

CULTURE

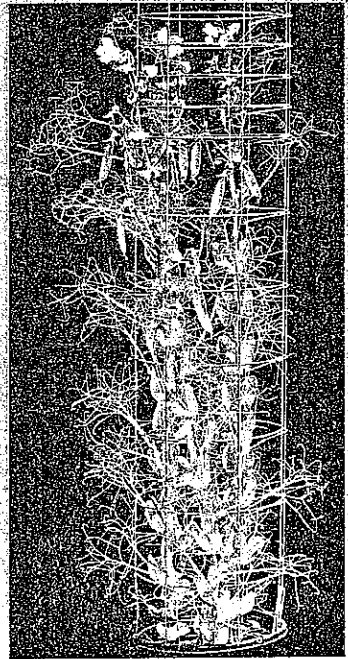
utilizing landmark research, **Genetic Resources, Chromosome Engineering, and Crop Improvement: Legumes, Volume 1** furnishes information on the availability of germplasm resources that breeders can use for producing high-yielding varieties. Written by an internationally renowned and innovative panel of experts, the book offers the most comprehensive and up-to-date information on genetic resources and their utilization for increasing the yield of the most widely grown and consumed grain legumes.

It consolidates information on germplasm resources, cytogenetic manipulation, and the breeding of grain legumes.

It presents methodologies for crop improvement, discusses the current status of taxonomy, genomic and chromosomal constitution, and geographical distribution of economically important grain legumes and their allied species.

It provides extensive literature citations in each chapter.

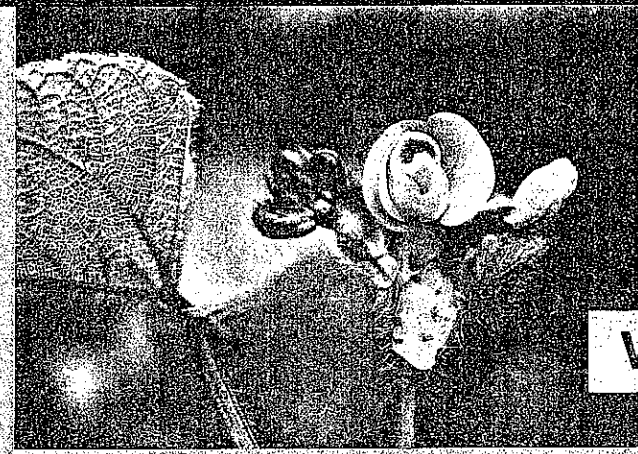
Even in succinct chapters, **Genetic Resources, Chromosome Engineering, and Crop Improvement: Legumes** focuses on the common bean, pea, mung bean, cowpea, faba bean, chickpea, lentil, lupin, pigeon pea, and azuki bean. Discussions for each crop begin with a brief introduction and then provide comprehensive information on the origin, genetic resources, cytogenetics, and improvement strategies by conventional, chromosome-engineering, and molecular breeding methods. Primary (GP-1), secondary (GP-2), and tertiary (GP-3) gene pools for a crop are identified and their use in producing high yielding varieties with resistance to several biotic and abiotic stresses are described as well. This book will benefit plant breeders, agronomists, cytogeneticists, taxonomists, molecular biologists, biotechnologists, graduate students, and researchers in these fields.



SINGH
JAUHAR

GENETIC RESOURCES, CHROMOSOME ENGINEERING,
AND CROP IMPROVEMENT: Grain Legumes, Volume 1

GENETIC RESOURCES, CHROMOSOME ENGINEERING,
AND CROP IMPROVEMENT SERIES



Volume 1

GENETIC RESOURCES, CHROMOSOME ENGINEERING, AND CROP IMPROVEMENT

Grain Legumes



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Taylor & Francis
Taylor & Francis Group

A CRC PRESS BOOK



CHAPTER 4

Pigeonpea [*Cajanus cajan* (L.) Millsp.]

K.B. Saxena

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Table 4.1 Regional Area, Production, Yield, and Compound Growth Rates of Pigeonpea

Region	1988-1990 Average			Compound Growth Rates (1970-1990)		
	Area (000 ha)	Production (000 t)	Yield (t ha ⁻¹)	Area (%)	Production (%)	Yield (%)
India	3555	2619	0.74	2.01	2.34	0.33
Other Asia	84	56	0.66	0.46	3.14	2.68
Africa	273	167	0.61	0.97	1.59	0.62
Latin America and Caribbean	62	46	0.74	1.58	-0.82	-2.40
World	3974	2888	0.73	1.88	2.25	0.37

Source: Adapted from Ryan (1996).

4.1 INTRODUCTION

Pigeonpea [*Cajanus cajan* (L.) Millsp.] occupies an important place among grain legumes due to its ability to grow under diverse cropping systems and environments and to recover from the losses caused by various biotic and abiotic stresses. The estimated global area of pigeonpea is more than 4 m ha, and the major pigeonpea growing countries are India, Myanmar, Nepal, Kenya, Malawi, Uganda, and Tanzania (Table 4.1). According to Ryan (1997), the global pigeonpea production trends largely reflect the situation in India, where area and production growth trends exceeded 2% a year⁻¹ from 1970 to 1990.

