiment Station Bulletin 85*. University of Hawaii, Honolulu, Hawaii, U.S.A.

Herrera, P.G., Lotero, C.J. and Crowder, L.V. (1966) Cutting frequency with tropical forage legumes. *Agricultura Tropicale* 22, 473-483.

Heynes, K. (1919) Food and fodder plants (redgram). *Kew Bulletin 15*. Kew, UK.

Hulse, J.H. (1977) Problems of nutritional quality of pigeonpea and chickpea and prospects of research. In: Hulse, J.H., Rachie, K.O. and Billingsley, L.W. (eds), *Nutritional Standards and Methods of Evaluation for Food Legume Breeders*. International Development Research Center, Ottawa, Canada, pp. 88-100.

Hulse, J.H. (in press) Nature, composition and utilization of grain legumes. In: *Uses of Grain Legumes: Proceedings of a Consultants' Meeting, 27-30 March 1989, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT.

ICRISAT (1984) *Annual Report 1983*. Patancheru, A.P., India: ICRISAT, pp. 172-173.

ICRISAT (1985) *Annual Report 1984*. Patancheru, A.P., India: ICRISAT, p. 186.

ICRISAT (1987) *Annual Report 1986*. Patancheru, A.P., India: ICRISAT, pp. 195-196.

Iyengar, A.K. and Kulkarni, P.R. (1977) Oligosaccharide levels of processed legumes. *Journal of Food Science and Technology* 14, 222-223.

Jain, K.C., Faris, D.G. and Chenchi Reddy, M. (1987) Performance of medium-duration pigeonpea genotypes for wood and grain yield in pigeonpeas. *International Pigeonpea Newsletter* 6, 34-35.

Jain, V.K., Jayal, M.M. and Pathak, N.N. (1980) Nutritional evaluation of gram *(Cicer arietinum)* and arhar *(Cajanus cajan)* chunies for cattle. *Animal Feed and Technology* 5, 315-320.

Jayal, M.M., Gupta, P.S. and Mahadevan, V. (1970) Nutritive value of arhar *(Cajanus indicus)* bhoosa for feeding cattle. *Indian Veterinary Journal* 47, 253-260.

Jyothi, E. and Reddy, P.R. (1981) The effect of germination and cooking on the *in vitro* digestibility of starch in some legumes. *Nutrition Reports International* 23, 799-804.

Kamath, M.V. and Belavady, B. (1980) Unavailable carbohydrates of commonly consumed Indian foods. *Journal of the Science of Food and Agriculture* 31, 194-202.

Khandiya, S.D. (1987) Short rotation firewood forestry on sodic soils in northern India–research imperatives. *Indian Journal of Forestry* 10(2), 75-79.

Kirtikar, K.R. and Basu, B.D. (1975) *Indian Medicinal Plants. Second edition, volume I*. M/s. Bishen Singh Mahendra Pal Singh, Dehra Dun, India, pp. 809-811.

Krauss, F.G. (1921) The pigeonpea–its culture and utilization in Hawaii. *Hawaii Agricultural Experiment Station Bulletin* 46, 1-23.

Krauss, F.G. (1932) The pigeonpea *(Cajanus indicus)*, its improvement, culture and utilization in Hawaii. *Hawaii Agricultural Experiment Station Bulletin* 64, 1-46.

Krishnaswami, S. and Saikia, D.R. (1959) Lac cultivation in Assam with notes on use of arhar, *Cajanus cajan* and other species as lac hosts. *Indian Lac Research Institute Bulletin, Ranchi* 97, 7.

Kumar, M.N.A., Sundareshan, K. and Sampath, S.R. (1978) Chemical composition and nutritive value of empty tur gram pod shells *(Cajanus cajan)*. *Mysore Journal of Agricultural Sciences* 12(1), 109-113.

Kumar, P. and Chauhan, N.S. (1976) Problems and prospects of lac-host breeding. *Indian Farming* 26(8), 31 and 33.

Kurien, P.P. (1981) Advances in milling technology of pigeonpea. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 321-328.

Kurien, P.P. and Parpia, H.A.B. (1968) Pulse milling in India I–Processing and milling of tur, arhar *(Cajanus cajan* Linn). *Journal of Food Science and Technology* 5, 203-207.

Kurien, S., Narayanaswamy, D., Daniel, V.A., Swaminathan, M. and Parpia, H.A.B. (1971) Supplementary value of pigeonpea *(Cajanus cajan)* and chickpea to poor diets based on kaffir corn and wheat. *Nutrition Reports International* 4, 227-232.

Lal, S., Singh, B.P. and Singh, R.K. (1976) Lac in dryland agriculture of Chotanagpur. *Indian Farming* 26(8), 21-22.

Lateef, S.S. and Bhagwat, V.R. (1985) Bird damage to pigeonpea in India. *International Pigeonpea Newsletter* 4, 60-62.

Macmillan, H.F. (1946) *Tropical Planting and Gardening*. Macmillan and Co. Ltd., London.

Manimekalai, G., Neelakantan, S. and Annapan, R.S. (1979) Chemical composition and cooking quality of some improved varieties of redgram dhal. *Madras Agricultural Journal* 66, 812-816.

Mansfield, G.R. (1981) Processing and marketing of green pigeonpeas: the case of the Dominican Republic. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 344-350.

Miller, C.D., Branthoover, B., Sekiguchi, N., Dening, H. and Bauer, A. (1956) Vitamin values of foods used in Hawaii. *Hawaii Agriculture Experiment Station Technical Bulletin* 30, 303-313.

Morton, J.F. (1976) The pigeonpea (*Cajanus cajan* Millsp.), a high protein tropical bush legume. *HortScience* 11(1), 11-19.

Morton, J.F., Smith, R.E., Lugo-López, M.A. and Abrams, R. (1982) *Pigeonpeas (Cajanus cajan Millsp.): A Valuable Crop of the Tropics*. Special Publication of the College of Agricultural Sciences, Department of Agronomy and Soils, University of Puerto Rico, Mayaguez, Puerto Rico, 123 pp.

Narasimha, H.V. and Desikachar, H.S.R. (1978) Objective methods for studying cookability of tur pulse *(Cajanus cajan)* and factors affecting varietal differences in cooking. *Journal of Food Science and Technology* 15, 47-50.

Norman, M.J.T., Searle, P.G.E., Dankittipakul, N., Ingram, K.C. and Baskoro, J. de B. (1980) Evaluation of pigeonpea *(Cajanus cajan)* as an autumn forage for coastal New South Wales. *Australian Journal of Experimental Agriculture and Animal Husbandry* 20, 55-62.

Nwokolo, E. and Oji, U.T. (1985) Variation in metabolizable energy of raw and autoclaved white and brown varieties of three tropical grain legumes. *Journal of Animal Feed Science Technology* 13, 141-146.

Ochse, J.J. (1931) *Vegetables of the Dutch East Indies*. Department of Agriculture, Industry, and Commerce of the Netherland East Indies, Buitenzorg, Java, 1006 pp.

Panikkar, M.R. (1950) Alternate fuel–arhar stalk. *Indian Farming* 11, 496.

Parbery, D.B. (1967) Pasture and fodder crop plant introductions at Kimberley Research Station, W. Australia 1963-1964. 1. Perennial legumes. *CSIRO Division of Land Research and Technology Memoir 67/6*. CSIRO, Melbourne, Australia.

Patel, B.M., Naphade, M.S. and Kamdar, L.D. (1972) Microbial population of strained rumen liquor of lactating cows fed with cluster bean and pigeon pea fodder. *Indian Journal of Microbiology* 12, 55-57.

Pathak, G.N. (1970) Red gram. In: *Pulse crops of India*. Indian Council of Agricultural Research, New Delhi, India, pp. 14-53.

Prema, L. and Kurup, P.A. (1973) Hypolipidaemic activity of the protein isolated from *Cajanus cajan* in high fat-cholesterol diet fed rats. *Indian Journal of Biochemistry and Biophysics* 10, 293-296.

Rachie, K.O. and Roberts, L.M. (1974) Grain legumes of the lowland tropics. *Advances in Agronomy* 26, 1-132.

Rahman, A.R. (1961) The effect of chemical pretreatment on the quality of dehydrated pigeonpea. *Journal of the Agricultural University of Puerto Rico* 45, 172-191.

Rajalakshmi, R. and Vanaja, K. (1967) Chemical and biological evaluation of the effects of fermentation on the nutritive value of foods prepared from rice and legumes. *British Journal of Nutrition* 21, 467-473.

Sallette, J.E. and Courbois, J.M. (1968) Agronomic aspects of pigeonpea in Marie-Galante. *Proceedings of the Caribbean Society of Food Crop Science* 6, 32-37.

Salunkhe, D.K. (1982) Legumes in human nutrition: current status and future research needs. *Current Science* 51, 387-394.

Salunkhe, D.K., Chavan, J.K. and Kadam, S.S. (1986) Pigeonpea as an important food source. *CRC Critical Reviews in Food Science and Nutrition* 23(2), 103-145.

Sammy, G.M. (1971) *Canning Potential of the Pigeonpea Cultivar Gl 26/2. Food Technology Series no. 4*. Faculty of Engineering, University of West Indies, Trinidad, 4 pp.

Sánchez-Nieva, F. (1961) The influence of degree of maturity on the quality of canned pigeonpeas. *Journal of the Agricultural University of Puerto Rico* 45, 217-231.

Sánchez-Nieva, F., Benero, J., González, M.A. and Colom Covas, G. (1963) Variations in maturity of pigeonpeas during the harvesting period. *University of Puerto Rico Agricultural Experiment Station Bulletin* 170, 1-21 (in Spanish).

Sánchez-Nieva, F. and Colom Covas, G. (1964) Advantages to the farmer of harvesting all the pods of pigeonpeas at the same time. *University of Puerto Rico Agricultural Experiment Station Bulletin* 181, 1-13 (in Spanish).

Sánchez-Nieva, F., González, M.A. and Benero, J.R. (1961a) The freezing of pigeonpeas for market. *Journal of Agriculture of the University of Puerto Rico* 45, 205-216.

Sánchez-Nieva, F., Rodríguez, A.J. and Benero, J.R. (1961b) Improved methods of canning pigeonpeas. *University of Puerto Rico Agricultural Experiment Station Bulletin* 157, 1-26.

Sankara Rao, D.S. and Deosthale, Y.G. (1981) Mineral composition of four Indian food legumes. *Journal of Food Science* 46, 1962-1963.

Savitri, A. and Desikachar, H.S.R. (1985) A comparative study of flatus production in relation to the oligosaccharide content of some legumes. *Nutrition Reports International* 31, 337-344.

Saxena, K.B., Faris, D.G., Singh, U. and Kumar, R.V. (1987) Relationship between seed size and protein content in newly developed high protein lines of pigeonpea. *Plant Foods for Human Nutrition* 36, 335-340.

Schaaffhausen, R.V. (1965) Weight increase of Zebu cattle grazing on legumes *Dolichos lablab* and *Cajanus indicus*. In: *Proceedings, Ninth International Grasslands Congress, Sao Paulo, Brazil*. pp. 965-968.

Sharma, Y.K., Tiwari, A.S., Rao, K.C. and Mishra, A. (1977) Studies on chemical constituents and their influence on cookability in pigeonpea. *Journal of Food Science and Technology* 14, 38-40.

Shemer, M. and Perkins, E.G. (1975) Degradation of methionine in heated soybean protein and the formation of β-methyl-mercaptopropionaldehyde. *Journal of Agriculture and Food Chemistry* 23, 201-204.

Shobana, Sangawan, P.S., Nainawatee, H.S. and Lal, B.M. (1976) Chemical composition of some improved varieties of pulses. *Journal of Food Science and Technology* 13, 49-51.

Singh, D.N. and Kush, A.K. (1981) Effect of population density on growth pattern and yielding ability in pigeonpea. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 165-174.

Singh, S., Singh, H.D. and Sikka, K.C. (1968) Distribution of nutrients in the anatomical parts of common Indian pulses. *Cereal Chemistry* 45, 13-18.

Singh, U. (1984) The inhibition of digestive enzymes by polyphenols of chickpea (*Cicer arietinum* L.) and pigeonpea [*Cajanus cajan* (L.) Millsp.]. *Nutrition Reports International* 29, 745-753.

Singh, U. (1988) Antinutritional factors of chickpea and pigeonpea and their removal by processing. *Plant Foods for Human Nutrition* 38, 251-261.

Singh, U. and Eggum, B.O. (1984) Factors affecting the protein quality of pigeonpea (*Cajanus cajan* L.) *Qualitas Plantarum/Plant Foods for Human Nutrition* 34, 273-283.

Singh, U., Jain, K.C., Jambunathan, R. and Faris, D.G. (1984a) Nutritional quality of vegetable pigeonpeas [*Cajanus cajan* (L.) Millsp.]: dry matter accumulation, carbohydrates and proteins. *Journal of Food Science* 49, 799-802.

Singh, U., Jain, K.C., Jambunathan, R. and Faris, D.G. (1984b) Nutritional quality of vegetable pigeonpeas [*Cajanus cajan* (L.) Millsp.]: mineral and trace elements. *Journal of Food Science* 49, 645-646.

Singh, U. and Jambunathan, R. (1981a) Methods for the estimation of protein in pigeonpea (*Cajanus cajan* L.) and the relationship between whole grain and dhal protein contents. *Journal of the Science of Food and Agriculture* 32, 705-710.

Singh, U. and Jambunathan, R. (1981b) Protease inhibitors and *in vitro* protein digestibility of pigeonpea (*Cajanus cajan* (L.) Millsp.) and its wild relatives. *Journal of Food Science and Technology* 18, 246-247.

Singh, U. and Jambunathan, R. (1982) Distribution of seed protein fractions and amino acids in different anatomical parts of chickpea (*Cicer arietinum* L.) and pigeonpea (*Cajanus cajan* L.). *Qualitas Plantarum/Plant Foods for Human Nutrition* 31, 347-354.

Singh, U., Jambunathan, R., Saxena, K.B. and Subrahmanyam, N. (in press) Nutritional quality evaluation of newly developed high protein genotypes of pigeonpea (*Cajanus cajan* L.) *Journal of the Science of Food and Agriculture.*

Singh, U., Kherdekar, M.S., Sharma, D. and Saxena, K.B. (1984c) Cooking quality and chemical composition of some early, medium and late maturing cultivars of pigeonpea (*Cajanus cajan* (L.) Millsp.). *Journal of Food Science and Technology* 21, 367-372.

Singh, U., Rao, P.V., Seetha, R. and Jambunathan, R. (1989a) Nutrient losses due to scarification of pigeonpea (*Cajanus cajan* L.) cotyledons. *Journal of Food Science* 54, 974-976.

Singh, U., Voraputhaporn, W., Rao, P.V. and Jambunathan, R. (1989b) Physicochemical characteristics of pigeonpea and mung bean starches and their noodle quality. *Journal of Food Science* 54, 1293-1297.

Springhall, J., Akinola, J.O. and Whiteman, P.C. (1974) Evaluation of pigeonpea seed *(Cajanus cajan)* meal in chicken rations. In: *Proceedings, Australian Poultry Science Convention, Sydney, Australia.* pp. 117-119.

Squibb, R.L., Falla, A., Fuentes, J.A. and Love, H.T. (1950) Value of *Desmodium*, pigeonpea fodder, Guatemalan and United States alfalfa meals in rations for baby chicks. *Poultry Science* 29, 482-485.

Sreenivasaya, M., Venugopalan, M. and Somayajulu, C.R. (1924) Contribution to the scientific study of the lac industry. Part III. A preliminary note on pot culture experiments with *Cajanus cajan* as host plant. *Journal of the Indian Institute of Science, Bangalore* 7, 114-119.

Stambaugh, S.U. (1942) How to insure Florida food and feed supply. *Florida Grower* December, 6 and 12.

Stambaugh, S.U. (1943) The pigeon pea as a food crop. *Proceedings Florida Horticulture Society* 56, 175-177.

Subpamong, C., Ruedenauer, M. and Imboriboon, N. (1986) Economics of lac-lice raising on pigeonpeas on contour bunds in northern Thailand. *Quarterly Journal of International Agriculture* 25, 374-380.

Sumathi, S. and Pattabiraman, T.N. (1976) Natural plant enzyme inhibitors: Part II–Protease inhibitors of seeds. *Indian Journal of Biochemistry and Biophysics* 13, 52-56.

Tangtaweewipat, S. and Elliott, R. (in press) Nutritional value of pigeonpea *(Cajanus cajan)* meal in poultry diets. *Animal Feed Science and Technology.*

Tripathi, R.D., Srivastava, G.P., Misra, M.C. and Sinha, S.C. (1975) Comparative studies in the quality characteristics of early and late cultivars of red gram (*Cajanus cajan* L.). *Indian Journal of Agricultural Chemistry* 8, 57-61.

Visitpanich, T., Batterham, E.S. and Norton, B.W. (1985) Nutritional value of chickpea *(Cicer arietinum)* and pigeonpea *(Cajanus cajan)* meals for growing pigs and rats. II. Effect of autoclaving and alkali treatment. *Australian Journal of Agricultural Research* 36, 337-345.

Wallis, E.S., Faris, D.G., Elliott, R. and Byth, D.E. (1986) Varietal improvement of pigeonpea for smallholder livestock production systems. In: *Proceedings of the Crop-livestock Systems Research Workshop, 7-11 July 1986, Khon Kaen, Thailand.* Farming Systems Research Institute, Department of Agriculture, Thailand and Asian Rice Farming Systems Network, International Rice Research Institute, Philippines, pp. 536-553.

Wallis, E.S., Woolcock, R.F. and Byth, D.E. (1988) *Potential for Pigeonpea in Thailand, Indonesia and Burma. CGPRT no.15.* Bogor, Indonesia: CGPRT Center, 74 pp.

Watt, Sir G. (1908) (reprinted in 1966) The pigeonpea *Cajanus indicus* arhar. In: *The Commercial Products of India.* (Today and Tomorrow's Printer and Publisher, New Delhi, India) Murray, London, pp. 196-200.

Whiteman, P.C. and Norton, B.W. (1981) Alternative uses of pigeonpeas. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 365-377.

Whyte, R.O., Nilsson-Leissner, G. and Trumble, H.C. (1953) *Legumes in Agriculture. FAO Agricultural Studies no. 21*. Food and Agriculture Organization of the United Nations, Rome, 367 pp.

Wijeratne, W.B. and Nelson, A.I. (in press) Processing and utilization of soybean and diversification of end-uses through extrusion processing. In: *Uses of Grain Legumes: Proceedings of a Consultants' Meeting, 27-30 March 1989, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT.

Wijnberg, C. and Whiteman, P.C. (1985) Effects of stocking rate of goats and stage of crop growth when grazed on grain yield and goat production from pigeonpea *(Cajanus cajan)*. *Australian Journal of Experimental Agriculture* 25, 796-805.

Chapter 17

PIGEONPEA: POSTHARVEST TECHNOLOGY

U. SINGH and R. JAMBUNATHAN

Biochemist, and Principal Biochemist and Program Leader, Grain Quality and Biochemistry Unit, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Andhra Pradesh 502 324, India.

INTRODUCTION

The area of postharvest technology includes all the operations that commence with the harvesting of grains from the field (Birewar, 1984). These operations, also referred to as the post-production systems, have important effects on the utilization of food crops. Efficient postharvest processing is essential to minimize qualitative and quantitative losses of food crop dietary nutrients. Harvesting, processing green and mature seeds, and storage are all important aspects of postharvest processing in pigeonpea. Each of the above processes involves a set of traditional practices dependant on the region of pigeonpea cultivation and consumption. Developing pods of pigeonpea are harvested and their green seeds shelled and used as a vegetable in India and in some Southeast Asian and African countries (Faris *et al.*, 1987). Canned or frozen green pigeonpeas are used in Latin American and Caribbean countries and are also exported to North America and Europe

(Mansfield, 1981). Dry whole seeds of legumes have a fibrous seed coat, also called the husk, hull, or skin (Aykroyd and Doughty, 1964). This seed coat is indigestible and sometime associated with a bitter taste; its removal improves the appearance, texture, cooking quality, and palatibility of grain legumes. Such antinutritional factors as polyphenols are mostly present in the seed coat and are thus removed by dehulling.

For use as a human food, dry pigeonpea seeds are consumed after dehulling, (or dehusking), and this process is the major postharvest operation before utilization. Like other pulse crops in India, pigeonpea is mainly consumed in the form of dhal which is cooked in water to a desired softness (Singh, 1987). Processing whole pigeonpea seed into dhal (decorticated dry split cotyledons) is an age-old practice with rural origins, but with the introduction and development of suitable machines, dehulling has been adopted on a large scale by dhal mill industries in urban areas.

Storage is an important component of the postharvest operations, and the loss of seed by insect infestation due to improper storage has been reported to be higher in pigeonpea than in the other commonly grown grain legumes in India (Mookherjee *et al.*, 1970). Pulses (including pigeonpeas) are commonly stored in overground structures and are attacked by pulse beetles, this seriously deteriorates grain and makes it unhygienic. Storage of pigeonpeas for long periods under improper conditions adversely affects its dehulling quality, consumer acceptability, and nutritive value (Parpia, 1973).

In view of the importance of the above-mentioned areas in pigeonpea utilization, this chapter presents the topic in four main categories; harvesting procedures, processing green seeds, dehulling operations, and storage practices.