In most breeding programs, besides increasing yield potential, the research has centered on understanding and alleviating important biotic and abiotic stresses. A significant breakthrough has been the shortening of maturity duration of the crop from the traditional 6 to 9 months to less than 3 months, which helps in the diversification of cropping systems. Besides protein-rich food, this environment-friendly crop also provides much needed fodder and fuel wood in the dry areas. Its cultivation over a period helps in improving the soil fertility (Kumar et al., 1983) and its structure. Roots help in releasing soil-bound phosphorus (Ae et al., 1988) and make it available to the crop plants. Therefore, considering its ability to perform in diverse environments and systems and multiple-uses, pigeonpea appears to have a great potential in the tropics and semi-arid tropics of the world.

4.2 ORIGIN AND DISTRIBUTION

There are two opposing views on the center of origin of pigeonpea — one favors India, and another Africa. Considering the presence of a vast natural genetic variability in pigeonpea and presence of its wild relatives in the region, van Rheede (1686), Linnaeus (1737), and De (1974) supported an Indian origin. Recent excavation of pigeonpea seeds dated from the second century BC to the third century BC in India (Kajale, 1974) further strengthen this view. On the contrary, based on the exclusive distribution of *Arylosia kerstingii* Harnes, a wild relative of pigeonpea in Africa, and the reported discovery of a pigeonpea seed in Egyptian tombs of the XII Dynasty (2200 to 2400 BC) at Dra Abu-Negga led Zeven and Zhukovskiy (1975) and Brucher (1977) to support the African origin.

A wild relative of pigeonpea, (*C. cajanifolius*), which resembles pigeonpea in all morphological traits except the presence of a prominent strophiole, is considered to be the vital single-gene link between the cultivated and wild forms of pigeonpea (De, 1974). van der Maesen (1980) collected and identified *C. cajanifolius* in the forest of Central India. This important discovery has further strengthened the view that India is the native home of pigeonpea. Based on the genetic diversity within various species, he further concluded that (1) pigeonpea originated in India, (2) Africa is a

secondary center of origin, and (3) Australia is an important center of diversity. The "Indian origin" theory has the most adherents and believes that the crop would have gone from India to Africa and Madagascar at least two millennia BC and to the new world along with the slave trade in post-Columbian time (De, 1974). It is also postulated that pigeonpea moved from India via the Malay Archipelago to Indo-China and Australia.

4.3 TAXONOMY AND NOMENCLATURE

The first scientific name to pigeonpea, *Arbor trifolia indica*, was given by Bauhin and Cherla between 1650 and 1651 (van der Maesen, 1986), and the first binomial nomenclature to pigeonpea, *Cytisus cajan*, was given by Linnaeus (1753). *Cajanus indicus*, *C. flavus*, and *C. bicolor* are other binomials found in early literature. According to the International Rules of Botanical Nomenclature, the name finally adopted for pigeonpea is *Cajanus cajan* (L.) Millspaugh. Pigeonpea has been classified in tribe Phaseoleae, subtribe Cajaninae, family Poaceae (Leguminosae), genus *Cajanus*, and species *cajan*. Within subtribe Cajaninae, there are 13 closely related genera, and among these, *Cajanus*, the only cultivated genera, was always considered to be genetically related to one of the wild type *Arylosia*. The genus *Arylosia* W. & A. consists of 34 species, and they contribute to the secondary or tertiary gene pool. At International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), van der Maesen (1986) studied *Cajanus* and *Arylosia* genera and, based on various morphological, cytological, and chemo-taxonomical data, merged genus *Arylosia* into *Cajanus*. Consequently, the subtribe Cajaninae now contains 12 genera, and pigeonpea is the only cultivated food crop of this tribe.

According to De (1974), the popular Indian names of pigeonpea have been derived from the Sanskrit language, and *Adhuki* or *Adhuka* became 'Arhar', while *Tuvarai* or *Tuvari* was later called *Tuar* or *Tur*. Some other names popular in different countries are 'Katjang' (Malaysia), 'Cguando' (Brazil), 'Gandolu' (Puerto Rico), 'Gungo' and 'Congo pea' (Jamaica), 'Quinchoncho' (Venezuela), 'Pois de Congo' (Africa), 'Kandulu' (southern India), 'Thora parippu' (Sri Lanka), and 'Mu dau' (China). It is called "red gram" or "pigeonpea" in English. The present-day internationally popular English name of this crop, pigeonpea, was coined by Plukenet (1692) in Barbados, where the crop was grown in barren lands primarily for feeding pigeons.

4.4 GENERAL BOTANY

Two prominent flowering habits, determinate and nondeterminate, are recognized in pigeonpea. In the determinate type, the apical bud of main shoot transforms into inflorescence, the flowering is more or less synchronous, and the flowers are borne in clusters at the top of a canopy. In the nondeterminate type, the apical bud is vegetative, and the floral clusters are borne in axillary racemes spread over considerable lengths of stem and branches. In the germplasm collection at ICRISAT, the number of days to maturity ranges from 85 to more than 280. Flowers of pigeonpea are predominantly yellow in color, with red streaks on the petals. Peduncles are 10 to 80 mm long. The pedicels are thin, 7 to 15 mm long, and covered with fine hairs. Bracts are 1 to 4 mm long, with a thick middle nerve and margins curved inward to form a boatlike structure. The calyx tube is campanulate with glandular hairs and bulbous base, about 5 mm long, with 5 subequal triangular lobes. The corolla is highly zygomorphic. The petals are imbricate in the bud. The standard petal is either erect or spreading. Wing petals are obovate, 15 to 20 mm long, and about 6 to 7 mm wide. Keel petals are boat-shaped, glabrous, and split dorsally. Stamens are 10, diadelphous, 15 to 18 mm long, flattening toward the base and tapering toward the top. Anthers are ellipsoid, about 10 mm long, dorsified and yellow in color. The ovary is superior, 5 to 8 mm long, sessile, densely pubescent, with 2 to 9 ovules. The stigma is capitate and glandular-papillate. The style is 10 to 12