HARVESTING

Green pigeonpea pods are harvested for different purposes. Near cities where they can be readily marketed they are harvested for sale as a vegetable. Fully developed, bright green seed is preferred (Faris *et al.*, 1987), so pods should be harvested just before they start loosing their green colour. It is important to remember that the appearance of pods at this stage varies between cultivars (Saxena *et al.*, 1983). Green pods used as a vegetable are commonly picked by hand, but they may be mechanically harvested for large-scale processing i.e., for canning and freezing. In the Caribbean countries, this type of harvesting has been mechanized by the successful adaption of mechanical green bean pickers (Mansfield, 1981). It is possible to continuously harvest green pods for vegetable consumption because pigeonpea is a perennial crop (Faris *et al.*, 1987), and the harvesting period can be extended if ratoonable cultivars are grown. Pigeonpeas can be grown as trees or shrubs for 4 or 5 years if irrigation or sufficient rainfall is available, and under these conditions, each flush of green pods can be harvested when the pods reach the right stage of maturity.

Pigeonpea, picked while it is still green is an excellent vegetable, but is currently an important market commodity in only a few areas of India. There is considerable potential for the increased consumption of vegetable pigeonpea in India because new high-quality vegetable cultivars are becoming increasingly available, and consumers are learning new ways of eating the crop (Faris *et al.*, 1987).

The dry seeds of pigeonpea are harvested when the pods are fully ripe and have turned yellow, but before the pods start to shatter. Nearly mature pods continue to ripen even after plants are cut, but very dry pods shatter and heavy crop losses occur when plants are cut. Harvesting is usually done manually by using a sickle to cut plants and vines, but occasionally by machines, and is followed by drying and threshing. Generally, harvested material is dried in the sun in the threshing yard for about a week, depending on the weather conditions. Threshing is done both manually and mechanically. Manual threshing, involves beating vines and pods with sticks to separate out the seeds, and in some places animals are allowed to walk on the dried produce to thresh it. In other places mechanical threshers are used.

PROCESSING GREEN SEEDS

After green pods are harvested, shelling, canning, and freezing are important processing operations. Canning and freezing involve several operations including cleaning, blanching, and filling cans and polyethylene bags (Figure 17.1).

Canning

In several developing countries, canning pigeonpea for the export market is encouraged as the demand for canned pigeonpeas has increased. Canning green pigeonpea seeds is a common, export-oriented business in some Caribbean countries, for example, in the Dominican Republic, about 80% of the annual harvest of green pigeonpea is canned and exported (Mansfield, 1981). Although the quality of green seed depends mainly on its maturity and agroclimatic environments, cultivars suitable for canning have been developed (Sammy, 1971). Cultivars with large, uniform, bright green seeds and pods at the canning stage are preferred for canning. Green seeds with a higher soluble sugars content are preferred by the consumer, but genotypes with this trait have not yet been developed (Singh *et al.*, 1984). Sánchez-Nieva (1961) observed that mature, green seeds can better than starchy yellow seeds.

Sánchez-Nieva *et al.* (1961) described traditional methods of canning pigeonpeas. Harvesting green seeds of similar maturity is an important step in obtaining a high quality canned product, but the nonsynchronized flowering characteristic of pigeonpea makes it difficult to harvest developing pods of similar maturity. Factors such as drained mass, volume, viscosity, and colour of brine, and uniformity of colour are all dependant on maturity (Sánchez-Nieva *et al.*, 1963).

Shelling

After the developing pods are harvested in the field, they are shelled to separate the green pigeonpeas from their pod walls. The ease with which pigeonpeas can be shelled depends on the characteristics of the cultivar, and there are large differences in the shelling recovery of vegetable pigeonpeas (Laxman Singh *et al.*, 1977; Yadavendra and Patel, 1983) suggesting that the recovery is higher in some cultivars than others. Shelling recovery is very important to processors and shelling is done mechanically or by hand depending on the volume of product handled by the processor. Hand shelling not only requires a low capital investment, but also helps produce a much better-looking product. It also results in higher yields than machine shelling. Fresh pigeonpeas that are sold packed in polythene bags, are invariably shelled by hand (Mansfield, 1981), and some frozen product packers also prefer hand shelling.

Cleaning

An appropriate cleaning procedure is followed depending on whether the shelling operation is by hand or machine. During hand-shelling for the fresh market and before freezing small quantities, the product is cleaned and inspected so that damaged seeds and foreign matter can be rejected.

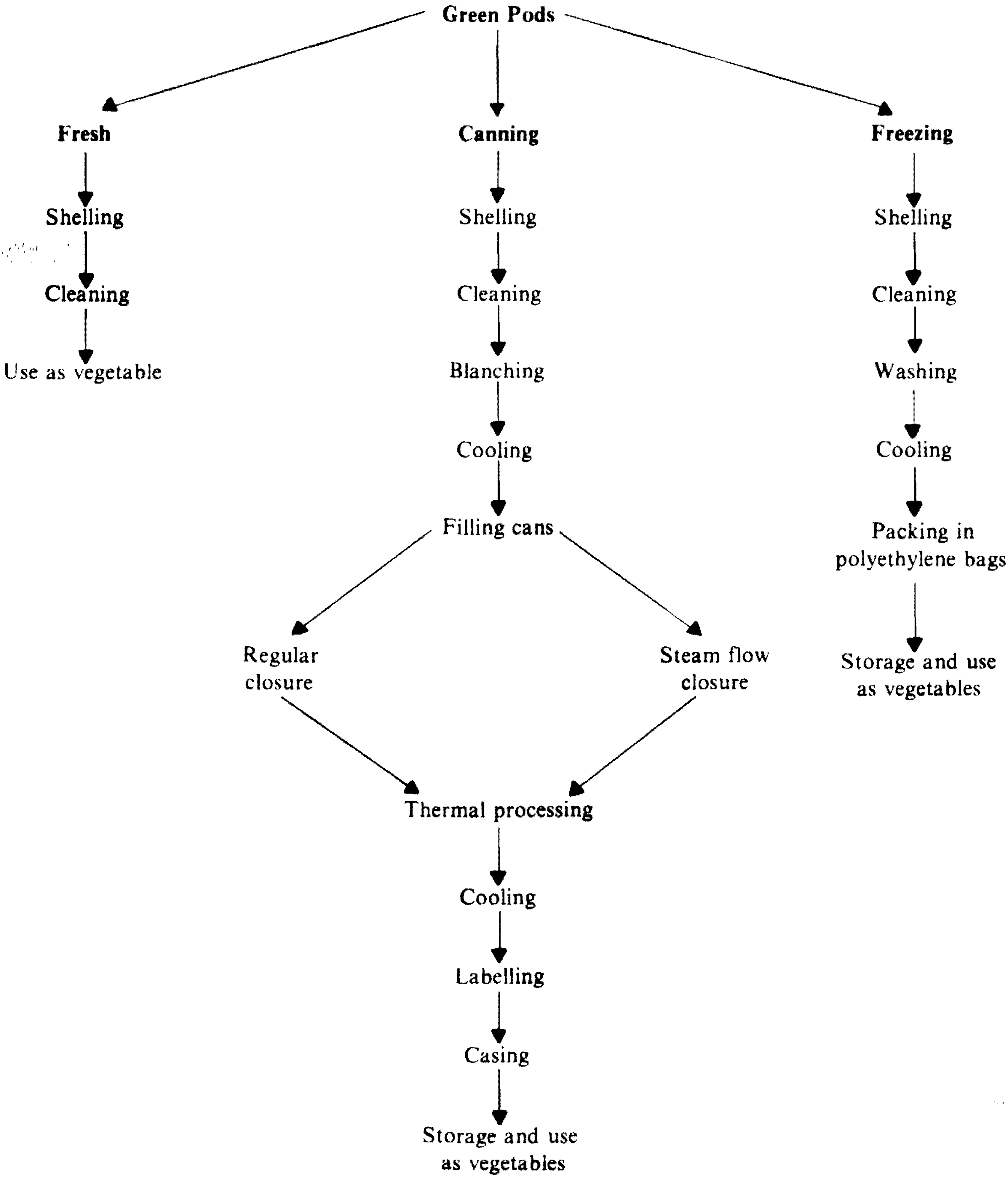


Figure 17.1. Methods of processing vegetable pigeonpeas.

Hand-shelled pigeonpeas for freezing, are cleaned by placing them in containers of cold water before blanching, so as to keep the blanching water as clean as possible. Fresh market produce is not washed, and cleaning is done by the shellers themselves.

Mechanically shelled seeds are transferred to conveyors for cleaning and washing. Small pieces of pod, and damaged and small seeds are removed by air-blast. The seeds then drop onto a large-mesh screen that allows them to drop through while the screen retains pieces of pod and other extraneous material (Mansfield, 1981). As a part of the cleaning operation, the seeds are washed with cold running water in various combinations and types of flotation washers.

Blanching

Blanching is an essential heat treatment operation in the canning and freezing process. According to Sammy (1971), blanching is primarily done to; fix the colour, improve the flavour, reduce the volume, and improve the texture to permit a large mass of peas to fit into the can, remove mucous substance(s) and free starch so as to obtain a clearer brine, and to remove intercellular gases from the seeds to lessen can strain during heating. Two methods of blanching have been reported. In the most commonly used method, to obtain a clear brine, seeds are heated at 185°F (85°C) for 5 min in hot water, and then cooled immediately in cold water to about 80°F (26.7°C) (Sánchez-Nieva *et al.*, 1961). The other method involves steam blanching, which causes less shrinkage and lower nutrient losses (Melmick *et al.*, 1944), but is more expensive because of the energy costs involved, and hence is an unacceptable alternative in developing countries.

After blanching and cooling, seeds are inspected to remove any off-coloured ones that did not appear before blanching, and to ensure complete removal of foreign matter before canning or freezing. As shown in Figure 17.1, all the above-mentioned steps are similar for both canning and freezing processes.

Filling, Closing, and Cooling Cans

After blanching and cooling, cans of different sizes are filled with seeds and a 2% brine solution at 195°F to 200°F (90.5°C to 93.3°C). No sugar or any other additives are added. To close small cans, the brine is maintained almost at boiling point and no mechanical exhaust is required. However, for large cans, the near-boiling brine does not create a sufficient vacuum before the cans are closed, so an additional means of creating a vacuum is needed. Closed cans are thermally processed as soon as possible after closure to inhibit the growth of thermophillic bacteria that may spoil the product later if it is stored at high temperatures (Mansfield, 1981).

Freezing

Freezing is by two methods; an automatic continuous system, and a labour-intensive batch system. In the automated system, blanched and cooled seeds are transported by conveyor to a fluidized bed freezer. In this process, that operates at a temperature well below freezing (-10°F to -20°F) (-23.3°C to -28.9°C) the seeds are individually quick-frozen. Once frozen, the seeds are hand-packed into cartons that have been specially wax-treated to prevent dehydration of the product, and are then stored at 0°F (-17.8°C).

In the batch system, blanched seeds are dropped into cooled water tanks as they come out of the hot-water blancher. After cooling, they are hand-packed into polyethylene bags, and placed in trays for freezing in a batch freezer (-10°F to -20°F) (-23.3°C to -28.9°C) for 4 to 10 h depending on the freezer design, package size, and the initial temperature of the product (Mansfield, 1981). Frozen bags are then placed in corrugated containers for storage at 0°F (-17.8°C).

DEHULLING

In many countries of the world, grain legumes are initially processed by removing the hull and splitting the seed into its dicotyledonous components (Siegel and Fawcett, 1976). In India, dehulling pigeonpea is a primary process that converts the whole seed into dhal. The dehulling operation is usually performed in two steps; the first involves loosening the husk from the cotyledons, and the second removing the husk from the cotyledons and spliting them using a roller machine or stone chakki (quern) (Araullo, 1974; Singh and Jambunathan, 1981a).

Dehulling Methods

Dehulling pigeonpea is an age-old practice in India. In earlier days hand-pounding was common, this was later replaced by stone chakkis. Several traditional methods are used (Kurien and Parpia, 1968), that can be broadly classified into two categories: The wet method that involves water soaking, sun drying, and dehulling, and the dry method that involves oil/water application, sun drying, and dehulling. A survey of dehulling methods in India indicated that pigeonpea is traditionally dehulled in two ways depending on the magnitude of operation (Singh and Jambunathan, 1981a). One is the large-scale commercial dehulling of large quantities of pigeonpea into dhal in mechanically operated mills, and the other is the small-scale home-processing method adopted by villagers using a stone chakki.

As shown in Figure 17.2, in large-scale processing the material is first graded and then passed through a roller machine which causes a mild abrasion – the tempering operation. This tempering causes slight scratches on the seeds and enhances their oil-and water-absorbing efficiency, leading to the loosening of the testa. The material is then treated with oil and water, and spread in the drying yard to dry under the sun. If necessary, the material is occasionally stirred. After sun drying, the material is dehusked with a roller machine (Figure 17.3). Various products i.e., dehusked split (dhal), dehusked unsplit (pearled), and undehusked material of split and unsplit seeds are obtained. These products are separated, and if required the whole operation is repeated to obtain more dhal.

For small-scale dehulling, the basic unit is a chakki comprising two grinding stones (Figure 17.4). The treatments given before dehulling in a chakki vary from region to region (Singh and Jambunathan, 1981a). For example, in the Indian states of Maharashtra, Uttar Pradesh, and Madhya Pradesh soaking pigeonpeas in water for 2-14 h is a common practice. In some other states, villagers prefer to treat the material with oil before dehulling. In some households, pigeonpea is first split using a "chakki", then treated with oil/water, and finally hand pounded to remove the seed coat. Another procedure, followed in Uttar Pradesh is heating the pigeonpea in an iron pan, with or without sand, before grinding. Figure 17.5 shows the various treatments used to dehull pigeonpea in different Indian villages.

In recent years, efforts have been made to develop improved methods and machinery to process pigeonpea more economically. Reichert and Youngs (1976) reported that attrition-type mills (plate mills) can be used for dehulling if the hull is not firmly attached to the cotyledons. If it is firmly attached, then abrasive-type mills are used; these incorporate carborundum to gradually abrade the seed coat from the cotyledon. However, this new technology has not been widely implemented.

Dehulling Losses

Both quantitative and qualitative losses occur during dehulling. The husk or seed coat content of pigeonpea cultivars ranges between 13.2 and 18.9%, with a mean of 15.5% of the whole seed

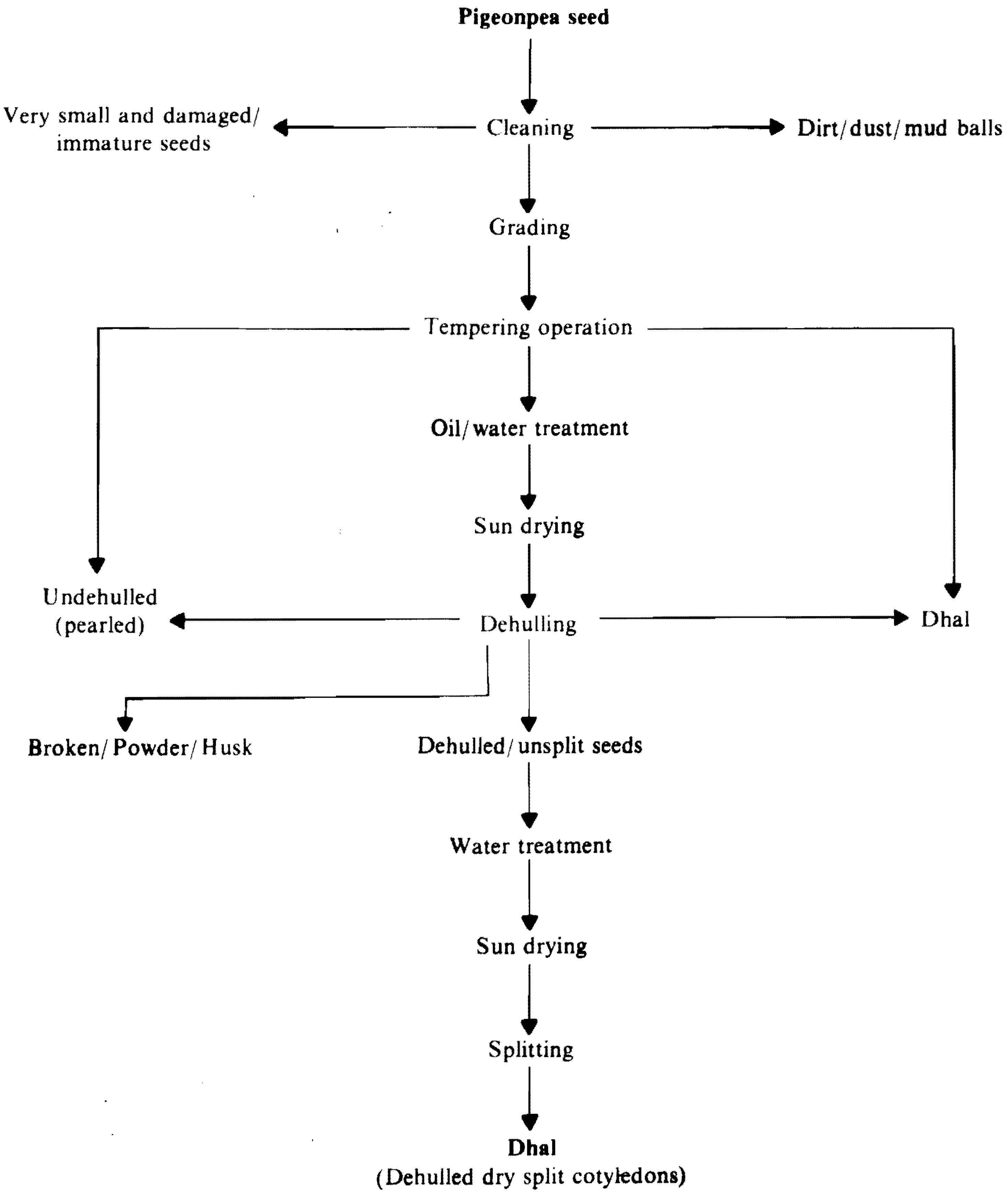


Figure 17.2. Pigeonpea milling procedure followed in Indian dhal mills.

mass. (Singh and Jambunathan, 1981b). The primary objective of dehulling is to remove the seed coat from the cotyledons, but noticeable amounts of cotyledons and germs are removed during the operation, during which four different fractions; dhal, brokens, powder, and husk are obtained (Table 17.1). Losses depend on the method of dehulling, and the grain characteristics of the pigeonpea cultivar. Kurien *et al.* (1972) reported that the average dhal yield from household and traditional commercial dehulling methods varies from 68 to 75%, 10 to 17% less than the theoretical average value of 85%.

Figure 17.3. A commercial Indian dhal mill used to dehull pigeonpeas.
Photo: ICRISAT.

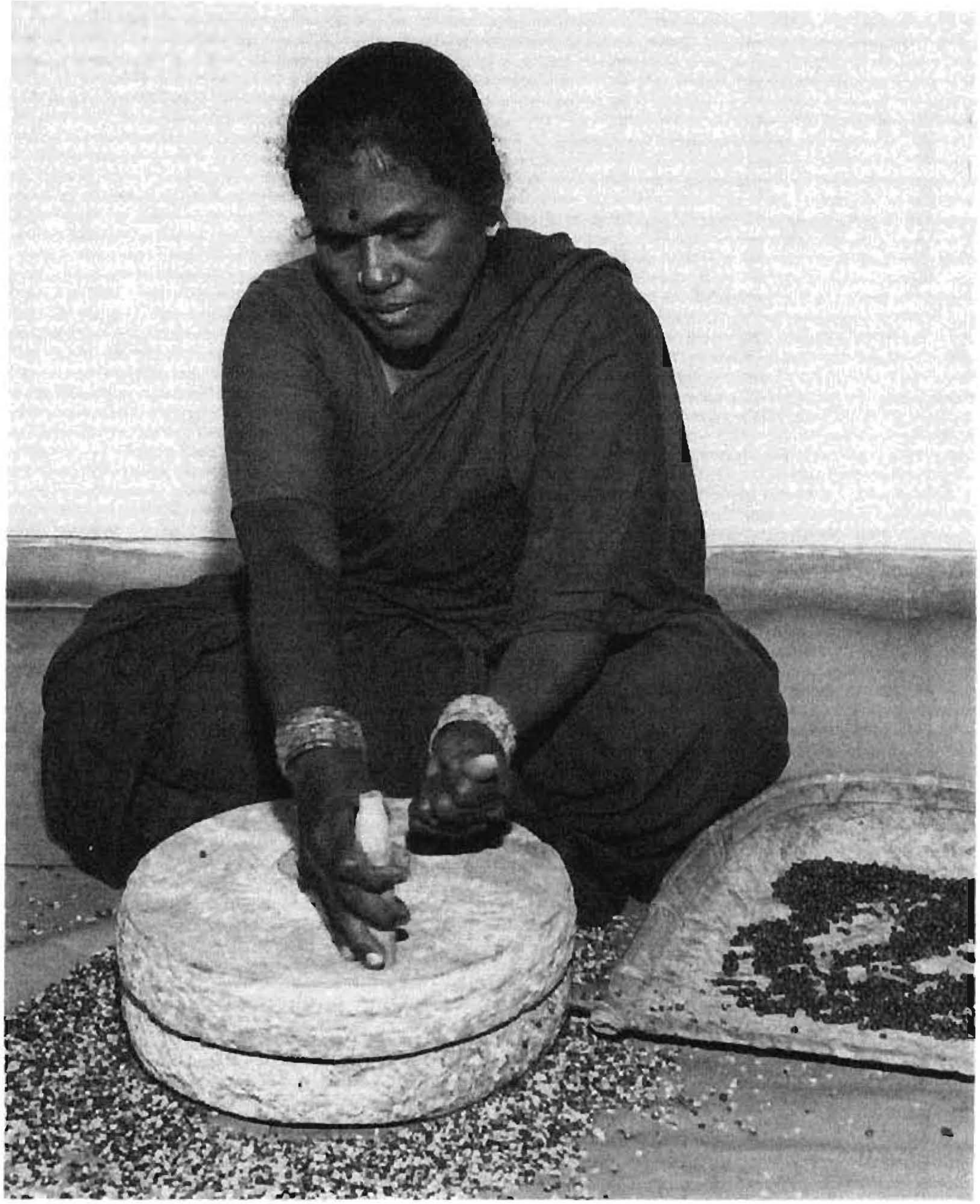


Figure 17.4. Dehulling pigeonpea using the traditional grinding stone or chakki.

Photo: ICRISAT.

Table 17.1 shows the ranges and mean values of fractions reported to be obtained by large- and small-scale dehulling methods (Singh and Jambunathan, 1981a). This study found that the dhal yield varied between 50 and 80% with a mean of 62% in small-scale milling, and between 60 and 85% with a mean of 70.6% in large-scale milling : indicating that the milling losses are significant, and vary with the scale of operation and process of dehulling. The highest dhal yield was reported to be obtained from a modern mill where material is heated in hot air before dehulling (Kurien, 1981). According to this report, the Central Food Technological Research Institute in Mysore, India has developed improved technology for milling pigeonpea, which allows a 24-h operation, is independent of weather conditions, and gives a higher recovery of dhal (80-84%). But this technology has not been adopted on a large scale, primarily due to its high operating costs. Losses in terms of broken and powder fractions are higher when a village chakki is used. Several factors influence dhal recovery, i.e.; methods of dehulling, and grain characteristics such as size, shape,

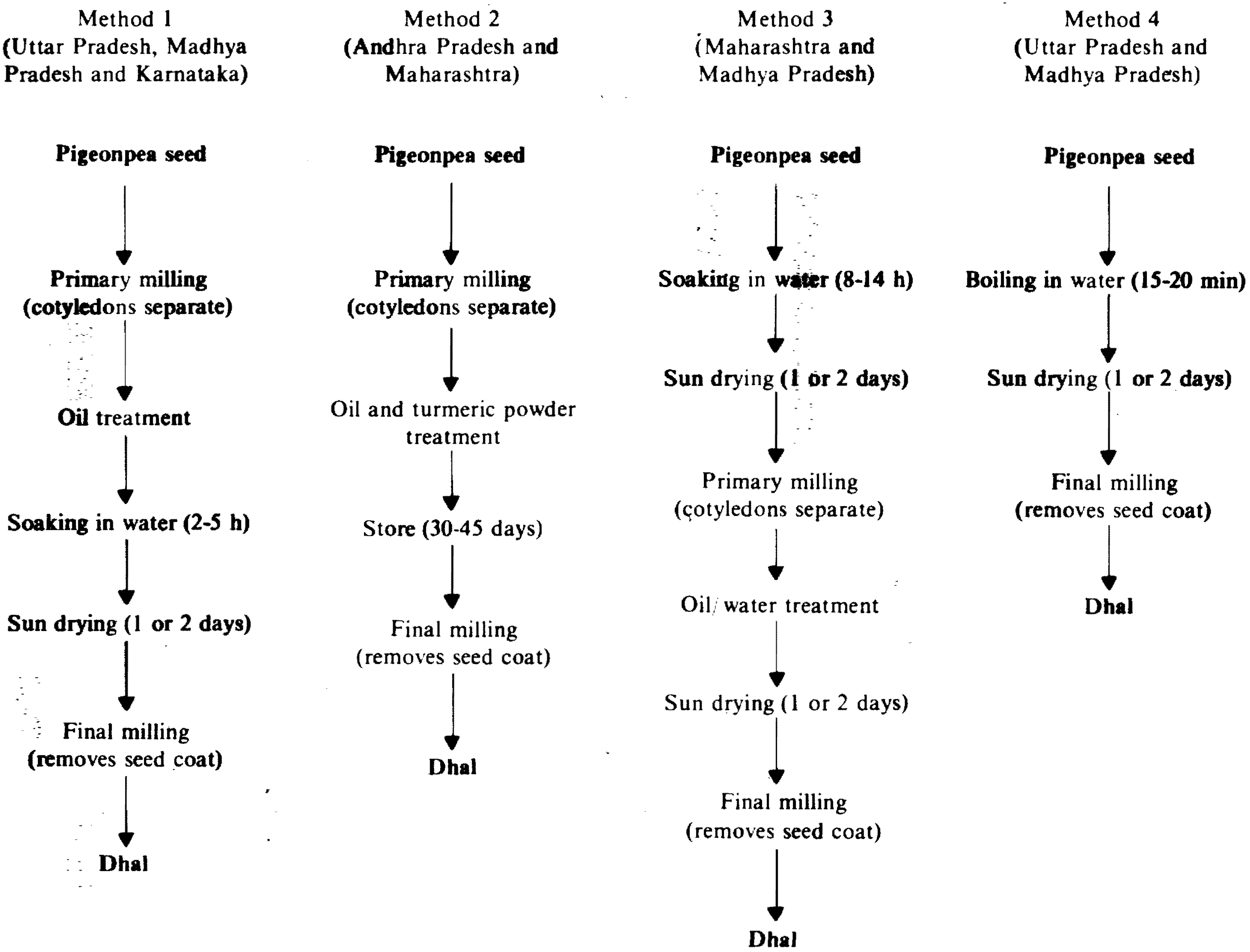


Figure 17.5. Traditional methods of dehulling pigeonpea followed in villages in various Indian states.

Table 17.1. Pigeonpea fractions obtained by traditional milling processes in the Indian states of Madhya Pradesh, Maharashtra, and Uttar Pradesh.

		Milling techniques			
		Large-scale (dhal mill)		Small-scale (village chakki)	
State	Fractions	Range (%)	Mean (%)	Range (%)	Mean (%)
Madhya Pradesh		(n[1] = 15)		(n[1] = 15)	
	Dhal	60.0-75.0	71.4	50.0-70.0	61.6
	Brokens	2.0-8.0	3.6	5.0-18.5	10.5
	Powder	12.0-15.0	13.0	7.0-20.0	11.0
	Husk	5.0-22.0	12.4	10.0-25.0	16.5
Maharashtra		(n = 13)		(n = 38)	
	Dhal	65.0-72.0	68.0	50.0-70.0	59.0
	Brokens	4.0-10.0	5.8	8.0-20.0	12.0
	Powder	10.0-15.0	12.6	10.0-20.0	13.5
	Husk	10.0-20.0	13.4	12.0-20.0	15.0
Uttar Pradesh		(n = 18)		(n = 60)	
	Dhal	60.0-85.0	70.6	50.0-80.0	62.0
	Brokens	2.0-10.0	4.1	5.0-20.0	10.2
	Powder	9.0-18.0	12.7	7.0-20.0	13.0
	Husk	10.0-25.0	12.9	10.0-25.0	14.4

1. n = Total number of interviews conducted during the survey.

Source: Singh and Jambunathan, 1981a.

and colour of seed. Pigeonpeas with white seed coats, and round, bold seeds give higher dhal yields (Singh and Jambunathan, 1981a). However, variation in dehulling characteristics was reported to be independent of size or husk content of pigeonpea grains (Ramakrishnaiah and Kurien, 1983). These workers further indicated that dhal yield was influenced by other varietal factors such as the adherence of the husk to the cotyledons, and moisture content. Dehulling losses are also influenced by splitting and scoring damage incurred in dehulling machines. Ramakrishnaiah and Kurien (1983) reported a large variation (72.3-82.0%) in the dhal yield of various pigeonpea cultivars, and suggested that the environment could influence dhal yield. The abrasive action of the dehulling machine, no doubt, has a significant influence on dehulling losses, but if dehulling conditions are the same the environmental influence among the cultivars can be eliminated (Ehiwe and Reichert, 1987). According to Ehiwe and Reichert (1987), pigeonpea cultivars exhibited less variation (79.0-83.0%) in dhal yield compared to other legumes.

Siegel and Fawcett (1976) reported that the husk is attached to the cotyledons through a layer of gum, the chemical nature, quantity, and level of hydration of which determine its tackiness, and influence the dehulling behaviour of grain legumes. In pigeonpea, nonstarchy polysaccharides in the seed coat have been reported to influence dhal yield (Ramakrisnaiah and Kurien, 1985). Important dehulling quality factors of pigeonpea seed are the resistance of cotyledons to splitting during dehulling, and a seed coat loosely bound to the cotyledons. The degree to which seeds are able to resist splitting into individual cotyledons when an abrasive force is applied is partly related to seed morphology (Reichert *et al.*, 1984). The microstructure of legume seed coats has yielded information on their dehulling properties. Differences in the seed coats, which contain external palisade cells, accounted for hydration and dehulling properties in cowpea (Sefa-Dedeh and Stanley, 1979). However, the physical and chemical nature of the pigeonpea seed'coat has not been fully studied. Singh and Jambunathan (1981a) identified grain parameters (shape, size, and hardness), pretreatment, and the dehulling operation as the important factors that influence dehulling losses. More importantly, dehulling losses can be attributed to the fact that the processing technologies employed in commercial dehulling mills are mostly scaled-up adaptations of traditional household techniques. To date, suitable, efficient dehulling methods and machinery that can reduce losses have not been developed and implemented.

Effect of Pretreatments on Dhal Yield

In traditional dehulling practices in India, pretreatments are aimed at loosening the husk. For pigeonpea, there are four types of pretreatments that involve; water, oil, chemicals, and heat.

Water

The seed coats of mung bean and cowpea are soft, while those of pigeonpea and dry beans are hard at normal moisture levels. The beneficial effects of soaking on cooking quality of legumes, including pigeonpea, have been summarized by Singh (1987); and soaking pulses before dehulling has been in practice for a long time (Kurien and Parpia, 1968). Soaking in water helps to loosen the binding action of the gum, possibly by dissolution and leaching. Increasing the moisture level helps to soften the seed coat. This is done in different ways depending on the dehulling method (Singh and Jambunathan, 1981a). At the village level, pigeonpeas are soaked for 2 to 14 h and then dried (Figure 17.5), while in large-scale dehulling in dhal mills the seed moisture level is increased by sprinkling the seeds with water. Comparatively smaller dehulling units practice alternate wetting and drying known as conditioning (Saxena, 1985).

Oil

In the most widely used pretreatment seeds are treated with oil. The pitted pigeonpea grains are throughly mixed with about 1% oil (preferably linseed), either manually or in a worm mixer, and the oiled grains then are sun-dried for 2-3 days. Oil appears to penetrate through the husk into the cotyledon layer and releases its binding under the mild heat of the sun. This loosening process may be slow, but the husk can be totally loosened if the treatment is extended to several days.

Chemicals

The use of chemicals to loosen the seed coats of pigeonpea has been reported. Reddy (1981) used sodium bicarbonate (5% solution) and reported a dhal yield of 75%. Krishnamurthy *et al.* (1972) substituted sirka (vinegar) for vegetable oil in the dry milling process. These authors also tried sodium bicarbonate, sodium carbonate, sodium hydroxide, acetic acid, and ammonia as a replacement for vegetable oil in the traditional process, and reported a considerable improvement in dhal yield when sodium bicarbonate was used. Saxena *et al.* (1981) treated pigeonpea grains with aqueous solutions of calcium hydroxide, sodium hydroxide, sodium bicarbonate, sodium carbonate, and sodium chloride of different normalities. Normal sodium bicarbonate solution was reported to be the most effective, resulting in a dhal yield of 78%, and hence these authors recommended the use of sodium bicarbonate which, in addition to loosening husk also reduced the cooking time of the resulting dhal. This was further confirmed by Srivastava, V. *et al.* (1988) who reported high dehusking efficiency when sodium bicarbonate was used as a soaking solution (Table 17.2).

Table 17.2. Effect of soaking on dehulling efficiency (%) of pigeonpea seeds of various cultivars[1].

	Presoaking treatment				
			$NaHCO_3$ (%)		
Cultivar	Control	Water	4	6	8
UPAS	65.4	66.3	71.1	81.3	77.2
T 21	70.4	71.2	87.2	80.5	80.3
Pant A 3	69.1	72.3	80.8	74.2	72.5
Pant 10	74.6	77.8	87.2	88.1	85.3

1. Seeds were soaked in water or sodium bicarbonate solution for 1 h at room temperature, and oven dried at 65°C for 150 min to obtain 10% moisture content.

Source: Srivastava, V. *et al.*, 1988.

Heat

Kurien (1977) reported that for better dhal yield, an efficient loosening of the seed coat involves conditioning the whole grain with hot air at 120-180°C in specially designed conditioning chambers, where the grain temperatures are 70-95°C depending on the cultivar. For effective heat transfer, a counter-current through-flow technique is adopted, using a conditioning chamber where hot air enters the grain mass and moves upwards, while the grain moves down by gravity. However, this treatment involves high energy costs. In India villagers sand roast at 100-125°C for 5-10 min to improve dhal yield in pigeonpea (Singh and Jambunathan, 1981a).

Effect of Dehulling on Nutrient Losses

Singh *et al.* (in press) reported that when the outer layers of the cotyledons are scarified there is a 12% quantitative yield loss known as the powder fraction. The outer layers of pigeonpea cotyledons are rich sources of protein (Reddy *et al.*, 1979), this is removed during dehulling, resulting in considerable protein losses. A systematic study (Singh *et al.*, in press), on the composition of dhal and powder fractions showed that as a result of scarification for different intervals, outer portions of the cotyledons are removed resulting in a net loss (Table 17.3). Subsequently, dhal yield is decreased and powder yield increased. Scarification was carried out using a Tangential Abrasive Dehulling Device (TADD) that was developed to simulate large-scale abrasive dehullers (Reichert *et al.*, 1986). The size and shape of unsplit pigeonpea cotyledons scarified for different intervals are shown in Figure 17.6. The study also reported that the outer portions of cotyledons were richer sources of protein, sugar, fibre and ash; and poorer sources of starch which appeared to be concentrated in the inner cotyledons layers. Following histochemical studies Reddy *et al.* (1979) reported that starch grain size and concentration gradually increased towards the inner cotyledon layers. They also observed that proteins were concentrated more towards the periphery immediately below the seed coat. Singh *et al.* (in press) further reported that considerable amounts of calcium (about 20%) and iron (about 30%) were removed by dehulling, but that the process did not adversely affect protein quality in terms of amino acids.

Table 17.3. Effect of duration of dehulling[1] on dhal and powder yields of pigeonpea C 11.

Dehulling time (min)	100-grain mass (g)	Recovery (%)	
		Dhal	Powder
0[2]	8.4	100.0	-
2	7.9	93.3	6.7
4	7.4	87.3	12.7
8	6.3	74.7	25.3
12	5.0	63.1	36.9
SE	±0.42	±1.30	±0.72

1. Using Tangential Abrasive Dehulling Device (TADD); seed coat was completely removed manually before mechanical dehulling for different intervals.
2. Sample not subjected to TADD mill.

Source: Singh *et al.*, in press.

STORAGE PRACTICES

The storage of food grains is important aspect of postharvest technology, because the food grain requirements of any country remain constant throughout the year regardless of the price and season. Therefore, the supply of food grains has to be maintained by proper storage throughout the year. Of the various postharvest losses, in India storage losses are considerably higher in pulses than in cereals (Huysmans, 1970). Pigeonpea is usually stored for long periods to ensure availability of whole seed at the time of sowing, and as dhal to meet consumer requirements. At the village level, small quantities of whole seeds are also stored for consumption. It is essential that during storage, pigeonpeas should remain in good condition and should not undergo deteriorative changes due to fungal or insect infestation, or attack by rodents.

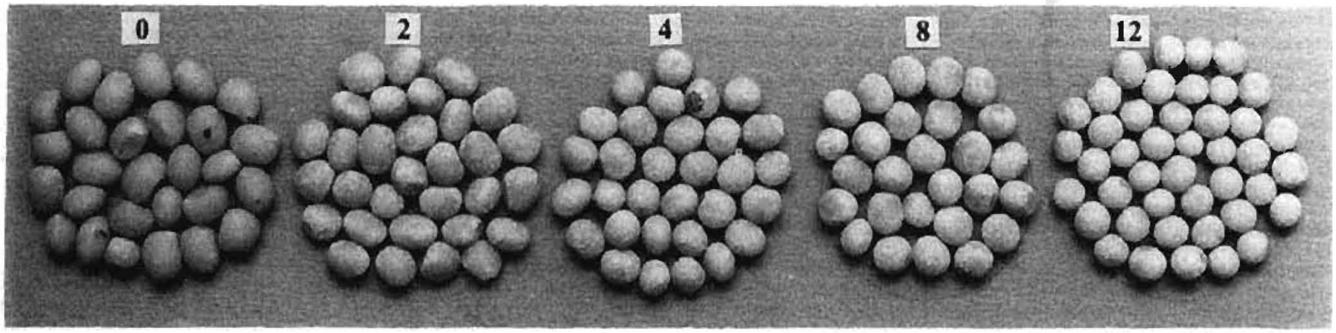


Figure 17.6. Pigeonpea (C 11) seeds showing effect of dehulling on size and shape of unsplit cotyledons (numbers indicate dehulling time in min).
Photo: ICRISAT.

Storage Pests

Pulse beetles popularly known as dhoras are important storage pests of pigeonpea in India. These include three bruchid species; *Callosobruchus chinensis* (L.), *C. maculatus* (F.) and *C. analis* (F.), of which *C. maculatus* is the most important. Sometimes these insects begin their infestation when the pods are in the ripening stage in the field, and are subsequently carried with the grain into the stores after harvesting, resulting in considerable losses. Howe and Currie (1964) gave a detailed account of the development rate, mortality, and oviposition of several species of *Bruchidae* breeding in stored pulses, and observed that *C. maculatus* and *C. chinensis* completed their life cycles in 4 weeks at 30°C and 70% relative humidity in stored pigeonpea.

Noticeable differences in susceptibility of pigeonpea cultivars to pulse beetle attack have been observed (Patnaik and Samalo, 1987). Among several cultivars of pigeonpea, seed infestation due to *C. maculatus* ranges between 7.0 and 28.7% (Table 17.4). Jadhav *et al.* (1984) recorded that beetle incidence was highest in JA 8 and lowest in ICPL 7 of the cultivars he tested. The relative susceptibility of 33 cultivars of pigeonpea to *C. chinensis* was studied under laboratory conditions by Khokhar and Singh (1987); ICPL 148 and ICPL 151 were found to be the least susceptible, and H 79-74 and ICPL 289 were the most susceptible. None of the cultivars was completely resistant to the attack, although susceptibility varied significantly among the cultivars studied. In different pulses, seed surface, seed coat thickness, and seed size have been linked with the mechanism of resistance to different species of *Callosobruchus* (Satya Vir, 1980). According to another study, both *C. maculatus* and *C. chinensis* showed ovipositional preferences for whole grains over dhal indicating that the seed coat provided the ovipositional stimulus (Singh *et al.*, 1980). However, seed characters such as size, colour, and texture were not related to beetle preferences, but seed-coat thickness influenced beetle incidence (Khokhar and Singh, 1987).

Storage Losses

Storage losses can be broadly categorized as losses in mass, quality, and nutritive value, and hygienic deterioration (Howe, 1965). About 90% of the total postharvest losses of pulses are

Table 17.4. Relative susceptibility of pigeonpea cultivars to the pulse beetle (*Callosobruchus maculatus*).

Cultivar	Eggs laid per female	Developmental period (days)	Females in the population (%)	Seed infestation (%)	Loss in yield (%)
H 76-20	39.33[1]	28.5	42.45	15.83	3.21
H 76-208	61.67	27.0	45.96	20.67	5.29
ICPL 1	28.00	27.7	44.59	10.17	4.90
ICPL 81	23.00	28.0	50.75	10.17	2.09
ICPL 87	18.33	26.3	60.47	7.00	3.08
ICPL 151	29.67	26.6	55.56	11.17	2.45
ICPL 142	56.00	26.0	56.02	16.83	2.72
ICPL 161	75.67	27.1	39.43	28.67	5.13
Pusa 33	42.33	25.6	52.38	15.00	2.82
Pusa 78	93.00	27.7	48.44	26.00	4.79
UPAS 120	41.33	25.6	51.60	18.00	2.63

1. All values are means of three replications studied under laboratory conditions.

Source: Patnaik and Samalo, 1987.

Table 17.5. Postharvest losses (%) of pulse production.

Loss stage	Production loss (%)
Threshing yard	0.5
Transport	0.5
Processing	-
Storage	
Rodents	2.5
Birds	0.5
Pests/insects	5.0
Moisture	0.5
Total	9.5

Source: Huysmans, 1970.

estimated to occur during storage (Table 17.5). Over 50% of such losses are due to storage pests and insects (Huysmans, 1970). According to a recent literature survey, more losses occur in pigeonpea than other legumes (Kadam *et al.*, 1989). Mookherjee *et al.* (1970) reported that damage in pigeonpea was 32.6%, cowpea 18.5%, urd bean 14.9%, mung bean 9.9%, and chickpea 4.8%. Pigeonpea storage losses due to insect infestation varied from 14 to 64% (Swaminathan, 1977). Jadhav *et al.* (1984) studied the growth and development of *C. maculatus*, and observed that pigeonpea supported more pest growth than cowpea and chickpea.

There are various biological and physical factors that influence storage losses. The extent of losses at the farm level depends on the temperature, humidity, and moisture content of the stored pigeonpea, the air concentration in storage structures, hygienic conditions, and use of pesticides. The three essential physical variables to be controlled in stored grain are temperature, moisture, and oxygen content (Hulse, in press). Of the biological factors, insects, moulds, bacteria, and yeast are important and cause considerable losses (Mehrotra and Yadav, 1982).

Methods of Storage

The methods of storage play an important role in reducing storage losses. It is often observed that farmers adopt various methods to prevent losses but they are only partially successful because of poor storage conditions, particularly store construction (Mehrotra and Yadav, 1982). At the farm level, storage structures made of steel, mud, wood, plastic, and concrete, and jute bags are frequently used to store pigeonpea. Mud bins are most commonly used by farmers (Srivastava, S. *et al.*, 1988). Storage in jute bags is common in markets and urban dhal mills. There is little difference in the storage structures meant for seeds or grains for consumption.