mm long, filiform, and glabrous. The mature pollen grains are three-colporate with areolate orientation (Reddy, 1990). In nondeterminate pigeonpea, flowering extends for a few weeks, and thousands of flowers are produced, of which only about 10% set pods (Pathak, 1970). Fertilization occurs on the day of pollination and seeds mature about 40 to 50 days after pollination. In the first three weeks after fertilization, the pod wall grows more rapidly than the young seeds. The pod walls are known to contain various tannins. The ovules are arranged on a marginal placenta of the single carpel ovary. In each raceme, about 1 to 5 pods are formed. The pods of most pigeonpea varieties are oblong, straight, or sickle-shaped; laterally compressed; green when young; straw-colored when ripe; and are often streaked to various degree with purple. Pod length varies from 20 to 80 mm, but rarely 130 mm (Reddy, 1990). The pods of most genotypes are nonshattering.

The most common seed shape is oval, but other types are also present in the germplasm. The common seed colors are brown and white, but other colors, such as purple, black, and various other combinations, are observed (Figure 4.1). The weight of 100 seeds ranges from 2.8 to 22.4 g. The average seed number per pod ranges from 2 to 9. However, the majority of the germplasm possess about 4 seeds pod⁻¹. The seeds are nonendospermic and contain two conspicuous cotyledons joined by gums. Strophiole is prominent on developing seeds, and it shrivels with maturity. Seeds do not have dormancy, and germination is hypogeal. The first trifoliate leaf emerges when the epicotyl is about 30 to 70 mm long. Secondary shoots, and sometimes multiple shoots, develop from the cotyledonary axils of the seeds in case the young plumules or axillary shoots are damaged (Reddy, 1990). In general, the large-seeded varieties produce bigger seedlings than those with small seeds, but such differences disappear as the plant attains growth (Narayanan et al., 1981). The first pair of leaves is simple, opposite, and caducous, but the subsequent leaves are compound, pinnately trifoliate, and arranged in a 2/5 type of spiral phyllotaxy. Leaflets are lanceolate or elliptic, with acute but sometimes obtuse apices (Reddy, 1990). Stems are ribbed, up to 150 mm in diameter, with prominent secondary growth. Most Asian lines have green stems, while African origin germplasm is characterized by purple color stems.

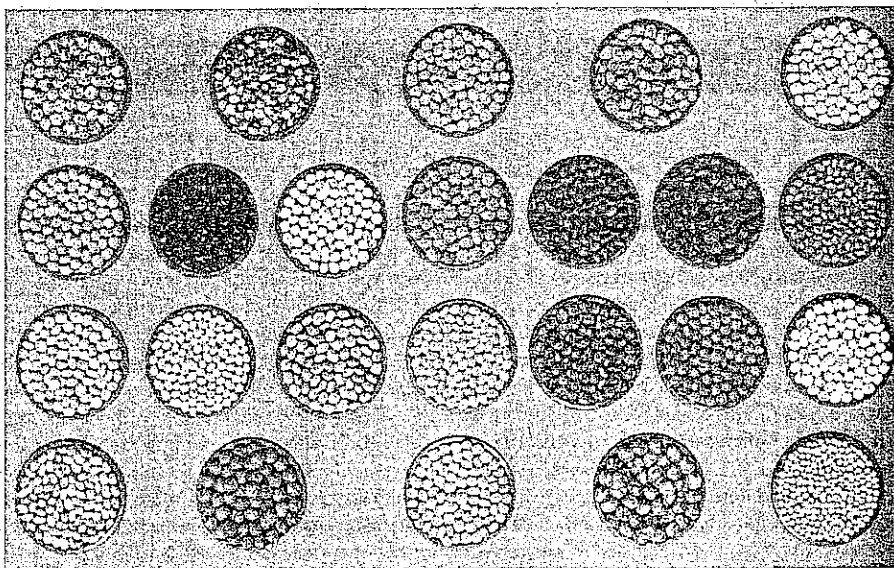


Figure 4.1 (See color insert following page 178) Seed color variation in pigeonpea.

Pigeonpea has a prominent tap root system with considerable lateral branching. The root growth begins shortly after sowing. The development of lateral roots occurs as soon as the primary leaves begin to unfold. Due to the perennial nature of the plant, the roots continue to accumulate dry matter and produce laterals throughout the growth of plant until harvested or killed by diseases (Chauhan, 1993). The continuous production of new roots enables the plant to exploit the receding soil moisture in the post-rainy season. Under normal field conditions the roots may grow to a depth of 3 m. Tall, upright varieties produce longer and more deeply penetrating roots, whereas spreading types produce more spreading and dense root systems (Pathak, 1970). The roots of perennial pigeonpea grow up to 4 m in southern China (Saxena, 2002). Most roots feed within the first 600 mm soil profile. The primary structure of the root is usually tetrach and its secondary thickening takes place as a result of cambial activity (Bisen and Sheldrake, 1981). Pigeonpea is nodulated by Rhizobia of the cowpea group.