Seed treatments to reduce storage losses are becoming increasingly important. Toxic chemicals are used to protect seed stocks against insects and seedborne pathogens. Contact instecticides such as DDT, BHC, and malathion are commonly applied as seed treatments. The use of ethylene dibromide as a fumigant, and malathion mixed with tricalcium phosphate at 0.2% have been found quite effective (Vimala and Pushpamma, 1985), but fumigation with toxic chemicals causes considerable loss of viability, probably because the chemicals react with enzymes in the seeds.

The coating of stored pulses with a thin film of edible oils to protect them against insect infestation is an age-old traditional practice in the villages of India. Girish *et al.* (1974) found that oil-treated pigeonpea seeds were not preferred by pulse beetles, and suggested that oil treatment could be useful for the safe storage of pigeonpea. Sangappa (1977) studied the use of mustard, sunflower, safflower, castor, cotton, neem (*Azadirachta indica*), and karanj or honge (*Pongamia glabra*) oils to check infestations of pulse beetle in pigeonpea, and observed that honge and neem oils at 1.0% were effective as surface protectants against attack by *C. chinensis*. According to this study, there was complete protection from infestation for 319 days using honge oil, and 161 days using neem oil. There is less pulse bettle infestation if pigeonpea is stored in the form of dhal (Girish *et al.*, 1974). In order to avoid storage losses, and to make consumable stocks safer because the use of chemicals can be avoided, pigeonpea seeds should be preferably processed and stored as dhal.

Effect of Storage on Cooking Quality and Chemical Constituents

A major drawback in the utilization of food legumes is their decreased cookability after storage under adverse conditions (Jackson and Varriano-Marston, 1981). According to Sefa-Dedeh *et al.* (1979) the cooking time of stored pulses generally increases with storage time (Table 17.6). Cooking time increased in both treated (ethylene dibromide and tricalcium phosphate treatments), and untreated pigeonpea samples during storage, indicating that improved storage methods may not have any beneficial effect on cooking time (Vimala and Pushpamma, 1985). Further, this study reported that the chemical treatments employed to reduce storage losses did not show signficant effects on the cooking time of pigeonpea that was stored for 12 months. Pigeonpea seed moisture, total ash, crude fibre, protein, and reducing sugar contents increased; whereas fat, carbohydrate, and nonreducing sugars decreased with the increase in insect infestation and the advancement of the storage period (Srivastava, S. *et al.*, 1988). As shown in Table 17.7, insect count, mass loss, and uric acid contents of pigeonpea grains increase with storage period (Vimala and Pushpamma, 1983). When pigeonpea seed was stored for 5 months, the total uric acid content increased to 205 mg $100g^{-1}$ and made it unacceptable to consumers (Daniel *et al.*, 1977). This study further reported that lysine, threonine, and the protein efficiency ratio, all considered as indices of protein quality, were all significantly reduced in pigeonpea because of insect infestation during storage in jute bags. The harmful effects of fungi and bacteria on stored pulses have been established. Discolouration of stored whole seed dhal, biochemical changes, and the toxins produced are all recognized

Table 17.6. Effect of storage on cooking time (min) of pigeonpea stored in different containers and treated with various pesticides.

	Cooking time (min)							
Storage period (months)	Bin		Mud pots		Jute bags			
	Control	EDB[1]	Control	EDB	Control	EDB	Malathion	TCP[2]
0	67	67	67	67	67	67	67	67
4	72	72	73	70	72	70	71	70
8	74	77	78	75	76	77	74	76
12	89	86	84	82	89	86	87	93

1. EDB = Ethylene dibromide
2. TCP = Tricalcium phosphate

Source: Vimala and Pushpamma, 1985.

Table 17.7. Effect of storage on moisture content, insect count, kernel damage, mass loss, and uric acid content of pigeonpea seed.

Storage time (months)	Moisture (%)	Insect count (insects $100g^{-1}$)	Kernel damage (%)	Mass loss (%)	Uric acid (g $100g^{-1}$)
0	10.9	-	-	-	-
4	11.1	5	2.2	1.1	4.1
8	11.3	7	4.9	1.8	14.4
12	11.8	17	13.1	4.6	20.3

Source: Vimala and Pushpamma, 1983.

harmful effects caused by microorganisms. Sinha *et al.* (1981) reported proteolytic spoilage of pigeonpea during storage. This happened due to an increase in oxalic, citric, and amino acid contents as a result of the decay process during which proteins were degraded into amino acids; it also resulted in the production of foul odours. Studies have also indicated that stored pigeonpea contained mycotoxins which might have been produced during storage (Habib *et al.*, 1976). It is evident from the above reports that undesirable quantitative and qualitative changes occur during storage of pigeonpea in adverse conditions.

FUTURE

Pigeonpea is traditionally harvested by cutting the plants and vines. In the absence of reliable, cheap, effective mechanical harvesters manual harvesting still remains a common practice with the majority of pigeonpea-growing farmers. The development of machines suitable for this purpose would be most useful. Threshing of both green and mature pods is a tedious and time-consuming operation. Although the development of cultivars with a high shelling yield of green and mature seeds would be a step forward, suitable mechanical threshers are needed to reduce shelling losses and seed damage during the operation. Because suitable canning and freezing techniques to process green seeds are not available in India, canned and frozen green pigeonpeas have not become popular. Efforts to develop suitable pigeonpea cultivars for canning and freezing have been successful; now canning and freezing processes including machinery need to be developed to enhance the utilization of green seed.

Dehulling dry pigeonpea seed causes quantitative and qualitative losses, and is the most important postharvest operation in India. An in-depth study on seed-coat microstructure, and dehulling properties would be useful to elucidate the factors that influence dhal yield. Dehulling losses can be attributed to the fact that the processing technologies employed in commercial mills are mostly scaled-up adaptations of traditional household techniques. To date, suitable and efficient dehulling methods and machinery have not been developed and implemented to reduce losses. The development by plant breeding of cultivars with improved milling characteristics has received little attention in the past. Among the pulse crops, pigeonpea unfortunately incurs maximum losses during storage. No cultivar completely resistant to storage pests has been identified, although susceptibility to pulse beetle attack varies significantly among the cultivars studied. Efforts must continue to find cultivars that suffer minimum quantitative and qualitative losses in storage. Degradation of the nutritive value and cookability, and hygienic deterioration are the most common phenomena of pigeonpea storage. The poorer storage quality of pigeonpea whole seed compared to dhal has been noticed, but the exact role of the seed coat in the storage instability of pigeonpea whole seed has yet to be systematically defined. Although stored seed material is treated with insecticides, no insecticide appears to be safe for use on consumable grains. This remains a controversial area where additional research would be useful.

REFERENCES

Araullo, E.V. (1974) Processing and utilization of cowpea, chickpea, pigeonpea and mungbean. In: *Proceedings of an Inter-disciplinary Symposium held in 1974 on Interaction of Agriculture with Food Science*. International Development Research Centre, Canada, pp. 131-142.

Aykroyd, W.R. and Doughty, J. (1964) *Legumes in Human Nutrition. FAO Nutritional Studies no. 19.* Rome: FAO, 138 pp.

Birewar, B.R. (1984) Post-harvest technology of pulses. In: Srivastava, H.C., Bhaskaran, S., Menon, K.K.G., Ramanujam, S. and Rao, M.V. (eds), *Pulse Production–Constraints and Opportunities.* Oxford and IBH Publishing Co., New Delhi, India, pp. 425-438.

Daniel, V.A., Rajan, P., Sanjeevarayappa, K.V., Srinivasan, K.S. and Swaminathan, M. (1977) Effect of insect infestation on the chemical composition and the protein efficiency ratio of the proteins of Bengal gram and red gram. *Indian Journal of Nutrition and Dietetics* 14, 70-73.

Ehiwe, A.O.F. and Reichert, R.D. (1987) Variability in dehulling quality of cowpea, pigeonpea, and mung bean cultivars determined with the Tangential Abrasive Dehulling Device. *Cereal Chemistry* 64, 86-90.

Faris, D.G., Saxena, K.B., Mazumdar, S. and Singh, U. (1987) *Vegetable Pigeonpea: A Promising Crop For India.* Patancheru, A.P., India: ICRISAT, 13 pp.

Girish, G.K., Singh, K. and Krishnamurthy, K. (1974) Studies on the oviposition and development of *Callosobruchus maculatus* (Fab.) on various stored pulses. *Bulletin of Grain Technology* 12, 113-116.

Habib, F.G.K., Mahras, G.H., Hilal, S.H., Gabrial, G.N. and Morcos, S.R. (1976) Phytochemical and nutritional studies on pigeonpea and kidney beans cultivated in Egypt. *Zeitschrift für Ernährwissenschaft Supplement* 15(2), 224-230.

Howe, R.W. (1965) Losses caused by insects and mites in stored foods and feeding stuff. *Nutrition Abstracts and Reviews* 35, 285-292.

Howe, R.W. and Currie, J.E. (1964) Some laboratory observations on the rates of development, mortality and oviposition of several species of Bruchidae breeding in stored pulses. *Bulletin of Entomological Research* 55, 437-477.

Hulse, J.H. (in press) Nature composition and utilization of grains. In: *Uses of Grain Legumes: Proceedings of a Consultants' Meeting, 27-30 March 1989, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT.

Huysmans, A.A.C. (1970) Storage of food grains–problems and prospects. *Bulletin of Grain Technology* 8, 92-97.

Jackson, G.M. and Varriano-Marston, E. (1981) Hard-to-cook phenomenon in beans: effects of accelerated storage on water absorption and cooking time. *Journal of Food Science* 46, 799-803.

Jadhav, L.D., Patil, S.M. and Salunkhe, V.S. (1984) Effect of different pulses on the growth and development of pulses beetle, *Callosobruchus maculatus* Fab. *Bulletin of Grain Technology* 22, 39-44.

Kadam, S.S., Salunkhe, D.K. and Kuo, C.Y. (1989) Harvesting and storage of legumes. In: Mathews, R.H. (ed), *Legumes: Chemistry, Technology, and Human Nutrition.* Marcel Dekker, Inc., New York, pp. 11-46.

Khokhar, K.S. and Singh, D. (1987) Relative susceptibility of different genotypes of pigeonpea to pulse beetle, *Callosobruchus chinensis* (Linnaeus). *Bulletin of Grain Technology* 25, 244-251.

Krishnamurthy, K., Girish, G.K., Ramasivan, T., Bose, S.K., Singh, K. and Tomer, R.P.S. (1972) A new process of removal of husk of redgram using *sirka*. *Bulletin of Grain Technology* 10, 181-186.

Kurien, P.P. (1977) Grain legume milling technology. In: *Proceedings, FAO Expert Consultation on Grain Legume Processing.* Rome, Italy. AGS/GLP/77/11.

Kurien, P.P. (1981) Advances in milling technology of pigeonpea. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 321-328.

Kurien, P.P., Desikachar, H.S.R. and Parpia, H.A.B. (1972) Processing and utilization of grain legumes in India. *Tropical Agriculture Research Series no. 6.* Ministry of Agriculture and Forestry, Tokyo, Japan.

Kurien, P.P. and Parpia, H.A.B. (1968) Pulse milling in India I–Processing and milling of tur, arhar (*Cajanus cajan* Linn). *Journal of Food Science and Technology* 5, 203-207.

Laxman Singh, Singh, N., Shrivastava, M.P. and Gupta, A.K. (1977) Charcteristics and utilization of vegetable types of pigeonpeas (*Cajanus cajan* (L.) Millsp.). *Indian Journal of Nutrition and Dietetics* 14, 8-10.

Mansfield, G.R. (1981) Processing and marketing of pigeonpeas: the case of the Dominican Republic. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 344-350.

Mehrotra, K.N. and Yadav, T.D. (1982) Problems of seed storage in India. *Bulletin of Grain Technology* 20, 51-59.

Melmick, D., Hachberg, M. and Oser, B.L. (1944) Comparative study of steam and hot water blanching. *Food Research* 9, 148-153.

Mookherjee, P.B., Jotwani, M.G., Yadav, T.D. and Sircar, P. (1970) Studies on incidence and extent of damage due to insect pests in stored seeds – II. Leguminous and vegetable seeds. *Indian Journal of Entomology* 32, 350-355.

Parpia, H.A.B. (1973) Utilization problems in grain legumes. In: *Nutritional Improvement of Food Legumes by Breeding.* PAG of the United Nations System, New York, 281-295.

Patnaik, H.P. and Samalo, A.P. (1987) Studies on the susceptibility of pigeonpea varieties to the pulse beetle, *Callosobruchus maculatus* Fabr. *Bulletin of Grain Technology* 25, 191-193.

Ramakrishnaiah, N. and Kurien, P.P. (1983) Variabilities in the dehulling characteristics of pigeonpea (*Cajanus cajan* L.) cultivars. *Journal of Food Science and Technology* 20, 287-291.

Ramakrishnaiah, N. and Kurien, P.P. (1985) Non-starchy polysaccharides of pigeonpea and their influence on dehulling characteristics. *Journal of Food Science and Technology* 22, 429-431.

Reddy, L.J., Green, J.M., Singh, U., Bisen, S.S. and Jambunathan, R. (1979) Seed protein studies on *Cajanus cajan, Atylosia* spp. and some hybrid derivatives. In: *Seed Protein Improvement in Cereals and Grain Legumes, volume II.* International Atomic Energy Agency, Vienna, pp. 105-117.

Reddy, V.P.R. (1981) Dehusking of arhar grains *(Cajanus cajan).* M Tech thesis, Govind Ballabh Pant University of Agriculture and Technology, Pantnagar, Uttar Pradesh, India.

Reichert, R.D., Oomah, B.D. and Youngs, C.G. (1984) Factors affecting the efficiency of abrasive-type dehulling of grain legumes investigated with a new intermediate-sized, batch dehuller. *Journal of Food Science* 49, 267-272.

Reichert, R.D, Tyler, R.T. York, A.E., Schwab, D.J., Tatarynovich, J.E. and Mwasaru, M.A. (1986) Description of a production model of the Tangential Abrasive Dehulling Device and its application to breeders' samples. *Cereal Chemistry* 63, 201-207.

Reichert, R.D. and Youngs, C.G. (1976) Dehulling cereal grains and grain legumes for developing countries. I. Quantitative comparison between attrition- and abrasive-type mills. *Cereal Chemistry* 53, 829-839.

Sammy, G.M. (1971) *Canning Potential of the Pigeonpea Cultivar Gl 26/2. Food Technology Series no. 4.* Faculty of Engineering, University of West Indies, Trinidad, 4 pp.

Sánchez-Nieva, N.F. (1961) The influence of degree of maturity on the quality of canned pigeonpeas. *Journal of Agriculture of the University of Puerto Rico* 45, 217-231.

Sánchez-Nieva, N.F., González, M.A., Benero, J.R. and Hernandez, I. (1963) The brine-grading of pigeonpeas. *Journal of Agriculture of the University of Puerto Rico* 47, 14-23.

Sánchez-Nieva, N.F., Rodríguez, A.J. and Benero, J.R. (1961) Improved methods of canning pigeonpeas. *University of Puerto Rico Agricultural Experiment Station Bulletin* 157, 1-26.

Sangappa, H.K. (1977) Effectiveness of oils as surface protectants against the bruchid, *Callosobruchus chinensis* Linnaeus infestation on red gram. *Mysore Journal of Agricultural Sciences* 11, 391-397.

Satya Vir (1980) Ovipositiition response and development of *Callosobruchus maculatus* Fabr. on different varieties of cowpea. *Bulletin of Grain Technology* 18, 200-203.

Saxena, K.B., Singh, U. and Faris, D.G. (1983) Does pod color affect the organoleptic qualities of vegetable pigeonpeas? *International Pigeonpea Newsletter* 2, 74-75.

Saxena, R.P. (1985) Milling of pigeonpea grain (*Cajanus cajan* L.) and associated aspects. PhD thesis, Govind Ballabh Pant University of Agriculture and Technology, Pantnagar, Uttar Pradesh, India.

Saxena, R.P., Singh, B.P.N., Singh, A.K. and Singh. J.K. (1981) Effect of chemical treatment on husk removal of arhar *(Cajanus cajan)* grain. Paper presented at the annual meeting of the Indian Society of Agricultural Engineering (ISAE), New Delhi, India.

Sefa-Dedeh, S. and Stanley, D.W. (1979) The relationship of microstructure of cowpeas to water absorption and dehulling properties. *Cereal Chemistry* 56, 379-386.

Sefa-Dedeh, S., Stanley, D.W. and Voisey, P.W. (1979) Effect of storage time and conditions on the hard to cook defect in cowpeas *(Vigna unguiculata)*. *Journal of Food Science* 44, 790-796.

Siegel, A. and Fawcett, B. (1976) *Food Legume Processing and Utilization (With Special Emphasis on Application to Developing Countries)*. International Development Research Centre, Canada, 88 pp.

Singh, U. (1987) Cooking quality of some important Indian grain legumes. Paper presented at the National Symposium on Present Status and Future Perspectives in Technology of Food Grains, February 1987, Central Food Technological Research Institute, Mysore, India.

Singh, U., Jain, K.C., Jambunathan, R. and Faris, D.G. (1984) Nutritional quality of vegetable pigeonpeas [*Cajanus cajan* (L.) Millsp.]: Dry matter accumulation, carbohydrates and proteins. *Journal of Food Science* 49, 799-802.

Singh, U. and Jambunathan, R. (1981a) A survey of the methods of milling and consumer acceptance of pigeonpea in India. In: *Proceedings of the International Workshop on Pigeonpeas, volume 2, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 419-425.

Singh, U. and Jambunathan, R. (1981b) Methods for the estimation of protein in pigeonpea (*Cajanus cajan* L.) and the relationship between whole grain and dhal protein contents. *Journal of the Science of Food and Agriculture* 32, 705-710.

Singh, U., Rao, P.V., Seetha, R. and Jambunathan, R. (in press) Nutrient losses due to scarification of pigeonpea (*Cajanus cajan* L.) cotyledons. *Journal of Food Science*.

Singh, Y., Saxena, H.P. and Singh, K.M. (1980) Exploration of resistance to pulse beetles I. Ovipositional preference of *Callosobruchus chinensis* Linnaeus and *Callosobruchus maculatus* Fabricius. *Indian Journal of Entomology* 42, 375-382.

Sinha, M.K., Singh, B.K. and Prasad, T. (1981) Changes in starch contents of pigeonpea seeds due to fungi. *Indian Phytopathology* 34, 269-271.

Srivastava, S., Mishra, D.P. and Khare,B.P. (1988) Effect of insect infestation on biochemical composition of pigeonpea [*Cajanus cajan* (L.) Millsp.] seeds stored in mud bin. *Bulletin of Grain Technology* 26, 120-125.

Srivastava, V., Mishra, D.P., Laxmi Chand, Gupta, R.K. and Singh, B.P.N. (1988) Influence of soaking on various biochemical changes and dehusking efficiency in pigeonpea (*Cajanus cajan* L.) seeds. *Journal of Food Science and Technology* 25, 267-271.

Swaminathan, M. (1977) Effect of insect infestation on weight loss, hygienic condition, acceptability and nutritive value of food grains. *Indian Journal of Nutrition and Dietetics* 14, 205-216.

Vimala, V. and Pushpamma, P. (1983) Storage quality of pulses stored in three agro-climatic regions of Andhra Pradesh–I–Quantitative changes. *Bulletin of Grain Technology* 21, 54-62.

Vimala, V. and Pushpamma, P. (1985) Effect of improved storage methods on cookability of pulses stored for one year in different containers. *Journal of Food Science and Technology* 22, 327-329.

Yadavendra, J.P. and Patel, A.R. (1983) Consumer preference of vegetable pigeonpea cultivars. *International Pigeonpea Newsletter* 2, 73-74.

Chapter 18

PIGEONPEA: MARKETS AND OUTLOOK

R.A.E. MÜLLER, P. PARTHASARATHY RAO, and K.V. SUBBA RAO

Principal Economist, and Senior Research Associates, Resource Management Program, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Andhra Pradesh 502 324, India.

INTRODUCTION

Purpose

Market economists are not unlike armchair sports fans: they follow events by analyzing the reports from the main arenas. On that score, the life of a pigeonpea market economist could be an idle one because there are precious few reports from pigeonpea market arenas. There is only one large reported market for pigeonpea–the one in India–and even that is small compared to India's market for pulses. It is then no wonder that there are neither economists nor statisticians specializing in pigeonpea markets.

In our review of pigeonpea markets we cannot rely exclusively on statistical market reports. We have to patch together a picture of pigeonpea markets from snippets found in the literature. Like most patchwork, the emerging picture is neither complete nor tidy. Unlike the pieces in a puzzle, the information snippets do not fit tightly together and gaps remain.

Markets, Exchange, and Marketing

A market is the institutional embodiment of the network of relationships that emerges out of voluntary exchanges between individuals (Buchanan, 1964). The main function of markets is to allow producers and consumers to adjust to changes in supply and demand, of which they have to know little else than what is reflected in price changes (Hayek, 1945). The state of the market for pigeonpea is then summarized by pigeonpea prices. Whenever possible, description of pigeonpea prices will therefore take an important place in our review of pigeonpea markets.

Marketing comprises the activities by market intermediaries, traders as well as processors. Much attention is usually paid to sorting, grading, storing, packaging, transporting, and other tasks that are not specific to commodity traders. The speciality of traders is an entrepreneurial one: to compete in the exploitation of unrealized arbitrage and speculation opportunities, benefiting producers and consumers in the process (Menger, 1981; Kirzner, 1973). Unfortunately, we cannot scrutinize the (im)perfection of arbitrage and speculation in pigeonpea markets. Most pigeonpea price statistics are in terms of averages, and as such do not allow discovery of persistent profit opportunities that point to unsatisfactory arbitrage and speculation.