4.5 CYTOGENETICS

Roy (1933) while studying the female gametophytic tissues of pigeonpea reported the presence of 11 chromosomes. Krishnaswamy and Ayyangar (1935) studied the pollen mother cells and confirmed $n = 11$, and they suggested that it was the basic chromosome number of the entire tribe. Naithani (1941) was the first to report $2n = 22$ somatic chromosome number. Akinola et al. (1972) examined 95 pigeonpea accessions of diverse origin and reported $2n = 22$ in the entire collection. van der Maesen (1986) observed that all of the 32 wild relatives carry the chromosome count similar to those of the cultivated types. However, in *C. kertsingii*, contrasting reports on chromosome numbers are found. Gill and Hussaini (1986) reported $2n = 32$, while Lackey (1980) recorded $2n = 22$ chromosomes; this large discrepancy needs to be verified.

Natural and induced tetraploids have been reported in pigeonpea. Pathak (1948), Pathak and Yadav (1951), and Saxena et al. (1982a) reported the existence of naturally occurring tetraploids ($2n = 44$). Tetraploids characteristically have larger and thicker leaves and flowers with partial pollen sterility. Kumar et al. (1945) and Bhattacharjee (1956) reported colchicine-induced tetraploids. The partial male sterility and poor pod set observed in the tetraploid genotypes were attributed to varying degrees of multivalent formation and irregular chromosome disjunction during meiosis (Pathak, 1948; Bhattacharjee, 1956; Chopde et al., 1979). D'Cruz and Jadhav (1972) reported the first case of aneuploidy ($2n = 23$). Anther-derived callus contained large variation in the chromosome number ($2n = 8$ to 28) (Bajaj et al., 1980).

The somatic chromosomes are small, with the longest measuring 2.7 μm and the shortest 1.35 μm (Naithani, 1941). Deodikar and Thakar (1956) conducted the first detailed karyotype. A considerable genotypic variation was reported for total chromosome length (Sinha and Kumar, 1979) and satellited chromosomes (Sharma and Gupta, 1982; Pundir and Singh, 1986). One chromosome bivalent was attached with the nucleolus (Dundas et al., 1983; Reddy, 1981) while Kumar et al. (1987) reported two sites for nucleolar organization. The first detailed pachytene analysis of pigeonpea chromosomes was performed by Reddy (1981), and the chromosomes were characterized based on relative length, arm length, nucleolar association, and chromomere structure and distribution.

4.6 GERMLASM RESOURCES

In 1973, ICRISAT was assigned the task of assembling pigeonpea germplasm on a worldwide basis to serve its own and other breeders across the globe. To assemble the germplasm, a number of field collection missions were undertaken in collaboration with various local institutions in 52 Asian, African, and Latin American countries. More than 13,548 pigeonpea accessions have been

Table 4.2. Phenotypic Variability for Different Traits Recorded in the Conserved Pigeonpea

Trait	Minimum	Maximum
Days to 50% flowering	45.0	237.0
Days to 75% maturity	85.0	299.0
Plant height (cm)	39.0	385.0
Primary branches (number)	2.0	66.0
Secondary branches (number)	0.3	146.0
Flacemes (number)	6.0	915.0
Seed pod ⁻¹ (number)	1.6	9.0
100-seed mass (g)	2.8	25.8
Seed protein (%)	12.4	32.0

Note: Germplasm grown at ICRISAT, Patancheru.

Source: Compiled from various ICRISAT reports.

collected and characterized. Besides some cultivated and uncultivated landraces, these include wild relatives representing 47 species belonging to six genera. According to van der Maesen (1981), a reasonable coverage has been achieved from the Indian subcontinent — the primary center of diversity. He emphasized that the habitats of most wild relatives of pigeonpea are threatened due to increased pressure for expanding agricultural activities in new areas. Pigeonpea is of rather recent introduction in the Americas and the Pacific, and reasonably, representative collection is available. Van der Maesen further opined that in Africa and the Far East, pigeonpea has been grown for at least 4000 years. Significant genetic variability is expected from these regions, hence, more collection missions are needed.

The available germplasm collection at ICRISAT offers an extensive range of variability for most yield components and various morphological and quality traits (Table 4.2). In addition, pigeonpea contains a number of unique traits, such as genetic male sterility, cytoplasmic male sterility, modified floral morphology, dwarf, decumbent, single-culm, etc. A number of biotic and abiotic stresses play a major role in the adaptation and stability of cultivars. The germplasm collection contains 321 lines resistant to sterility mosaic, 29 to fusarium wilt, and 140 to P₂ race of phytophthora blight disease. These valuable resources offer plenty of opportunities for developing varieties with single or multiple disease resistance.