Like traders, processors have a dual task in markets. The first is the task of physically transforming pigeonpea into a food product: the other is the entrepreneurial task of creating new products, or product forms for new markets. From a static perspective, product transformation and its efficiency is the relevant aspect of processing. For the outlook for pigeonpea, the decisive question is whether we can expect processors to discover new pigeonpea products and new market niches by innovating entrepreneurs.

Countries and Regions

Pigeonpea plants have been spotted in many corners of the world, but in only a few countries is pigeonpea grown as a field crop, and fewer countries still report statistics of pigeonpea production. India dominates world pigeonpea production with a share in world pigeonpea production of more than 90% during the last decade (Figure 18.1). The only other countries with a notable pigeonpea production are Malawi and Uganda along with some other countries in eastern Africa, Nepal and Myanmar in Asia, and the Dominican Republic in the Americas.

Pigeonpea market statistics are available only from India; for the other producing countries we have no, or only fragmented, market reports. Only the market in India can therefore be characterized in quantitative terms, whereas the markets in other countries can not.

DOMESTIC MARKET IN INDIA

Supply

Production, Area, and Yield

Pigeonpea, like other pulses, is considered a subsidiary crop in the cropping systems of Indian farmers (Sharma and Jodha, 1982). Often relegated to marginal soils, intercropped pigeonpea receives little or no purchased inputs, nor does it attract much of the farmers' crop management attention. However, farmers in some pigeonpea-growing areas are beginning to grow more sole crops of pigeonpea for sale, and the crop is increasingly gaining status as a cash crop. Pigeonpea yields more energy, protein, and beta-carotene per hectare than other important pulse crops (Figure 18.2).

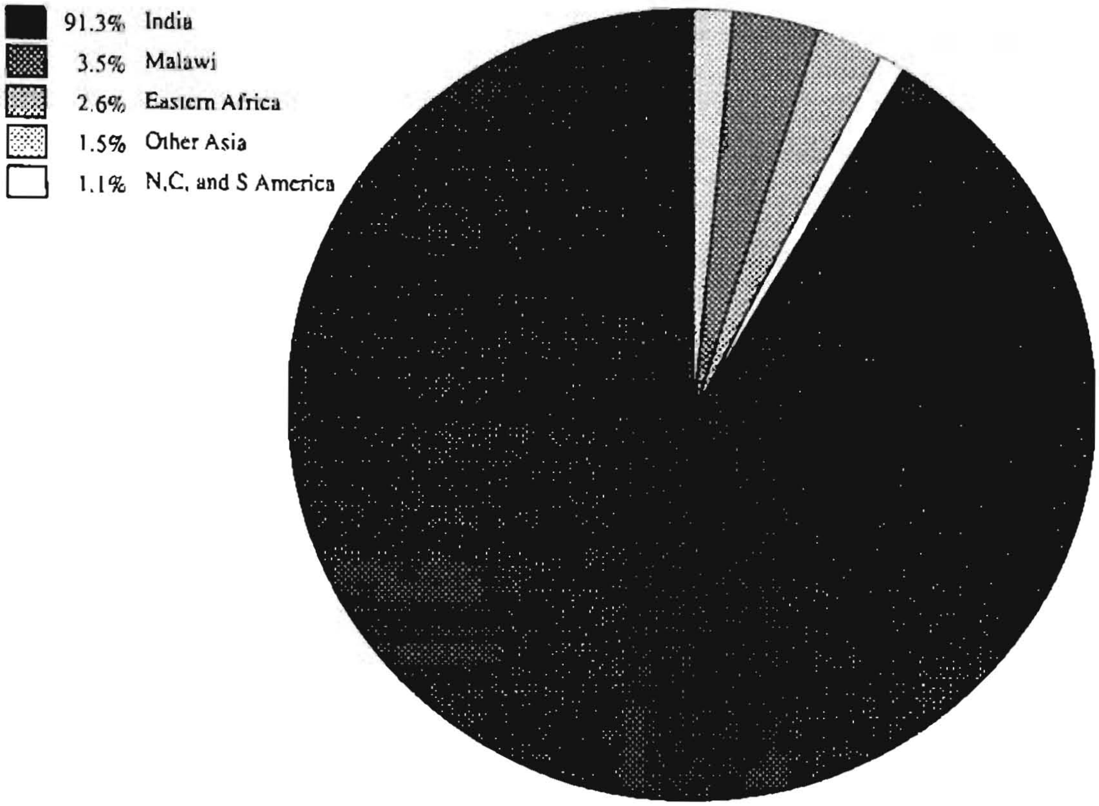


Figure 18.1. Share in world pigeonpea production of major pigeonpea-producing countries and regions, 1987.

Source: E.A. Kueneman, FAO, Rome, personal communication.

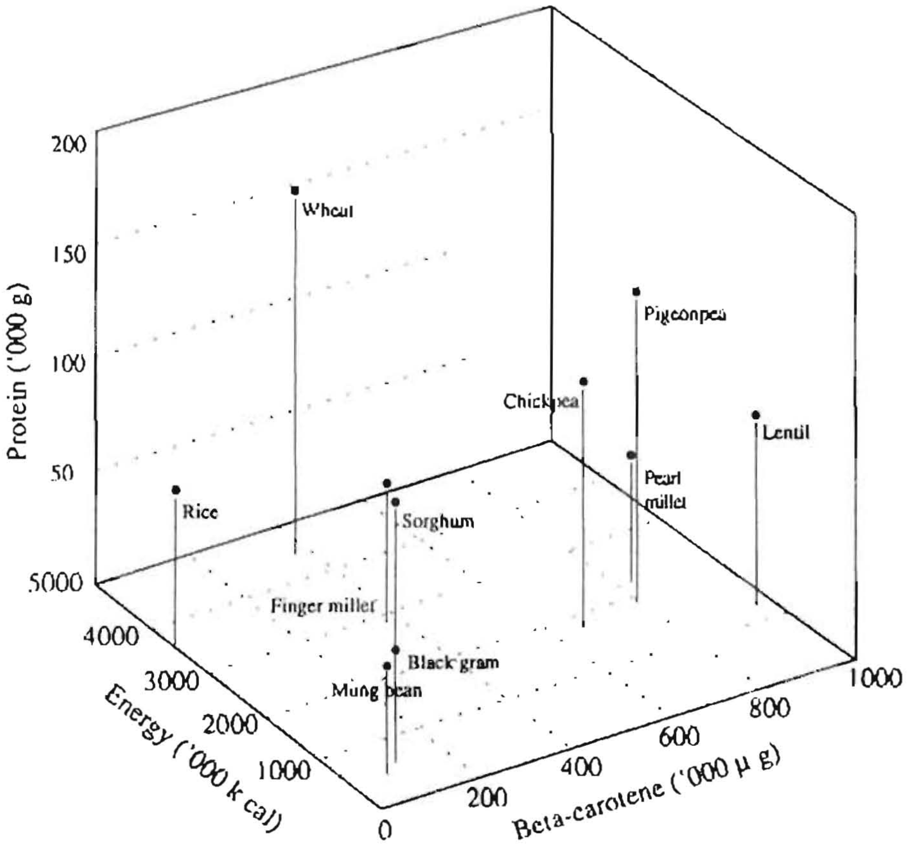


Figure 18.2. Yield of protein, energy, and beta-carotene ha^{-1} from food crops in major pigeonpea- producing states in India.

Production of pigeonpea in India has slowly but steadily increased from about 1.7 million t in 1950/51, to 2.0 million t in 1960/61, and little more than 2.3 million t in 1986/87. Growth in production has been achieved through growth in area, particularly since the late 1970s (Figure 18.3). Average yields have varied within a stable range from about 0.4 t ha^{-1} to 0.8 t ha^{-1} (400-800 kg ha^{-1}), and have contributed little to increased production (Figure 18.4).

Increases in area led to a growing share of pigeonpea in the total pulse area from 10.3% in 1960/61, to 11.2% in 1976/77, and 14% in 1986/87. Pigeonpea's share in pulse production, in contrast, declined from 20.4% in 1950/51, to 16.3% in 1960/61, and less than 16% in 1976/77. Since then the share has risen again to nearly 20% in 1986/87.

Uttar Pradesh, Madhya Pradesh, Maharashtra, and Gujarat are the main pigeonpea-producing states in India, and together account for about two-thirds of India's pigeonpea production (Figure 18.5).

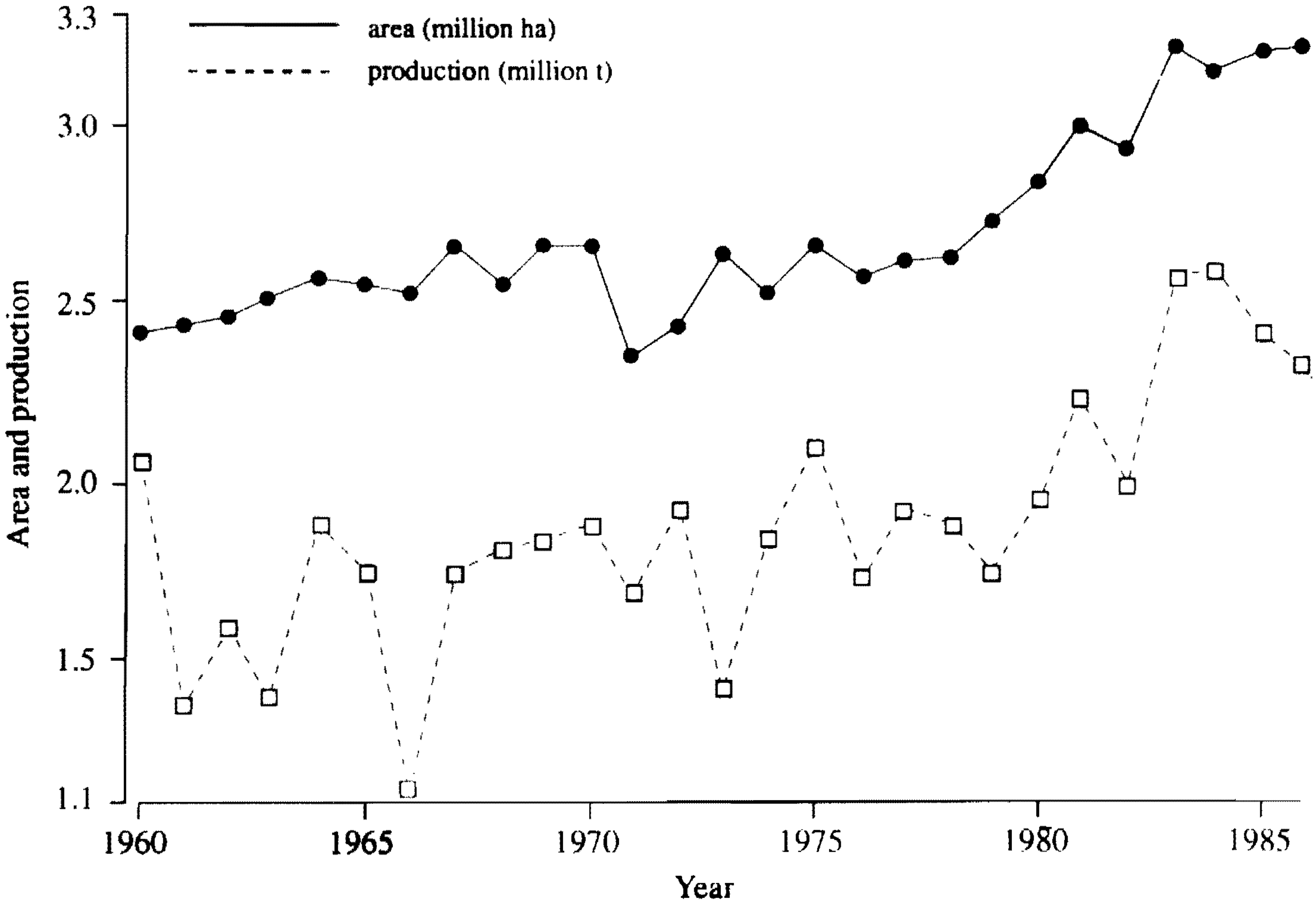


Figure 18.3. Pigeonpea area and production in India, 1960–1986.

Source: Government of India, Area and Production of Principal Crops in India.

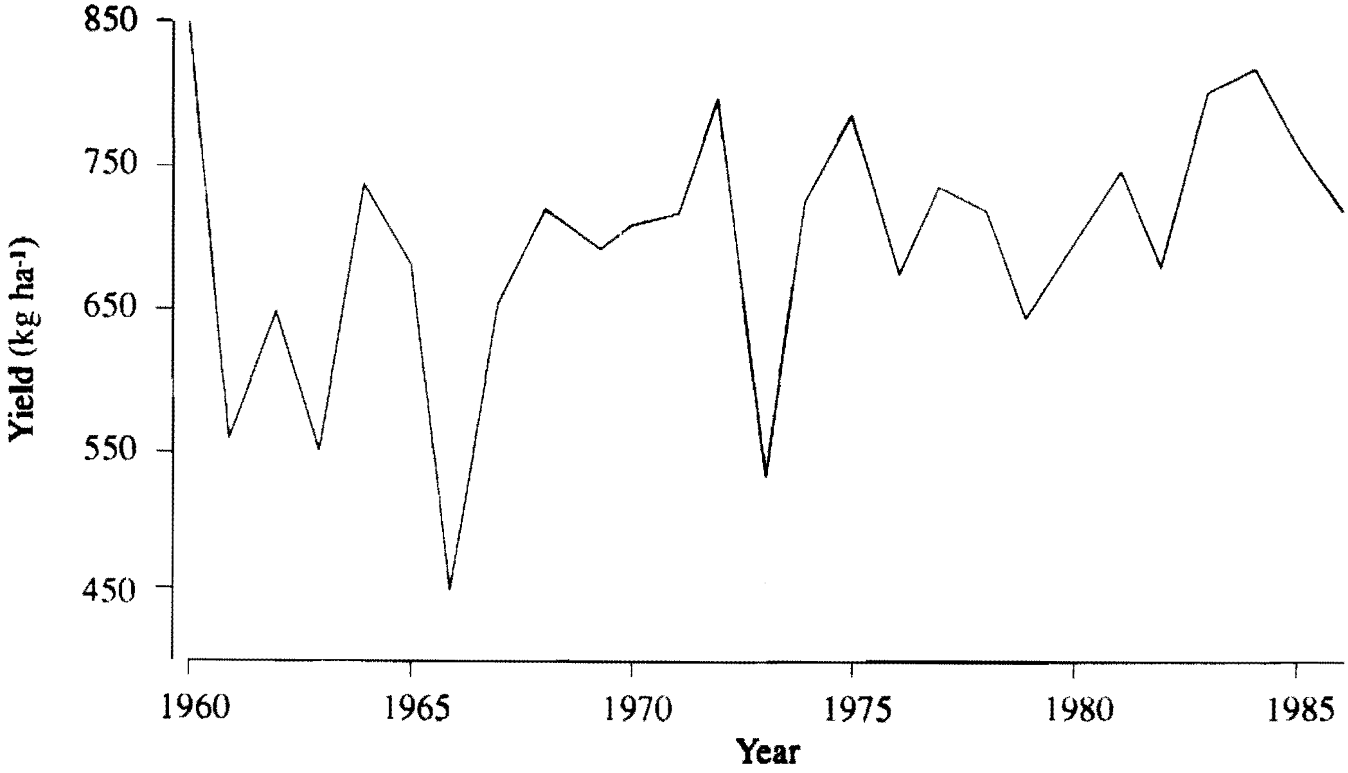


Figure 18.4. Pigeonpea yield in India, 1960–1985.
Source: Government of India, Area and Production of Principal Crops in India.

Availability of Pigeonpea

Growth in production during the last 20 years has been adequate to maintain the daily availability of pigeonpea at slightly less than 10 g per caput day^{-1} for India's rapidly growing population. In contrast, the availability of pulses per caput has steadily fallen from nearly 70 g day^{-1} in 1960 to a low in 1980 when only about 30 g day^{-1} were available (Figure 18.6).

Both stagnating availability of pigeonpea, and falling availability of pulses compare poorly with the availability of cereals where the "green revolution" resulted in increases in good crop years that more than compensated for reductions in poor years.

Marketed Surplus

Pigeonpea is regarded as a crop mainly grown for home consumption. Estimates of marketed surplus vary considerably: von Oppen (1981) estimated the marketed surplus to be about 35% of production, whereas Bolaria (1982) considered it to be 64%. The difference in the estimates may, to some extent, be caused by different definitions of marketed surplus. The estimate by von Oppen (1981) excludes pigeonpea sold in exchange for labour, whereas Bolaria (1982) appears to define marketed surplus as the quantity not retained for home consumption.

The comparison of the estimates of marketed surplus of pigeonpea with the proportion of the agricultural population does not support the contention that pigeonpea is mainly grown for home consumption. The proportion of farmers and farm labourers in the total workforce in India is an indicator for the proportion of the agricultural population in the total population. This proportion is 66% in India, and ranges from 60 to 76% in the major pigeonpea-producing states. The low estimate of marketed surplus by von Oppen (1981) indicates that the share of farm people in pigeonpea consumption is about equal to the share in total population. The high estimate of marketed surplus by Bolaria (1982), in contrast, indicates that the share of pigeonpea retained is much smaller than the share of the agricultural population in total population.

Records of pigeonpea sales by a panel of farms in three districts in Andhra Pradesh and

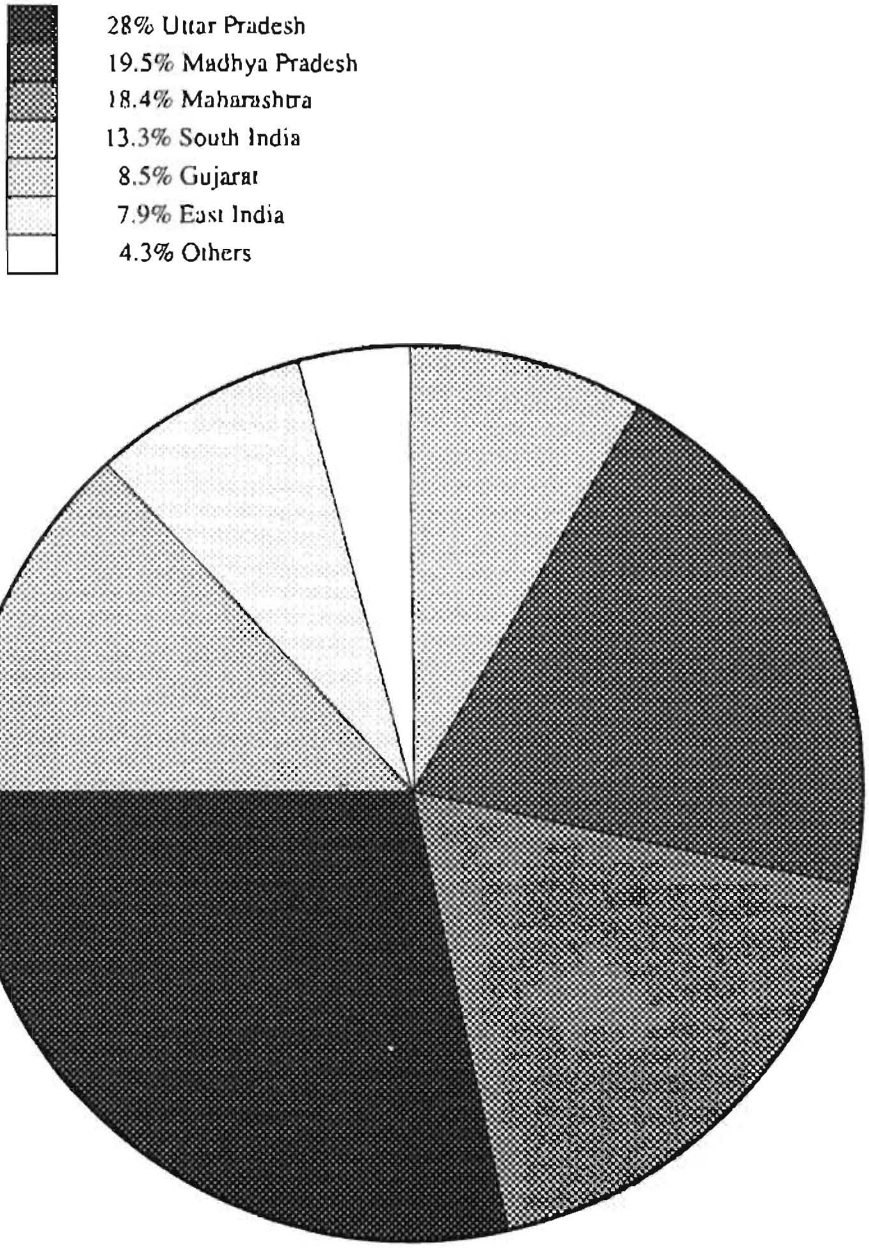


Figure 18.5. Average share in pigeonpea production of regions and states in India, 1982–1984.

Source: Government of India, Area and Production of Principal Crops in India.

Maharashtra indicate that pigeonpea sales are highly variable. Within a span of only 3 years the average proportion of pigeonpea production sold ranged from 21% to 96%. Invariably, however, the average proportion of pigeonpea sold tended to be higher the larger the farm (von Oppen, 1981).

The considerable and sometimes high proportion of pigeonpea production that is sold contradicts the characterization of pigeonpea as a crop for subsistence consumption. All that can be said with confidence is that a considerable proportion is consumed by the producers. That, however, is not surprising for a crop that requires little processing to be used as food by a large farming population, and for which demand is price-elastic.

Demand

Pigeonpea for Food

Pigeonpea contains between 15 and 29% protein and is thought to be an important source of protein in the diet of people who can ill afford animal protein, or whose religion discourages eating animal protein (Salunkhe *et al.*, 1986). This opinion is encouraged by influential international agencies such as the Food and Agriculture Organization of the United Nations (FAO) which recently wrote: "Pulses play an important role in the diets in a large number of countries. They are a major source of protein in many developing countries, especially among the poorer sections of the population" (FAO, 1987).

There is increasing doubt that the characterization stands up to the facts. Bidinger and Nag (1981) found in a survey of diets in villages in the semi-arid tropics of India that rural people eat between 35 and 40 g pigeonpea day^{-1} (Table 18.1) providing less than 10% of the protein and 5% of the energy in their diets. Ryan *et al.* (1984) wrote in their conclusions from that survey: "Proteins and essential amino acids were not generally limiting, except in particular circumstances, as is increasingly found by nutrition studies". Sukhatme (1987) summarized the debate on the alleged

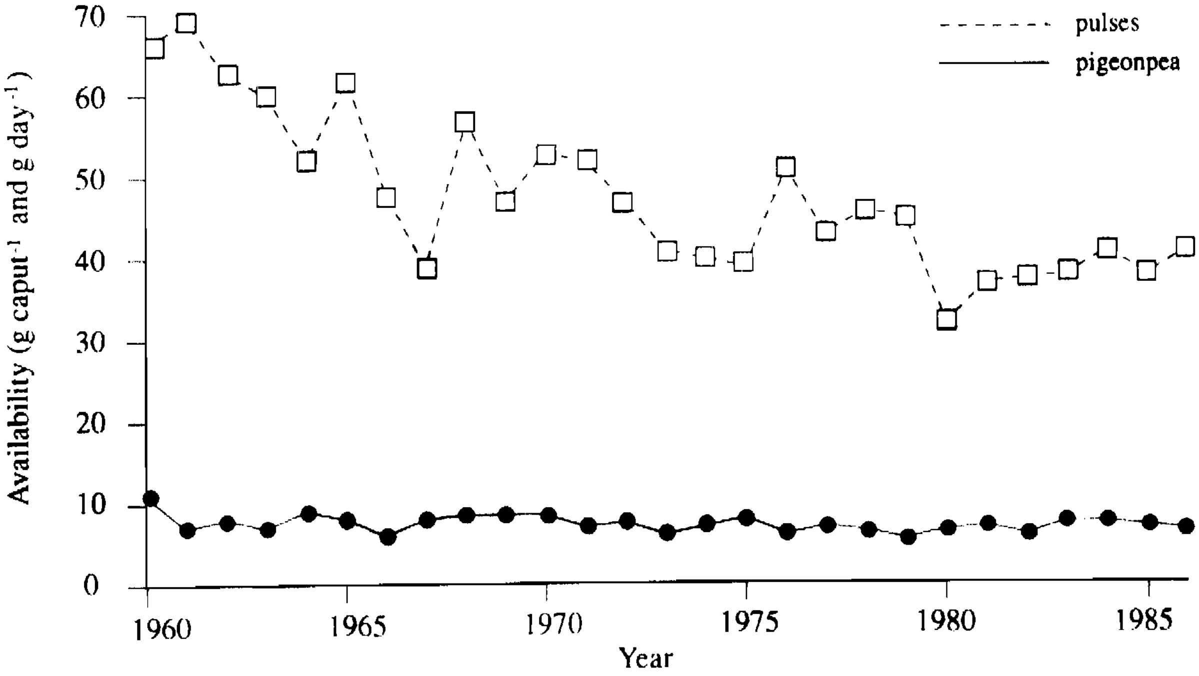


Figure 18.6. Availability of pigeonpea and pulses per caput and day in India.

Source: Government of India, Bulletin on Food Statistics; United Nations Demographic Year Book (various issues).

Table 18.1. Consumption (g caput^{-1} day^{-1}) of pigeonpea by age group and land-holding class in six SAT Indian villages during 1976-1978.

Age group (years)	Land-holding class (mean ± SE)				
	Labour	Small	Medium	Large	Total
1-6	18.8±1.7	26.7±2.4	27.7±2.2	21.5± 1.3	23.8±1.0
7-18	30.6±2.9	31.5±1.6	30.5±1.4	35.2± 1.9	32.6±1.0
>18	36.4±1.9	37.4±1.5	36.2±1.4	38.7± 1.3	37.4±0.8
Men >18	37.3±2.8	37.7±2.1	37.3±2.1	38.9± 1.9	37.9±1.1
Women >18	35.4±2.8	37.1±2.3	34.8±1.8	39.2± 2.0	37.0±1.1
Pregnant women	34.3±9.5	16.0±3.6	36.6±8.4	52.0±17.6	34.8±5.6
Lactating women	46.7±8.9	36.6±4.0	36.9±3.9	40.7± 4.1	39.6±2.4

Source: Bidinger and Nag, 1981.

protein deficiency of poor peoples' diets saying: "Subsequent research however showed that the limiting factor in the diet of the developing countries was not protein but energy".

A more accurate portrayal of the importance of protein in the diet of people who have only little money to spend on food is required for the proper characterization of pigeonpea's contribution to meeting such people's protein requirements.

Minimum Cost Diets

Although pigeonpea has a higher protein content than cereals, it is, at current prices, also a relatively expensive source of protein, energy, and beta-carotene. Figure 18.7 shows that much more protein, energy, and beta-carotene can be purchased with one rupee spent on pearl millet or sorghum, than on pigeonpea.

A diet consisting of only one food item could not be considered balanced, and may not meet all requirements for man's nourishment. A richer model of choice of food items than implied in Figure 18.7 is required to assess the importance of pigeonpea as a carrier of nutrients. In order to make a more valid assessment the authors therefore modelled the choice of foods of a consumer who attempts to meet dietary requirements, as specified by nutritionists, at least cost. Such a model is consistent with the emphasis that is given to pigeonpea as a source of protein for poor people who can ill afford to buy food items other than those that provide the most nutrients.

The Model

The choice of quantities of food items to meet nutrient requirements at least cost can be modeled as a linear programming problem (Lancaster, 1971). A limitation of the model is the assumption of a "linear consumption technology" that does not allow for interactions among nutrients. Furthermore, when using the model no account can be made for the reduced digestibility of proteins from legumes and other undesirable characteristics of pigeonpea that are believed to constrain its consumption (Salunkhe *et al.*, 1986). Finally, we cannot accommodate in the model consumers' preferences for home-grown food and food diversity. Not allowing for diversity invalidates our model for the prediction of the composition of actual diets. Even poor people tend to choose a more diverse diet over a more nutritious one once their income rises above what is required for survival (Shah, 1980; Behrman *et al.*, 1988). The model is, nevertheless, useful for illustrating substitution between pigeonpea and other foods in a diet purely determined by nutritional requirements, and costs of nutrients from different food items.

Food Items, Nutrient Contents, Food Prices, and Nutrient and Food Requirements

We determined the set of food items included in the model from the results of a 24-h diet recall survey of 40 households in each of six villages in the semi-arid tropics of India, that was conducted in 3-4 months intervals from 1976 to 1978 (Ryan *et al.*, 1984). The nutrient contents of the edible portion of the food items were taken from Gopalan *et al.* (1971). The food items, their nutrient contents, and prices are listed in Table 18.2. Prices are wholesale market prices from 1989, and were collected from price reports in national and regional newspapers.

Nutrient requirements in terms of energy, protein, fat, calcium, iron, beta-carotene, and ascorbic acid were determined as the average daily requirements of men and women doing moderately heavy work. We also included minimum daily requirements for groups of similar foods. The food group requirements listed in Table 18.3 reflect "balanced diets" for vegetarians and non-vegetarians as recommended by Gopalan *et al.* (1971).

Model Results

The cheapest balanced diet would cost Rs 4.65 day^{-1} for a vegetarian, and Rs 4.66 day^{-1} for a non-vegetarian. The cost of pigeonpea would account for 12% of the total cost of the vegetarian, and 10% of the non-vegetarian diet. All the pulse requirements in both diets would be met with pigeonpea, which would contribute 21% of the total protein content in the vegetarian diet, and 16% in the non-vegetarian one. A higher protein content of pigeonpea would have no effect on pigeonpea consumption because protein is not a limiting factor in the cheapest possible balanced

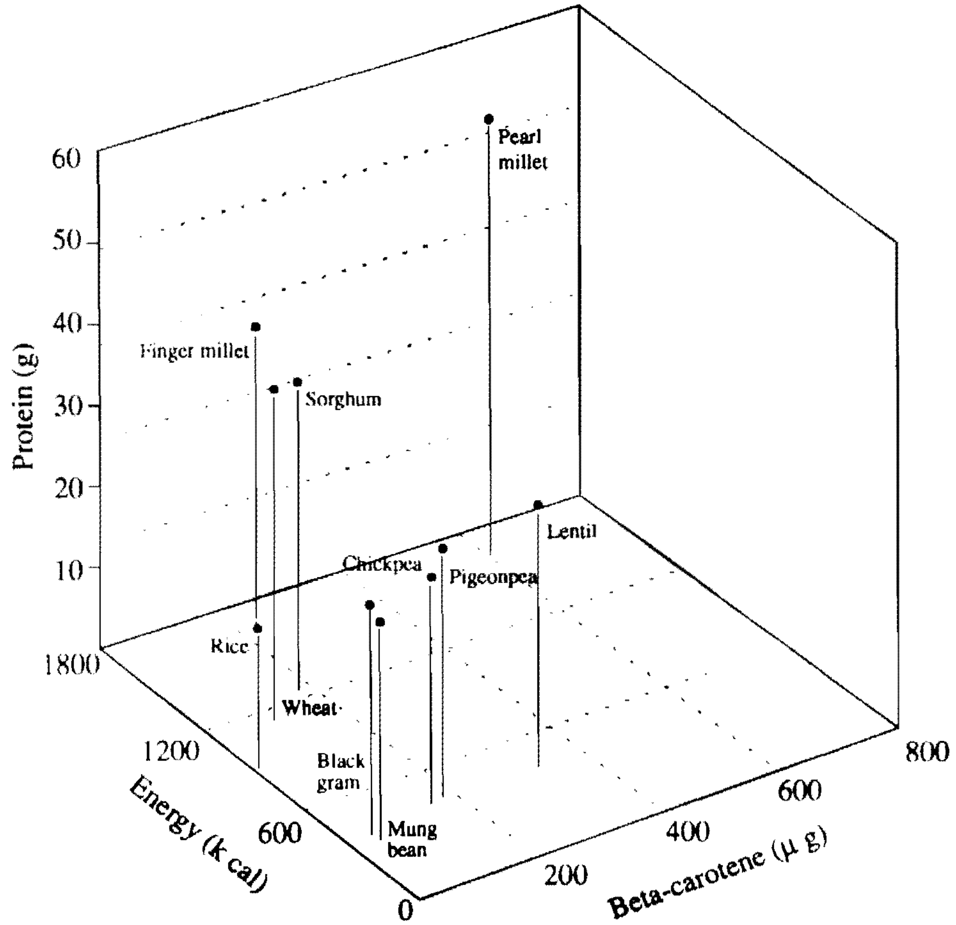


Figure 18.7. Protein, energy, and beta-carotene Rs^{-1} spent on food items.

Table 18.2. Nutrient contents of the edible portion of 1 kg of food items included in the model, and prices of foodstuffs.

Food item	Energy (k cal)	Protein (g)	Calcium (mg)	Iron (mg)	Fat (g)	β-Carotene (μg)	Ascorbic acid (mg)	Price (Rs kg^{-1})
Maize	3420	116	100	20	36	900	-	2.5
Rice	3450	68	100	31	5	-	-	3.9
Pearl millet	3610	116	420	50	50	1320	-	2.2
Sorghum	3490	104	250	58	19	470	-	2.8
Finger millet	3280	73	3440	64	13	420	-	2.0
Wheat	3410	121	480	115	17	290	-	3.0
Pigeonpea dhal	3350	223	730	58	17	1320	-	7.5
Mung bean dhal	3480	245	750	85	12	490	-	9.6
Black gram dhal	3470	240	1540	91	14	380	-	8.8
Chickpea dhal	3720	208	560	91	56	1290	-	8.0
Lentil dhal	3430	251	690	48	7	2700	-	8.1
Sugar	3980	1	120	-	-	-	-	7.0
Milk	1170	43	2100	2	88	960	10	5.5
Eggs	1730	133	600	21	133	8160	-	11.0
Mutton	1180	214	120	29	36	180	-	40.0
Chicken	1090	259	250	14	6	-	-	30.0
Groundnut oil	4500	-	-	-	50	-	-	20.5
Safflower oil	4500	-	-	-	50	-	-	23.0
Spinach	260	20	730	109	7	55800	280	6.5
Amaranthus	450	40	730	109	5	55800	270	7.0
Onion	500	12	470	7	1	-	110	2.5
Potato	970	16	100	10	1	200	-	3.0
Tomato	230	19	480	4	1	3510	270	3.2
Other vegetables	340	20	260	20	3	400	200	4.0
Banana	1160	12	170	9	3	780	70	7.0
Other fruits	650	8	200	12	4	5600	270	6.5
High-protein pigeonpea dhal	3805	299	730	58	25	1320	-	7.5

Source: Gopalan *et al.*, 1971.

Table 18.3. Food requirements (g day^{-1}) of balanced diets for vegetarians and non-vegetarians.

Food item	Balanced diet: Vegetarian	Balanced diet: Non-vegetarian
Cereals	415	415
Pulses	75	60
Vegetables and fruits	320	320
Oils and fats	40	40
Milk	200	100
Meat, fish, and eggs	-	60
Sugar and jaggery	35	35
Total	1085	1030

Source: Gopalan *et al.*, 1971.

diets. If pigeonpea were not available, chickpea would be consumed to meet the pulse requirements of the balanced diets.

We further explored the role of pigeonpea as a source of protein in modified diet models where we assumed that consumers would attempt to maximize protein consumption from a diet that meets all the other constraints of a balanced vegetarian diet, and a budget constraint. We then varied the budget constraint and the minimum requirement for pulses in the diet. We found that at all budget levels and all levels of minimum pulse requirements, pigeonpea would be the only pulse consumed, but that no pigeonpea would be consumed in excess of the minimum required quantity of pulses. The objective of maximizing protein consumption would be achieved not by buying more protein-rich pigeonpea, but by buying more low-protein cereals. As a consequence, the contribution of pigeonpea to total protein consumption would fall when both budget constraint and minimum pulse requirement were relaxed (Figure 18.8).

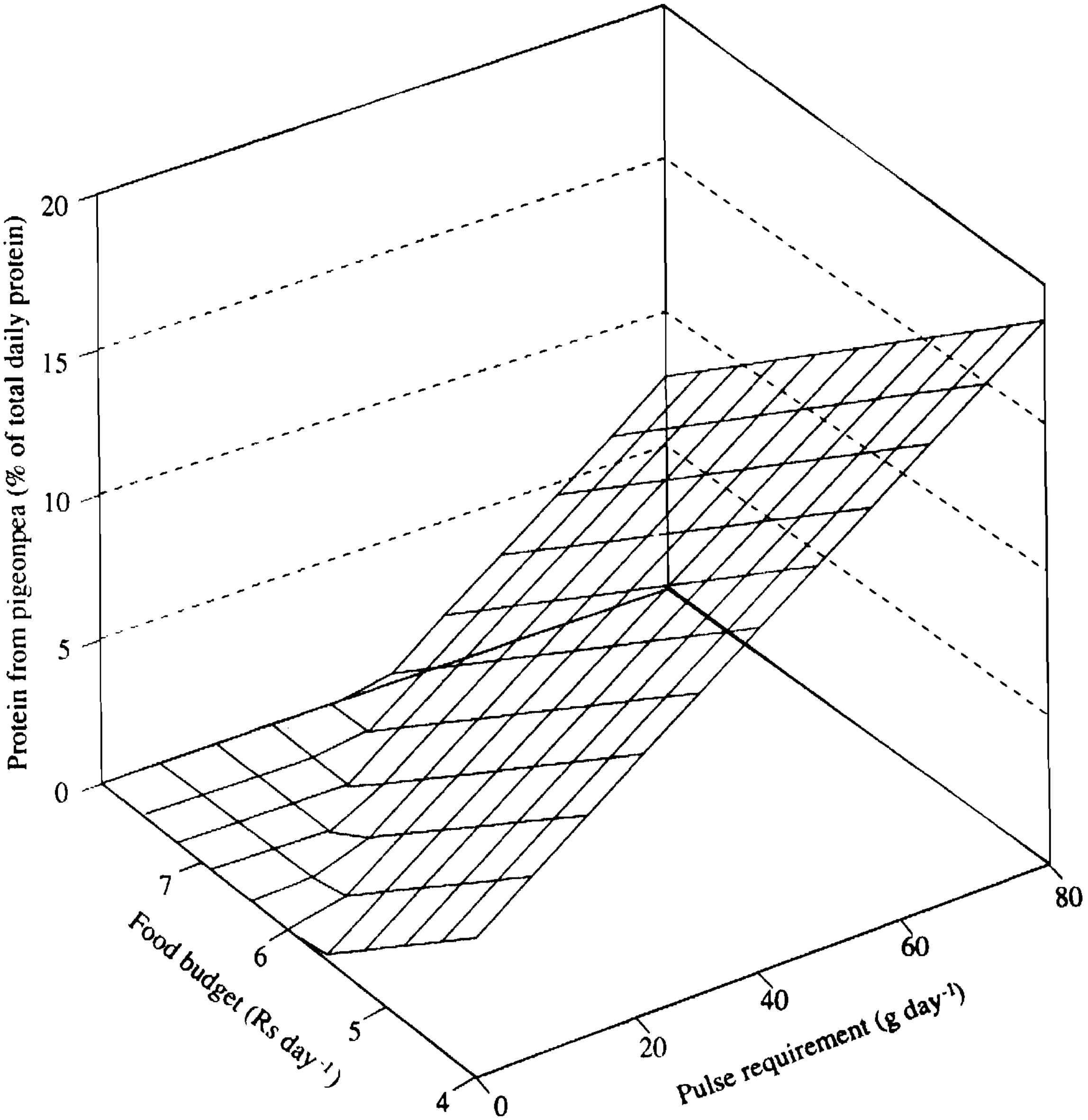


Figure 18.8. Linear interpolation of the contribution of pigeonpea to total protein in a daily diet as a function of food budget (Rs day^{-1}) and pulse requirement (g day^{-1}).

Model results thus also contradict the contention that pigeonpea is a cheap source of protein for the diets of poor people. It is included in diets to achieve nutritional balance, and, we suspect, because people have a taste for it.

Prices

Real prices for pigeonpea were highly variable with a weak upward drift. The price index for cereals, in contrast, has steadily declined with the spreading of the "green revolution" in India. The real price index for pigeonpea reached its highest level during the period 1971-1986 at 144 in 1978, and its lowest at 71 in 1976 (Figure 18.9). The coefficient of variation of the price index is 15% for pigeonpea, and 11% for pulses. The price indices for pigeonpea and pulses moved in opposite directions in 9 out of 16 years, and their correlation is low (r = 0.45).

Nominal prices for pigeonpea have increased considerably since the early 1970s. A price support scheme for pulses administrated by the National Agricultural Marketing Federation has not increased prices. The scheme is largely ineffective because market prices have been higher than the support prices (Figure 18.10). Only negligible purchases have therefore been made by the price support agency (Kahlon and George, 1985).

Seasonal variation in average monthly prices is moderate. Wholesale prices at Kanpur in Uttar Pradesh, a major pigeonpea market, are on average more than 6% above their de-trended average

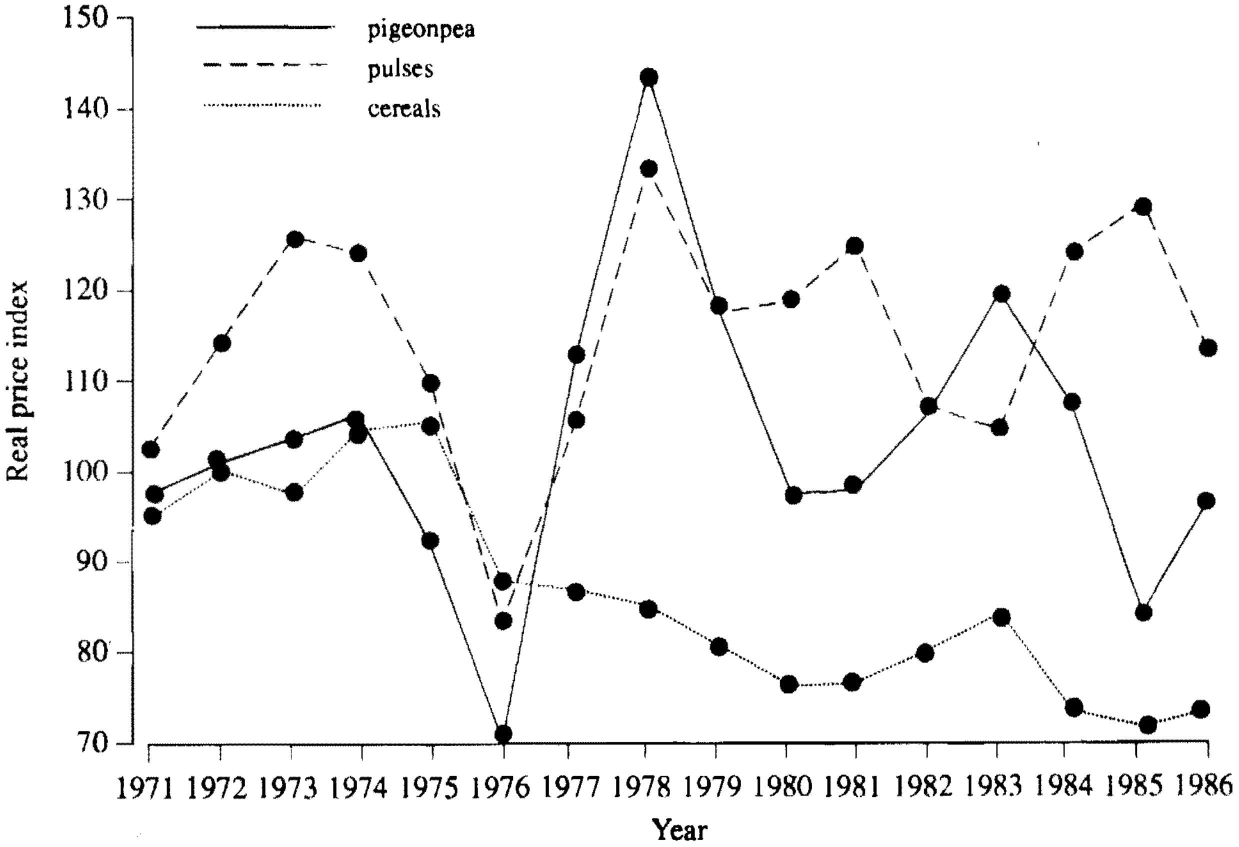


Figure 18.9. Wholesale price indices for pigeonpea, pulses and cereals in India (base 1970/71 = 100).