In general, the pigeonpea landraces are heterogeneous for various traits primarily due to uncontrolled natural cross-pollination. This natural outbreeding produces a considerable genetic variability, and from such germplasm the breeders have identified some outstanding recombinants and a number of high-yielding popular varieties, such as C 11, BDN 1, Maruti, T 7, and UPAS 120. On the other hand, due to natural outcrossing, the maintenance and conservation of pigeonpea germplasm has become difficult and expensive. The botanists, however, try to conserve the available intra-accession variability by reconstituting the original population as close as possible. For this purpose, in each rejuvenation cycle one or two branches of individual plants of an accession are covered with muslin bags and 25 to 30 selfed seeds are bulked in equal number for storage and further use. The seeds can be safely stored under low temperature and low relative humidity. For long-term conservation at ICRISAT, the moisture content of seeds is brought down to about 5 ± 1% at 15% relative humidity, and the temperature is maintained at -20°C. The working germplasm, however, is conserved in a medium-term storage at 4°C and 20% relative humidity.

Secondary and tertiary gene pools are valuable resources for pigeonpea improvement. Many wild relatives such as *C. scarabaeoides*, *C. sericeus*, *C. lineatus*, *C. acutifolius*, *C. albicans*, *C. trinervius*, and *C. reticulatus* can be crossed (Table 4.3) with the cultivated pigeonpea and have been successfully used in the crop improvement programs. In comparison to the cultivated types, the wild species contain significantly higher amounts of seed protein. Accessions of *C. albicans*, *C. lineatus*, *C. sericeus*, and *C. crassus* have been found resistant to sterility mosaic disease. *Cajanus*

Table 4.3. Crossable Wild Relatives of Pigeonpea and Their Main Characteristics

Species	Habitat	Major Features	Reference
<i>Cajanus scarabaeoides</i>	India, Sri Lanka, Australia, Africa	Widely distributed in many countries; Antibiopsis for pod borer; creeper climber; rectangular-rounded, grey seeds with black mosaic	Roy and De, 1966
<i>C. sericeus</i>	India	Erect shrub; 1 to 1.5 m tall, densely branched; grey or black rectangular-rounded seeds	Kumar et al., 1958
<i>C. albicans</i>	India, China	Perennial climber with woody base; rectangular, dark-colored seeds	Reddy et al., 1981
<i>C. cajanifolius</i>	India	Erect, open branches; 1 to 2 m tall; rectangular-rounded seeds with black and grey color	Reddy et al., 1981
<i>C. acutifolius</i>	Australia	Erect or spreading shrub; 1 to 2 m tall, leaves covered with short silvery hairs; seeds dark and oblong	Dundas, 1984
<i>C. lancaolatus</i>	Australia	Erect, slender shrub; 1 to 3 m tall, seeds globose to compressed and dark mottled	Kumar, 1985
<i>C. latisepalus</i>	Australia	Erect shrub; 0.6 to 1.5 m tall, pubescent branches, seeds flattened-globose	Kumar, 1985
<i>C. lineatus</i>	India, Sri Lanka	Erect shrub; 0.5 to 2.5 m tall, open growth habit; seeds flattened-orbicular	Deodikar and Thakar, 1956
<i>C. reticulatus</i>	Australia	—	Dundas, 1984
<i>C. trinervius</i>	India	Erect shrub; 0.5 to 2 m tall, stem and branches densely pubescent; seed dark colored and rectangular	Reddy et al., 1981

platycarpus is resistant to phytophthora blight, while *C. scarabaeoides* has shown a fairly high level of tolerance to Helicoverpa pod borer. Occasionally, some naturally outcrossed plants have been noticed in *C. scarabaeoides* and *C. sericeus*, but these wild species are generally maintained under natural conditions. A considerable genetic variation has been reported among the accessions of a wild species for various economic traits, such as disease resistance, seed protein, etc. (Saxena et al., 1990a). Therefore, to achieve rapid success in a breeding program involving exotic germplasm, a careful selection of a parent accession within a wild species is essential.

4.7 GERmplasm ENHANCEMENT

In pigeonpea, where phenology is sensitive to environmental influences, a basic problem encountered in breeding for quantitative traits is the interpretation of results. Mating designs are influenced by physiological changes associated with phenological differences (Saxena et al., 1981). The estimates of important genetic parameters such as yield and its associated traits are also confounded with pleiotropic effects of genes influencing phenology. Saxena and Sharma (1990) reviewed the literature related to gene action and heritability of various economic traits in pigeonpea and reported low to high heritabilities and presence of both additive as well as nonadditive gene action for yield and major yield components such as pods plant⁻¹, seed size, seeds pod⁻¹, plant height, and days to flower and maturity. This suggests that for genetic improvement, besides pure line breeding, the population improvement and heterosis breeding programs can also be effective.

4.7.1 Agro-Ecological Adaptation

The adaptation of pigeonpea to different agro-ecological niches is governed by its duration, perennial nature, nondeterminateness, photothermal sensitivity of phenology, and susceptibility to biotic and abiotic stress factors. Photoperiod sensitivity has been reported to be associated with maturity (Wallis et al., 1981). The traditional medium- and long-duration cultivars are highly sensitive to photoperiod, and therefore, their adaptation is limited between 0° and 30°N or S latitudes. The

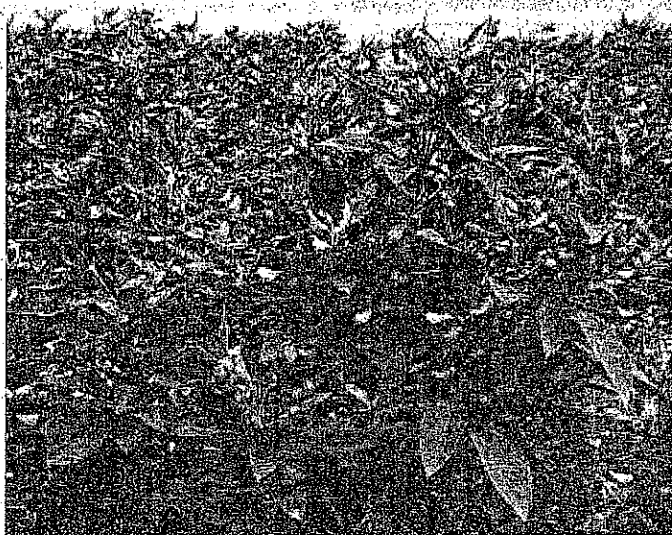


Figure 4.2 A short-duration variety of pigeonpea.

medium-duration cultivars are mainly grown between the Tropic of Cancer and the Tropic of Capricorn where winters are mild. In this range of latitudes, the long-duration cultivars generally suffer from terminal drought, except where rainfall is bimodal or temperatures are relatively mild due to high altitudes. The short-duration types are more or less insensitive to photoperiodic changes, and these can be grown successfully over a range (0 to 45°) of latitudes. This maturity group is receiving importance in breeding and agronomy research. A number of genotypes with wide adaptation have been bred (Saxena and Singh, 1996). Davis et al. (1995) reported that the short-duration pigeonpea cultivars bred at Patancheru (17°N) appear uniform under shorter day-lengths, but when tested under the long day-lengths of Minnesota (45°N), they were variable in flowering response. A further selection under long photoperiod environments resulted in the development of lines that were uniform for flowering in both environments. Such lines, when tested again in Patancheru, produced low biomass and yield and matured in only 85 to 90 days. Their biomass and yield, however, increased more rapidly than other cultivars under the artificially extended photoperiods as their maturity duration increased by 25 to 30 days (Chauhan, 2001). This suggests that the materials developed at higher latitudes can be grown successfully at lower latitudes, but the reverse may be difficult. Therefore, in order to develop cultivars adapted to particular latitudes, the day-length should be ideally longer than that prevails in the target location. The cultivars developed at higher latitudes under high temperature would flower too soon in climates with low temperatures and would not be able to accumulate sufficient biomass to produce high individual plant yield. This is indeed the case when Patancheru (17°N) bred material is taken to the highlands in Kenya. For achieving high yields in such environments, pigeonpea cultivars with long juvenile phase would be needed (Figure 4.2).

4.7.2 Natural Outcrossing

Howard et al. (1919) were the first to report 14% natural outcrossing in pigeonpea. Saxena et al. (1990b) reported a large variation (0 to 70%) in the extent of natural outcrossing in different genetic materials at diverse locations (Table 4.4). The large yellow- and red-colored flowers attract a variety of insects. These insects sit on the fully grown or open flowers and work on them. During

Table 4.4 Percent of Natural Outcrossing Recorded in Pigeonpea in Various Countries

Country/Place	Outcrossing (Range) (%)
India	
Pusa	01.6 to 12.0
Nagpur	03.0 to 48.0
Niphad	11.6 to 20.8
Ranchi	03.8 to 26.7
Varanasi	10.3 to 41.4
Badnapur	00.0 to 08.0
Coimbatore	10.0 to 70.0
Hyderabad	00.0 to 42.1
Kenya	12.6 to 45.9
Hawaii	05.9 to 30.0
Puerto Rico	05.5 to 06.3
Australia	02.0 to 40.0
Uganda	08.0 to 22.0

Source: Adapted from Saxena et al. (1997).

this tripping process, a load of pollen grains stick to the body of the insects, and when they visit other flowers and repeat tripping resulting in cross-pollination. Pathak (1970) reported *Apis mellifera* and *Apis dorsata* as the main pollinating agents. Williams (1977) reported a variety of insects visiting pigeonpea, but the *Megachile* spp. and *Apis mellifera* were found responsible for transferring pollen grains from one plant to another. She estimated there are between 5,500 and 107,333 pollen grains on the body of each insect, and more than 90% of those pollen grains belonged to pigeonpea. In Kenya, Onim (1981) found 24 insect species visiting pigeonpea flowers, each visit lasted between 15 to 55 seconds, and that *Xylocopa* spp. (carpenter bee) and *Bombus* spp. (bumble bee) play an important role in cross-pollination. Brar et al. (1992) reported *Apis mellifera*, *A. dorsata*, *Xylocopa* spp., *Megachile lanata*, and *Ceratina binghami* visited pigeonpea flowers, but only *Megachile lanata* and *Apis dorsata* effected cross-pollination, while Verma and Sidhu (1995) reported high populations of *Megachile lanata* and *Xylocopa* spp. The large range in outcrossing reported in the literature might be due to a variety of combinations of various factors, including the number and type of pollinating insects, wind velocity, habitat, and crop growth. The number and type of pollinating vectors, however, are the most important factors. In addition, genotypic variation in floral morphology, such as tightly wrapped petals (Byth et al., 1982) and cleistogamous flowers (Saxena et al., 1992a), record reduced outcrossing.