Source: Government of India, Bulletin on Food Statistics (various issues).

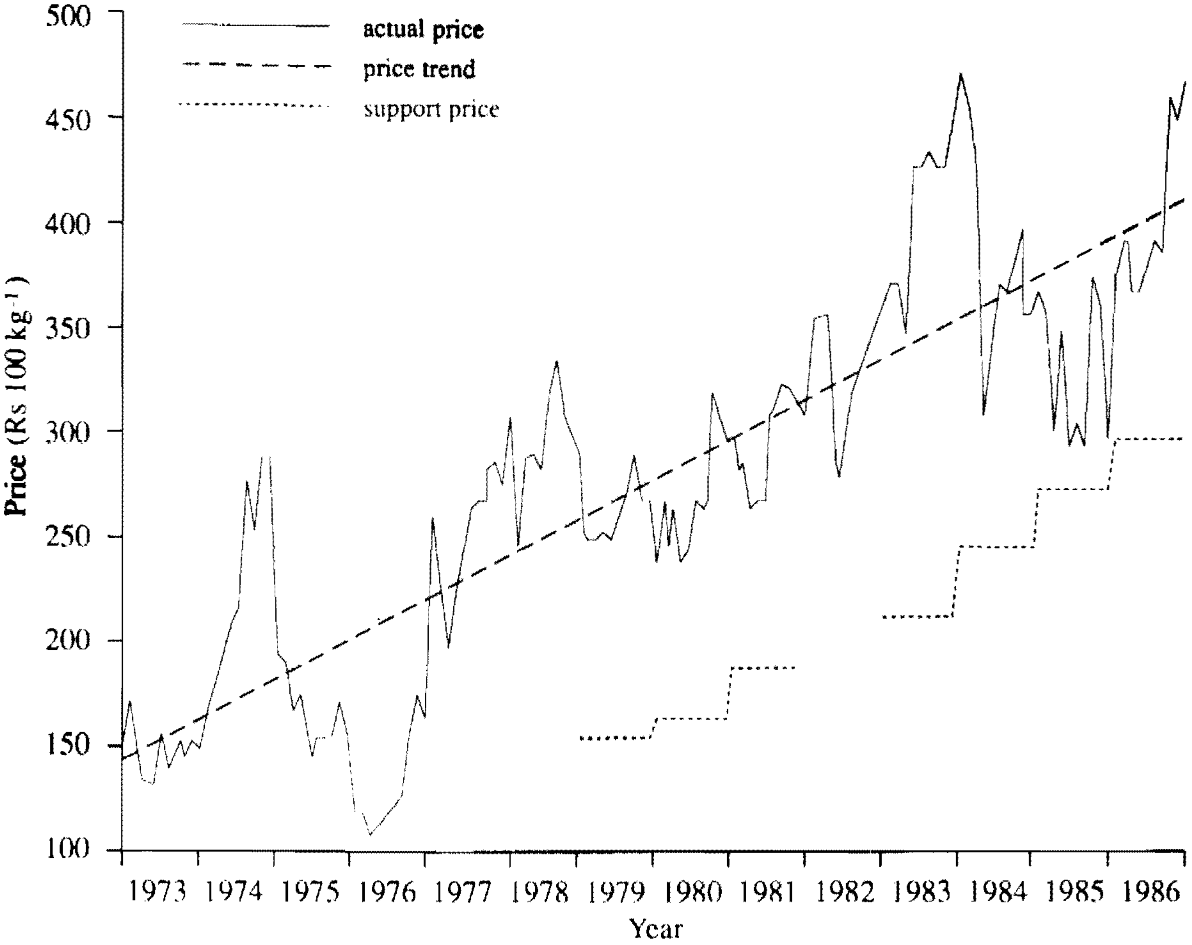


Figure 18.10. Pigeonpea actual prices and trend in Kanpur market, Uttar Pradesh, India, and support price, from Jan 1973 to Dec 1986.

Source: Government of India, Bulletin on Food Statistics (various issues).

level when they reach their peak in November, and are little more than 5% below the average in the trough in April (Figure 18.11).

Regional price levels are high in Tamil Nadu and Karnataka in the south of India, compared to prices in Madhya Pradesh further to the north. Price levels are believed to be lowest in Uttar Pradesh and Bihar (von Oppen, 1981). Seed colour, 100-seed mass, immature green seed, and broken seed are major quality characteristics affecting pigeonpea prices (von Oppen, 1978).

Estimates of price and income elasticities of demand are available for pulses but not for pigeonpea. Murty (1983) estimates income elasticities of demand for pulses ranging from 0.1 for urban consumers in the highest income group, to 1.8 for rural consumers with the lowest income. Chopra and Swamy (1975) estimate an elasticity of 0.6. Pigeonpea, like most pulses, may be on average considered a necessity, a luxury item for people with little money to spend, and an inferior item for people with high incomes.

Demand for pulses is price-inelastic with elasticity estimates ranging from -0.6 (Chopra and Swamy, 1975) to -0.9 (Murty and Parthasarathy Rao, 1987). The estimates can, at best, provide an upper bound (lower bound on the absolute value) of the price elasticity of demand for pigeonpea. Demand for pigeonpea is likely to be more price-elastic than demand for pulses, because there are more close consumption substitutes for pigeonpea than for pulses. Given the estimates for pulses, demand for pigeonpea can be expected to be price-elastic.

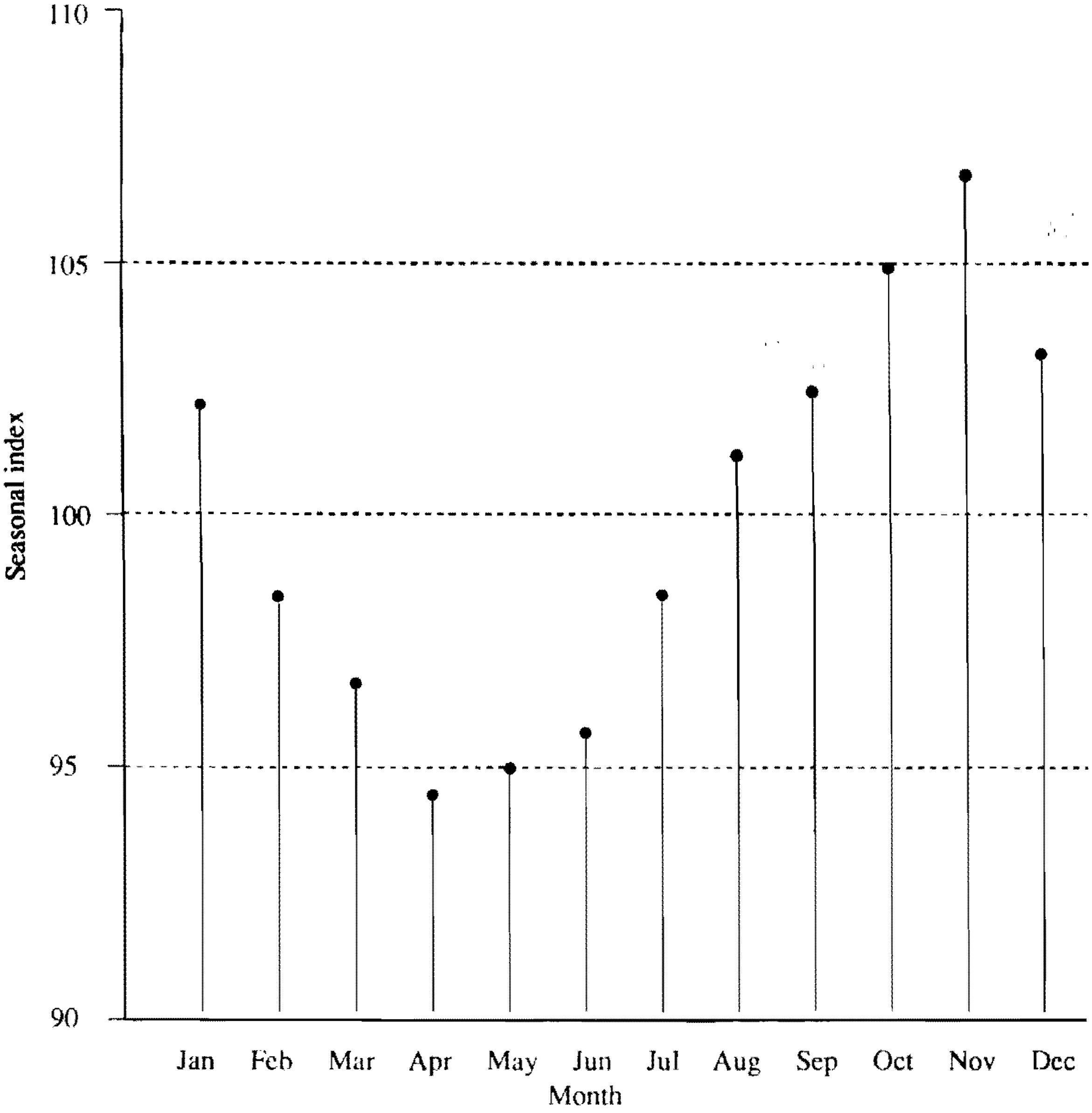


Figure 18.11. Multiplicative seasonal index of **pigeonpea** price at Kanpur, Uttar Pradesh, India, 1975–1986.

Marketing in India

Processing, Market Channels, and Price Determination

Pigeonpea dhal is the dominant form in which pigeonpea is sold to consumers, and the only form of processed pigeonpea marketed in India. Dhal is produced at a single stage in the market channel. Dhal yield varies with the size and technology of the mills. In small mills yields range from 50 to 80% with a mean of 62%; in large mills yields are higher with a mean of 71% and a range from 60 to 85% (Singh and Jambunathan, 1981). Processing pigeonpea yields three grades of dhal: 40-50% is of the best grade obtained from the first rolling, the second rolling yields 35-40% of the second grade dhal, and the lowest grade is the 10-15% obtained from immature, deformed, or damaged peas. Third grade dhal is not usually sold separately but mixed with second grade dhal (Kurien and Parpia, 1968). The processing cost of pigeonpea varies from Rs. 100 to 120 t^{-1}. The farmers' share in the consumer price varies with location, and estimates range from two-thirds (Bolaria, 1982) to three-quarters (von Oppen, 1981) of every rupee spent on dhal.

The channel for pigeonpea from producer to consumer is straightforward. Pigeonpea is sold directly by farmers in rural assembly markets, or to middlemen. Local dhal millers are either supplied by middlemen, or procure pigeonpea from local assembly markets. About 30% of the pigeonpea traded goes directly to local dhal mills (von Oppen, 1981). Wholesale traders supply dhal millers in urban centres from their procurements in assembly markets. Retailers distribute dhal from millers to consumers (Figure 18.12).

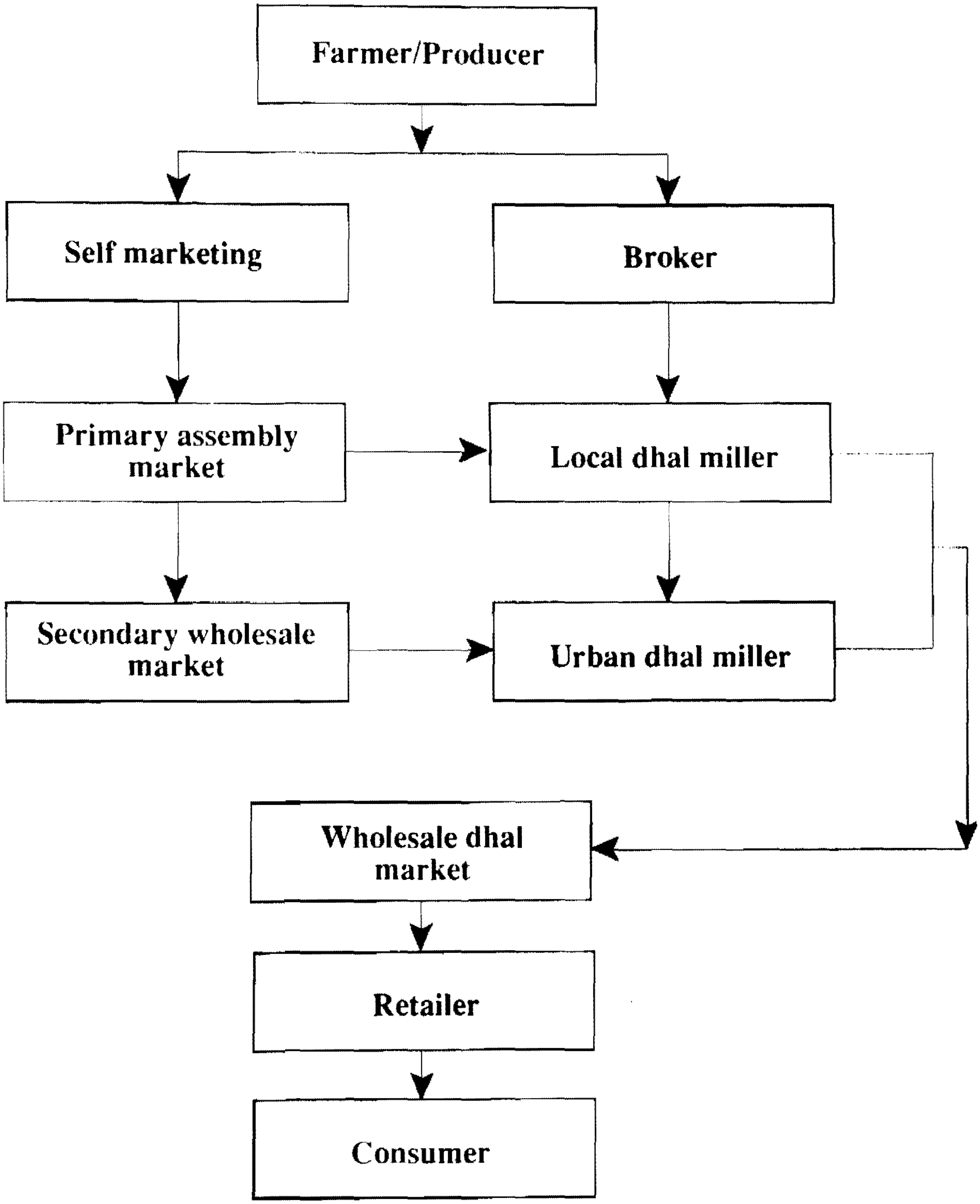


Figure 18.12. Marketing channels for pigeonpea in India.

In regulated assembly markets prices are determined in open, ascending-bid auctions for fully displayed lots. Lots are ungraded and their sizes vary. Buyers can inspect lots before auction. Sellers are not required to sell lots offered at auction, and may privately negotiate the sale of lots withdrawn from auction.

Storage Losses

Concern about inadequate storage facilities at the various market levels is not supported by broad estimates of storage losses of between 2-8% (Bolaria, 1982). A detailed survey of damage by Mookherjee *et al.* (1970), however, found that one-third of stored pigeonpea samples were damaged by insects. Salunkhe *et al.* (1986) point out that protein quality deteriorates in insect-infested stored pigeonpea.

Marketing Problems

Bolaria (1982) lists marketing problems for pulses. The list comprises complaints about redundant middlemen, prices plummeting after harvest, absence of grades and standards, and improperly planned production and procurement because "..information on area, production, price, farm retention, and marketable surplus are [sic] not available to the farmers".

By implication, these problems should also exist for pigeonpea. Evidence supporting the concerns is not available. However, comparison of dhal processing cost with the farmers' share in consumers' expenditure for dhal suggests a slim average profit margin for middlemen. Prices certainly vary during the season, but this seasonal variation is moderate; grades and standards may evolve spontaneously, and the costs of enforcing grades in a large number of small assembly markets may outweigh their benefits. Finally, it is the function of market prices to guide production, and farmers would have little use for statistics intended for national planners.

Product Innovation

No new pigeonpea products have penetrated consumer markets. The only perceptible innovation is dhal sold in polyethylene bags rather than out of the sack. Selling pre-packed dhal is, at this time, limited to the small supermarkets emerging in Indian cities.

Matanhelia (1981) recommends dehusking whole pigeonpea (gota) rather than splitting the cotyledons for dhal production. Dehusking would increase pigeonpea supply for consumption by 2-2.5% and processing cost could be reduced by 25%. Matanhelia (1981) acknowledges, however, that consumer acceptance is for split peas and gota is not a commonly marketed product.

DOMESTIC MARKETS IN THE REST OF THE WORLD

Australia, and Asia other than India

Pigeonpea is produced in Australia on a tiny scale. In 1987/88 Australia produced 1601 t valued at A$ 793,000 from 2975 ha (Australian Bureau of Statistics, personal communication). Most, or even all, of the pigeonpea is produced in Queensland, and the total pigeonpea area is equivalent to the size of one or two commercial farms in that state.

Suzuki and Konno (1982) conducted a mailed questionnaire survey of selected respondents in India, Nepal, Pakistan, Sri Lanka, Indonesia, the Philippines, Thailand, the People's Republic of China, Japan, and Republic of Korea. Only the respondents from India and Nepal reported pigeonpea production. The pigeonpea area in Nepal was 16,000 ha in 1976, or 4% of Nepal's area under grain legumes. Pigeonpea area had declined to 12,700 ha in 1983/84 producing some 4,800 t. Nearly all the pigeonpea is produced in the Terai region of Nepal (Khatiwada *et al.*, 1988). According to Bharati (1982), pigeonpea is frequently grown as a subsidiary crop on rice bunds in low-lying areas. The average pigeonpea area of farms surveyed by Khatiwada *et al.* (1988) was a minute 400 m^2 per household. Although average farm-household production is a meagre 31 kg, it exceeds the average annual household consumption of 29 kg. Marketing is organized by the private sector without government regulation, and most of the production is processed into dhal. Trade in assembly markets is in very small lots, as can be expected from the small quantities produced by individual farmers. At the primary market level traders assemble produce from farmers who do not meet the minimum lot size of 10 kg required by wholesale traders. Farmers receive about 50% of the consumer expenditure for dhal. Dhal mills in Nepal have a low capacity of only 60 bags of pigeonpea per day (Khatiwada *et al.*, 1988).

Pigeonpea production in Myanmar was 52,000 t from 77,000 ha harvested in 1985/86 (Wallis *et al.*, 1988). Pigeonpea accounts for about 14% of the area sown with major pulses, and for slightly less than 10% of Myanmar's pulse production. Pigeonpea is consumed locally, and is the pulse preferred by people of Indian and Nepalese origin. About 20% of pigeonpea production is exported. There are no reports on the domestic markets for pigeonpea. Given the central planning orientation of Myanmar's economy, and the importance of consumption in producing regions, the domestic market is bound to be economically insignificant.

West Indies

A viable pigeonpea industry is reported from the Dominican Republic (Mansfield, 1981). The industry was created when the pigeonpea canning industry from Puerto Rico was moved to the Dominican Republic to take advantage of lower taxes and labour costs. The industry is driven by export demand for canned pigeonpea from Latin American emigrants to the USA. Close to 80% of the national crop is exported.

Pigeonpea is mostly grown on small farms of less than 2 ha farm size. In 1976 pigeonpea area was close to 14,000 ha yielding on average some 2 t ha^{-1}. More than 60% of production is processed into canned pigeonpea, about 15% is sold as mature, green, fresh peas, and negligible quantities are frozen. Market intermediaries assemble the crop from producers and sell to agents of pigeonpea canners. Canners sell forward to distributor-wholesalers who often sell canned peas under proprietary brand names.

Domestic consumption of pigeonpea is not widespread in the Dominican Republic. Only about 8% of the households surveyed by Tufts University consumed dried pigeonpea, about 26% ate green pigeonpea, and average daily consumption per caput of consuming households was 13 g of green peas. Demand for green pigeonpea is price-inelastic with a price elasticity of -0.9 (A. Swindale, personal communication).

Faris (1982), reports from other parts of the Caribbean islands widespread consumption of pigeonpea as a green vegetable. Here, as in eastern Africa, sizable concentrations of ethnic Indian populations, particularly in Trinidad and Guyana, have stimulated the evolution of markets for pigeonpea dhal.

Eastern Africa

Pigeonpea is produced in eastern Africa on an area of uncertain size. Kay (1979) wrote: "..it is generally accepted that reported production figures for many African countries could be low by a factor of two or three times, since the crop is grown extensively in village compounds and kitchen gardens...but the crop is not reported". The situation has not changed much since then. The best evidence available are reports of travelers interested in pigeonpea, such as Faris (1981). The picture that emerges from their travel reports is that pigeonpea is widely produced in household gardens for home consumption, or occasionally grown as a cash crop for dhal mills supplying the local ethnic Indian population. The travel reports do not, however, contain information on pigeonpea markets.