4.7.3 Breeding Strategies

India accounts for more than 85% of global pigeonpea production, the national productivity ranges between 0.6 to 0.7 t ha⁻¹, and there has been no change in these statistics over the past few decades. This gives a dismal picture, and concerted efforts are needed to improve the yield levels.

Since pigeonpea is grown under a wide range of cropping systems and environments, and new systems have emerged, it is impossible to have similar breeding objectives, as such objectives may vary from one cropping system to the other, and approaches. The maximum gain in productivity will result from parallel advancement in both genetic and crop management. Since the phenology and estimates of genetic parameters are known to be highly sensitive to photothermal effects, and the existing production systems have evolved around them, breeding methods should address the core issues of the individual production and cropping systems, and therefore specific breeding programs need to be developed (Byth et al., 1981). However, there are certain areas for which the breeding programs can be oriented across the environments and cropping systems. These include

identification of the source of resistance for diseases and pests, transfer of a specific trait from the wild relatives, and various biotechnology related aspects. For a successful breeding program aimed at yield enhancement, a clear understanding of the physiological basis of yield and the genetics of important agronomic traits and their interrelationships under different ecosystems is essential. In comparison to cereals and other legumes, pigeonpea is relatively less researched and the available scientific knowledge is scanty in areas of physiology, breeding, genetics, and adaptation. Since additive as well as nonadditive genetic variances determine the expression of important agronomic traits, the breeding methodologies in pigeonpea should be geared to exploit them. The pigeonpea germplasm originating from Asia, Africa, and South America contain distinctly prominent traits. For the improvement of yield and adaptation, hardly any attempt has been made to use this genetic wealth systematically, and most breeding programs suffer with this deficiency. Therefore, a targeted program for utilizing this genetic variation — and that from the crossable wild relatives of pigeonpea — will help in fulfilling the breeding objectives.

Three major maturity groups are recognized in pigeonpea. These are short (120 to 140 days), medium (180 to 200 days), and long (>250 days). Traditionally, the long-duration types are grown in northern India (27°N latitude) and Africa, while the medium-duration group is cultivated in Maharashtra, Andhra Pradesh, Karnataka, and Tamil Nadu in India and in Myanmar. The short-duration types generally have wide adaptability, and they can be grown in a range of environments. It has been observed that in several pigeonpea growing areas, the maturity of the cultivars does not match with the prevailing soil type, temperature, moisture availability, and cropping systems, which results in poor adaptation and yield. For example, in parts of southern India, long-duration types are traditionally grown, which suffer from high evapotranspiration and terminal drought at the crucial reproductive stage and yield ranges from 0.4 to 0.5 t ha⁻¹. Shifting to earlier maturing cultivars is likely to raise the productivity in these areas.

The subject of breeding varieties specifically suited for intercropping is always open for debate, largely due to a variety of crop combinations and their management practices. Green et al. (1981) summarized the results of a four-year trial and concluded that with 33% selection intensity only 55% of the highest yielding pigeonpea lines in intercrop with sorghum would have been selected from the pure crop. In all the pigeonpea breeding programs, selection and on-station evaluation of advance generation of materials is done as sole crop, while their final products are always grown under intercrop, as this may be the reason for low probability of success.

The natural outcrossing in pigeonpea is substantial, and it has significant influence on breeding efficiency. Since production of genetically pure seed in each generation of selection is practically impossible due to outcrossing, the gains from pedigree selection, especially for quantitative traits like yield, are limited. To overcome this limitation, Green et al. (1981) recommended the use of bulk hybrid advance, population breeding, and hybrid breeding. In the past, pedigree breeding has been successfully exploited for incorporating disease resistances, earliness, determinate growth habit, dwarfing, large seed size, white seed color, and long pod. On account of repeated natural outcrossing and vast segregation in each cycle of cultivation, invariably all the cultivars of pigeonpea have become highly heterogeneous for various qualitative and quantitative traits. This variability is considered a rich genetic resource pool from which useful variants can be selected. Shaw et al. (1933) were the first to recognize the value of this phenomenon and they identified 86 variants, of which some were highly resistant to fusarium wilt disease. A number of varieties have been developed from such inter- and intra-accession variability including popular cultivars like T 21, Prabhat, UPAS 120, C 11, BDN 1, HY 3C, HY 3A, T 7, LRG 30 in India, and ICEAP 00040 and ICEAP 00053, etc. in southern and eastern Africa.

Breeders are researching for any floral modification that would discourage natural outcrossing and produce seed with greater genetic purity. Two such variants have been identified. Abnormal free anthers and twisted petals characterize cleistogamous flower. Natural outcrossing ranges from 1 to 2% (Saxena et al., 1994). In other variants, where the petals convolutedly overlap, the natural outcrossing is also considerably reduced (Byth et al., 1982), but this trait is not dependable, as

under certain environments a considerable degree of outcrossing takes place (Saxena et al., 1987b). The cleistogamous variant is easy to identify and simply inherited (Saxena et al., 1992a) and, therefore, recommended for developing new stable sources of resistance and pure line cultivars less threatened by genetic contamination under open pollination.