INTERNATIONAL TRADE IN PIGEONPEA

The quantity of pigeonpea internationally traded is insignificant and trade statistics are incomplete. For example, the Australian Bureau of Statistics does not keep separate statistics for pigeonpea because the International Harmonised Classification groups all dry peas together (Australian Bureau of Statistics, personal communication). During the years 1976-1978 about 3,200 t of pigeonpea were internationally traded. Out of every 625 t of pulses traded during that period only one was pigeonpea (Kim, 1982).

The main reason for the virtual absence of trade in pigeonpea was that India, the main producer and consumer of pigeonpea, trades only in very small quantities. Incomplete records indicate that there were some pigeonpea exports, that never exceeded 5,000 t year^{-1}, from India in the period 1966-1975. The countries of destination were Malaysia, UK, Singapore, Bahrein, and Nepal (Kay, 1979). India imported small quantities of pigeonpea in the period 1981-1986 from Nepal, Myanmar, and, more recently Australia (Table 18.4).

Table 18.4. Indian[1] imports of total pulses, and pigeonpea by country.

Year	Total pulses	Pigeonpea						Pigeonpea as % of total pulses
		Nepal	Myanmar	Tanzania	Australia	Thailand	Total	
1981/82	128 066	1122	-	-	-	-	1122	0.88
1982/83	91 055	118	1243	-	-	-	1361	1.37
1983/84	227 929	194	1297	164	-	-	1655	0.73
1984/85	235 390	-	1788	-	420	85	2293	0.97
1985/86	431 441	411	4146	-	1173	-	5730	1.33

1. All quantities in t.

Source: Directorate General of Commercial Intelligence and Statistics (various issues 1981-1986).

Nepal's trade in pigeonpea, most or all with India, is only partially reported. Reported net exports were 386 t in 1983/84, and in 1984/85 net imports were 287 t (Khatiwada *et al.*, 1988). Bharati (1982) notes that pigeonpea was also exported to the Peoples Republic of China, but that records were not kept. Malawi is said to have exported pigeonpea dhal, and Kenya has exported some canned pigeonpea (Faris, 1981). Myanmar exported 10,000 t of pigeonpea to India and Singapore in 1985/86. In earlier years Myanmar's pigeonpea exports were as high as 30,000 t year^{-1}. The export price was approximately US$ 330 t^{-1} free on board Rangoon in 1985/86. In the past, Myanmar's pigeonpea exports were mostly as dhal sold at prices of up to US$ 700 t^{-1}, but now pigeonpeas are exported whole (Wallis *et al.*, 1988). Export is the driving force for pigeonpea production in the Dominican Republic, and exports of canned pigeonpea to the USA account for between 65-80% of the national crop (Mansfield, 1981; Faris, 1982).

OUTLOOK

The capacity to look into the future of pigeonpea markets is commensurate with the availability of facts for assessing the probabilities of future market developments. There are not enough facts available for most pigeonpea markets to confine speculation to probable directions, and we limit our outlook to the markets in India, Indonesia, and Thailand.

India

The pigeonpea market in India is well established, largely free from government intervention, and has been unexciting. Pigeonpea production in India is likely to increase considerably with the advent of high-yielding, short-duration cultivars, and with increasing subsistence demand for biomass. Optimistic Delphi-estimates by scientists of grain yield potentials in the year 2000 predict an increase of about 70% over levels in the early 1980s (von Oppen and Subba Rao, 1985). Increases in demand for pigeonpea dhal from population increase and income growth will be of a similar order of magnitude. Imbalances between growth in pigeonpea production and demand for pigeonpea dhal will have no substantial effect on consumer prices if the price-elasticity of demand is about unity. The effect of market imbalances on producer income will be even smaller, because only about one third of production is marketed.

The most significant characteristic of the pigeonpea market in India is the exclusive reliance on a single consumer product, dhal, and the absence of market penetration by any innovative product. The economic conditions in India may explain the absence of product innovation in some part. Innovating entrepreneurs must be stimulated by profit opportunities. To reap the benefits from product innovation an entrepreneur must establish a product with a brand name recognizable on retailers' shelves, and the product must be promoted through advertizing. The tasks are difficult to accomplish, and their outcome would have been extremely risky in an economy that used to be heavily regulated, where the retail sector was dominated by specialized traders in generic products, which had only a nascent network of national mass media, and where quality control (a precondition for brand names) is less than perfect.

The other condition that may have prevented product innovation is the perception of pigeonpea as a source of protein, particularly for low-income groups. Entrepreneurs innovate with market purchasing-power in mind, not just numbers of people. But even if some entrepreneur had been enticed to develop a new protein-rich pigeonpea product, the product would most likely have flopped because there is no shortage of protein, not even in the diets of many poor people.

Finally, the nutrient composition of pigeonpea is not conducive to pigeonpea being used as a component in a composite food product. Pigeonpea contains a bit of everything except fat, but it contains no single nutrient, not even protein, in exceptionally high concentration. Whenever pigeonpea is blended for some of its nutrients, it also contributes significant quantities of other nutrients, which may add no or little value to the composite product.

Does all this mean that the future for pigeonpea will remain in dhal alone? Not necessarily. The economic conditions of consumer markets are rapidly changing and are already conducive to the introduction of innovative products by entrepreneurs not blinded by pigeonpea's image as a cheap source of protein. The emergence of innovative products will largely depend on whether some entrepreneur will get permission to produce a pigeonpea food product that; 1. overcomes the compositional disadvantage of pigeonpea, 2. exploits consumers' familiarity with tur, and 3. contributes to food variety. The challenge is formidable, and the pigeonpea markets in India will still be dominated by demand for dhal for some time to come.

Rest of the World

Pigeonpea for Broiler Feed in Thailand

Pigeonpea is not presently grown as a field crop in Thailand. Wallis *et al.* (1988) after a tour of Thailand in 1985, suggested that short-duration, photoperiod-insensitive pigeonpea could be grown in northeastern Thailand on more than 100,000 km^2, and be used as a substitute for soybean meal in feed for broilers exported to Japan by the well-developed industry for boneless, frozen chicken meat. Research in the interim has shown that pigeonpea can be successfully grown in the suggested environment, and feed mixers in Thailand could incorporate ground pigeonpea into chicken feed. Finally, broiler-feeding experiments suggest that pigeonpea should not exceed 30% in broiler diets, and that edible oil must be added to compensate for the lack of fat in pigeonpea (Tangtaweewipat and Elliott, in press). With the feasibility of pigeonpea production and use assured, the viability of a pigeonpea industry in Thailand will depend on whether the production niches in the farming systems of the northeastern region, and the niches for pigeonpea in the market for chicken feed will be large enough to sustain each other.

Pigeonpea's niche in the farming system will be constrained by the area occupied by rice, because of the extraordinary status of rice as a food crop. Break-even analysis of rapidly assembled statistics on production costs and returns indicated that pigeonpea is unlikely to be able to compete with cassava, the most important cash crop in the northeastern region. Furthermore, the profitability of pigeonpea production will rapidly erode if the crop needs several insecticide applications (Mueller *et al.*, 1989).

The size of the market niche for pigeonpea will depend on the size of the industry for chicken meat, and the competitiveness of pigeonpea against soybean meal. Thailand's chicken exports have grown impressively. The industry began exporting chicken to Japan in 1973 when a modest 142 t were shipped. Since then exports have grown to an estimated 95,000 t in 1987. Earnings from chicken exports have grown nearly twenty-fold in the period 1977-1986 and are believed to have reached Bt 6 billion (US$ 243 million) in 1987 (Sricharatchanya, 1988).

The profitability of substituting pigeonpea for soybean meal will crucially depend on the availability of soybean meal in Thailand, and on the world market prices for soybean meal and edible oils. Domestic production of soybean in Thailand has more than trebled in the period 1977/78 to 1986/87 and is expected to reach one million t in 1995 (Sriplung, 1987). Domestic demand for soybean and soybean products far outstrips domestic production, and 48% of the total average domestic supply of some 576,000 t of bean equivalent was imported during 1984-1986. Domestic demand is, however, not expected to grow so quickly as domestic production. Soybean imports, that have increased twenty-fold in the decade beginning in 1976, are expected to have peaked in 1987, and self-sufficiency in soybeans is projected for the year 1995 (Sriplung, 1987).

A new-born pigeonpea industry in Thailand will therefore have a tenuous production-foothold in the northeast, and faces an uphill struggle against the better-established and growing domestic soybean industry. A pigeonpea industry is unlikely to become established and overcome the initially high costs of small scale production if either soybean prices are low, or edible oil prices high, or both, in the near future.

Market Potential for Pigeonpea in Indonesia

Pigeonpea has been grown in Indonesia as a minor crop in back-yard gardens and on field bunds since the 18th Century. Traditionally, pigeonpea is grown in the eastern islands, and in Java for green pods or green seeds that are used in various vegetable dishes. Although pigeonpea has been known to farmers for a long time, field cropping of pigeonpea for dry seed production has not yet evolved in Indonesia.

Trials with determinate pigeonpea cultivars of short-duration and stature in Java, Sumatra, Sulawesi, and Bali have confirmed that pigeonpea has a grain-yield potential of up to 3.3 t ha^{-1} at suitable locations in Indonesia. However, lack of market demand is one of the factors believed to constrain adoption of pigeonpea by farmers. Pigeonpea could serve as a substitute for soybean in indigenous food preparations, and in broiler chicken rations.

Pigeonpea in Indigenous Indonesian Food Preparations

Pigeonpea can be substituted, partially or wholly for soybean in tempe and soysauce production, and it has been added to rice snacks. In organoleptic tests with laboratory staff, pigeonpea soysauce was ranked at the same level as a popular brand. Adding pigeonpea flour increases protein content and improves the texture of rice snacks, but colour, flavour, and appearance deteriorate. Both these innovative uses of pigeonpea are presently pursued with only a marginal research effort.

A considerable market potential for pigeonpea lies in tempe production. Tempe is a fermented soybean product that is widely consumed in east Java. Tempe produced from a pigeonpea-soybean mixture may not be rated by consumers as equally palatable as pure soybean tempe. Furthermore, the processing costs of tempe will increase when pigeonpea is added. Pigeonpea tempe has, at this time, only been produced in laboratories. The perceptions and attitudes toward mixed pigeonpea-soybean tempe of commercial tempe producers, either housewives who produce tempe part-time, or small factories, are not known.

A sizable demand for pigeonpea for use in tempe production will evolve if; prices paid for pigeonpea can absorb the tempe price discount that may be necessary to compensate for the lower quality of mixed pigeonpea-soybean tempe, or if soybean was rationed and tempe producers had to stretch limited soybean supplies with pigeonpea.

Pigeonpea would most likely be produced on the eastern islands of Indonesia where local demand from tempe producers may not assure uptake of the crop. The decisive question will be what prices pigeonpea might fetch in soybean-deficit regions, and how these prices would translate into assembly market prices in potential producing regions. Domestic soybean prices in Indonesia are about double world market prices to support domestic soybean growers. An infant pigeonpea industry would benefit from this price support. Transport from producing to consuming regions will be considerable, and will create a large spread between prices paid by tempe producers and received by pigeonpea growers. Inefficiencies in the pigeonpea market are not expected, since rural assembly markets closely approach the ideal of effective market competition (Hayami *et al.*, 1987).

Pigeonpea for Chicken Feed: Experiences from Thailand

Given the homogeneity of chicken breeding stocks and chicken production technologies, the experiences with pigeonpea as chicken feed from Thailand appear to be directly transferable to Indonesia. But market conditions in the two countries differ. The feed industry in Indonesia has to operate under different market constraints and regulations from the Thai industry. The constraints and regulations may affect the milling technologies used, and their scale of operations. Furthermore, Indonesian broiler producers do not have a developed high-price export market for boneless, frozen chicken. Indonesia is at this time conducting feeding trials with pigeonpea and it is too early to assess the potential demand for pigeonpea from the chicken industry.

REFERENCES

Behrman, J.R., Deolalikar, A.B. and Wolfe, B.L. (1988) Nutrients: impacts and determinants. *World Bank Economic Review* 2, 299-320.

Bharati, M.P. (1982) Nepal. In: *Grain Legumes Production in Asia.* Asian Productivity Organization, Tokyo, pp. 449-472.

Bidinger, P.D. and Nag, B. (1981) The role of pigeonpeas in village diets. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 357-364.

Bolaria, T.S. (1982) India. In: *Grain Legumes Production in Asia.* Asian Productivity Organization, Tokyo, pp. 297-356.

Buchanan, J.M. (1964) What should economists do? *Southern Economic Journal* 30, 213-222.

Chopra, K. and Swamy, G. (1975) *Pulses: An Analysis of Demand and Supply in India 1951-1971.* Institute for Social and Economic Change (Bangalore, India), Monograph 2. Sterling Publishers, New Delhi, India, 132 pp.

Directorate General of Commercial Intelligence and Statistics (1986) *Monthly Statistics of Foreign Trade.* Ministry of Commerce, New Delhi, India (various issues from 1981 to 1986).

FAO (1987) The world pulse economy. Commodity review and outlook, 1986-87. *FAO Economic and Social Development Series* no. 43. FAO, Rome, pp. 111-125.

Faris, D.G. (1981). Tour of pigeonpea areas in eastern and southern Africa (Kenya, Malawi, Zambia and Tanzania), 8-26 July, 1981. Patancheru, A.P., India: Legumes Program, ICRISAT, 18 pp. (Limited distribution).

Faris, D.G. (1982). Tour of the Caribbean Islands and Mexico, 19 November-14 December, 1982. Patancheru, A.P., India: Legumes Program, ICRISAT, 47 pp. (Limited distribution).

Gopalan, C., Rama Sastri, B.V. and Balasubramanian, S.C. (1971) *Nutritive Value of Indian Foods.* National Institute of Nutrition, Hyderabad, India, 204 pp. (reprinted).

Government of India (Ministry of Agriculture) (1986) *Area and Production of Principal Crops in India.* Ministry of Agriculture, Government of India, New Delhi, India (various issues from 1960 to 1986).

Government of India (Ministry of Agriculture) (1986) *Bulletin on Food Statistics.* Directorate of Economics and Statistics, Ministry of Agriculture, Government of India, New Delhi, India (various issues from 1960 to 1986).

Hayami, Y., Kawagoe, T., Morooka, Y. and Siregar, M. (1987) *Agricultural Marketing and Processing in Upland Java: A Perspective from a Sunda Village. CGPRT no. 8.* Bogor, Indonesia: CGPRT Centre.

Hayek, F.A. (1945) The use of knowledge in society. *American Economic Review* 35(4), 519-530.

Kay, D.E. (1979) *Crop and Product Digest no. 3–Food Legumes.* Tropical Products Institute, London, pp. 322-347.

Kahlon, A.S. and George, M.V. (1985) *Agricultural Marketing and Price Policies.* Allied Pubishers, New Delhi, India, 283 pp.

Khatiwada, M.K., Poudel, S.K. and Gurung, D.K. (1988) *Socio-economic Constraints to Pulse Production in Nepal. CGPRT no. 18.* Bogor, Indonesia: CGPRT Centre, 90 pp.

Kim, S.K. (1982) Trends in demand and supply of pulses in the ESCAP region. In: *Grain Legumes Production in Asia.* Asian Productivity Organization, Tokyo, pp. 95-112.

Kirzner, I.M. (1973) *Competition and Entrepreneurship.* Chicago University Press, Chicago, USA.

Kurien, P.P. and Parpia, H.A.B. (1968) Pulse milling in India I–Processing and milling of tur, arhar (*Cajanus cajan* Linn.). *Journal of Food Science and Technology* 5, 203-207.

Lancaster, K. (1971) *Consumer Demand.* Columbia University Press, New York, NY, USA.

Mansfield, G.R. (1981) Processing and marketing of green pigeonpeas: the case of the Dominican Republic. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 344-450.

Matanhelia, K.G. (1981) Commercial dhal milling in India. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India.* Patancheru, A.P., India: ICRISAT, pp. 329-331.

Menger, C. (1981) Principles of economics. Translation by J. Dingwall and B.F. Hoselitz of

Grundsaetze der Volkswirthschaftslehre (no more published). New York University Press, New York, NY, USA.

Mookherjee, P.B., Jotwani, M.G., Yadav, T.D. and Sircar, P. (1970) Studies on incidence and extent of damage due to insect pests in stored seeds–II. Leguminous and vegetable seeds. *Indian Journal of Entomology* 32, 350-355.

Mueller, R., Virakul, P. and Troedson, R. (1989) Pigeonpea in Northeast Thailand: In search of production niches. *ACIAR Food Legume Newsletter* 10, 2-4.

Murty, K.N. (1983) Consumption and nutritional patterns of ICRISAT mandate crops in India. *Economics Program Progress Report no. 53*. Patancheru, A.P., India: Resource Management Program, ICRISAT, 27 pp. (Limited distribution).

Murty, K.N. and Parthasarathy Rao, P. (1987) India's food grain surplus: a demand-supply policy simulation. *Economics Group Progress Report no. 81*. Patancheru, A.P., India: Resource Management Program, ICRISAT, 51 pp. (Limited distribution).

Ryan, J.G., Bidinger, P.D., Prahlad Rao, N. and Pushpamma, P. (1984) *The Determinants of Individual Diets and Nutritional Status in Six Villages of Southern India. Research Bulletin no. 7.* Patancheru, A.P., India: ICRISAT, 140 pp.

Salunkhe, D.K., Chavan, J.K. and Kadam, S.S. (1986) Pigeonpea as an important food source. *CRC Critical Reviews in Food Science and Nutrition* 23(2), 103-145.

Shah, C.H. (1980) Food preferences and nutrition: a perspective on poverty in less developed countries. *Indian Journal of Agricultural Economics* 35, 1-39.

Sharma, D. and Jodha, N.S. (1982) Pulses production in the semi-arid regions of India–constraints and opportunities. *Economic and Political Weekly* 17, A135-A148.

Singh, U. and Jambunathan, R. (1981) A survey of the methods of milling and consumer acceptance of pigeonpeas in India. In: *Proceedings of the International Workshop on Pigeonpeas, volume 2, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 419-425.

Sricharatchanya, P. (1988) Not just chicken feed. A Thai agribusiness multinational grows by leaps and bounds. *Far Eastern Economic Review* 139(9), 58-59.

Sriplung, S. (1987) Policy on soybean self-sufficiency. *Agricultural Economics Report 56/2530*. Office of Agricultural Economics, Ministry of Agriculture and Cooperatives, Bangkok, Thailand (in Thai).

Sukhatme, P.V. (1987) Poverty and malnutrition. *Economic and Political Weekly* 22, 83-84.

Suzuki, F. and Konno, S. (1982) Regional report on grain legumes production in Asia. In: *Grain Legumes Production in Asia*. Asian Productivity Organization, Tokyo, pp. 15-93.

Tangtaweewipat, S. and Elliott, R. (in press) Nutritional value of pigeonpea *(Cajanus cajan)* meal in poultry diets. *Animal Food Science and Technology*.

United Nations (1988) *Demographic Year Book 1986*. Department of International Economic and Social Affairs, Statistical Office, United Nations, New York.

von Oppen, M. (1978) An attempt to explain the effects of consumers' quality preferences on prices of food grains at different levels of productivity. *Economics Program Discussion Paper no. 8*. Patancheru, A.P., India: Resource Management Program, ICRISAT, 11 pp. (Limited distribution).

von Oppen, M. (1981) Marketing of pigeonpeas in India. In: *Proceedings of the International Workshop on Pigeonpeas, volume 1, 15-19 December 1980, ICRISAT Center, India*. Patancheru, A.P., India: ICRISAT, pp. 332-343.

von Oppen, M. and Subba Rao, K.V. (1985) Yields of mandate crops projected by ICRISAT scientists. *Economics Program Progress Report no. 69*. Patancheru, A.P., India: Resource Management Program, ICRISAT, 26 pp. (Limited distribution).

Wallis, E.S., Woolcock, R.F. and Byth, D.E. (1988) *Potential for Pigeonpea in Thailand, Indonesia and Burma. CGPRT no. 15*. Bogor, Indonesia: CGPTR Centre, 74 pp.

Index

The Pigeonpea

Edited by Y.L. Nene, Susan D. Hall, and V.K. Sheila, International Crops Research Institute for the Semi-Arid Tropics, India

Pigeonpea is one of the major grain legumes (pulse) crops of the tropics and subtropics. It has an important place in the farming systems adopted by many smallholder farmers in a large number of developing countries, including India, Myanmar (formerly Burma), Kenya, Malawi, Uganda and several countries in Central America. Although ranking sixth in area and production in comparison to other grain legumes such as beans, peas and chickpeas, pigeonpea is used in more diverse ways. Besides its main use as dhal, its green seeds are used as a vegetable, crushed dry seeds as animal feeds, green leaves as fodder, and stems as fuel wood and to make huts, baskets etc.

This book represents a comprehensive volume on pigeonpea and is written by leading scientific research workers on the subject, most of whom are based at or have been associated with the International Crops Research Institute for the Semi-Arid Tropics, the world's principal research institute for work on this crop. Topics covered include: geography and importance; origin, history and taxonomy; morphology and cytology; genetics, breeding and genetic resources; physiology and adaptation; mineral nutrition and nitrogen-fixation; agronomic management and cropping systems; pest and disease management; pigeonpea products, marketing and trade. The volume should therefore represent the standard reference work on this subject.

ISBN 0 85198 657 9

C·A·B International

Headquarters: Wallingford, Oxon OX10 8DE, UK *Tel*: (0491) 32111. *Fax*: (0491) 33508

North America: 845 North Park Avenue, Tucson, Arizona 85719, USA *Tel*: 800/528-4841. *Fax*: 602/621-3816

Asia: PO Box 11872, 50760 Kuala Lumpur, Malaysia *Tel*: (03) 255 2922. *Fax*: (03) 255 1888