In conclusion, while developing a breeding program, consideration should be given to the prevailing cropping systems and agro-ecological parameters. Care should be taken to incorporate maximum genetic diversity in the selecting of parents for hybridization. Perhaps evaluation of potential parental lines for one or two seasons will be useful in achieving the optimum gains from a breeding program. The mating and selection methods should also consider the availability of human and financial resources.

4.7.3.1 Pure Line Breeding

4.7.3.1.1 Breeding for Seed Yield

Breeding for high grain yield and stability has long been the prime objective in most programs. Significant gain in yield has been achieved in pigeonpea by increasing area. However, the productivity of the crop has remained stagnant for decades. Considerable efforts have been made to improve the yield of traditional medium- and long-duration varieties through conventional breeding, but success has been elusive in most cases. Swaminathan (1973) attributed this failure to inefficient selection efficiency and various inherent physiological and management limitations of the crop. Chauhan et al. (1994) viewed it as the consequence of inherently poor partitioning of carbohydrates resulting in storage of high proportion of food reserves in nonreproductive parts and resulting in poor harvest index. The development of annual type may help in improving the harvest indices in pigeonpea (Saxena et al., 1992b).

Green et al. (1981) emphasized the influence of genotype-environment interactions on the manifestation of growth and yield in pigeonpea. They demonstrated that such interactions were particularly significant at macro and micro levels. They concluded that environmentally induced interplant variance is very high and, therefore, in early generation, selection for yield based on individual plants may not be effective. They recommended that the selection for yield must be based on progeny or family performance. To minimize the influence of different cropping systems and environments on selection, Byth et al. (1981) advocated that breeding activities should be targeted for each specific environment. Saxena and Sharma (1983) concluded that the low-yielding crosses can be safely rejected based on F₁ performance. High-yielding crosses in the F₁ should be tested in the F₂ as well for confirming the cross-performance and final selection, since the relationship between F₂ performance and that of later generations was more consistent.

In the short-duration group, which differs grossly in phenology and is cultivated as sole crop, a significant progress has been made in developing new high-yielding cultivars. The first high-yielding short-duration variety, ICPL 87, was developed at ICRISAT from a single cross involving a long-duration large-seeded line and a short-duration small-seeded cultivar. The selections made in F₂ generation were handled through the pedigree method. This variety produced a 10% higher yield than the control, with a 30% increase in seed size in the multilocation testing. This success encouraged breeders, and a number of varieties were released in this maturity group. They include ICPL 151, ICPL 2 (in India), ICPL 87091 (in Kenya, Malawi, and Uganda), Hunt, Quantam, Megha, and Quest (in Australia), and MN 1, MN 5, and MN 8 (in the U.S.). Since early maturity is associated with photoperiod insensitivity, these varieties showed relatively wider adaptation (Wallis et al., 1981). In the International Nurseries conducted by ICRISAT, such lines produced 2 to 3 t ha⁻¹ yield (Table 4.5) at latitudes ranging from 0 to 42° N and S.

Saxena et al. (1986) demonstrated a quantum jump in the yield potential through heterosis breeding. The genetic male sterility-based hybrid ICPH 8 recorded 25 to 30% yield advantage in the farmers' fields (Saxena et al., 1992c). The development of more efficient cytoplasmic male

Table 4.5 Seed Yield (t ha⁻¹) of Extra-Short-Duration Pigeonpea Lines at Different Latitudes 1988-89.

ICPL No.	Latitude (°N)									
	7	9	17	23	29	31	32	34	46	
83015	2.32	1.48	2.35	1.75	1.06	1.74	3.73	1.86	2.06	
83019	2.21	1.39	1.46	1.43	1.00	1.36	3.58	1.67	1.76	
84023	2.34	1.14	1.42	1.83	1.37	1.87	2.99	2.49	1.59	
85010	2.79	1.55	1.59	1.88	1.17	1.25	3.16	2.33	2.15	
85024	1.43	0.91	1.11	1.25	0.63	2.01	2.71	1.17	1.36	
83006	3.09	1.51	2.22	1.49	1.28	2.73	3.38	2.00	1.43	
85030	1.52	1.11	1.21	1.29	0.98	1.16	2.52	0.83	2.46	
86010	1.67	1.08	1.86	1.78	1.80	1.20	3.47	1.23	1.33	
Mean	2.17	1.27	1.65	1.59	1.16	1.67	3.19	1.70	1.77	
SE	± 0.28	± 0.17	± 0.15	± 0.24	± 0.10	± 0.05	± 0.04	NA	NA	
CV%	22.8	23.3	14.5	29.2	12.9	4.70	17.1	NA	NA	

NA = Not available, single replication data.

Source: Saxena (2002).

sterility systems (Saxena and Kumar, 1999) has helped for greater gains in the productivity of this crop. This is discussed in greater detail in a later section.

4.7.3.1.2 Breeding for Disease Resistance

Breeding pigeonpea resistant to wilt, sterility mosaic, and phytophthora diseases has been attempted. Considerable success has been achieved in wilt and sterility mosaic resistance breeding, due to the development of an effective field screening technique. For developing a wilt-sick plot, sufficient inoculum is maintained uniformly in the field while for sterility mosaic disease, a simple spreader-row technique is used (Nene et al., 1981). Since both diseases are important from an adaptation point of view, a single nursery for both the diseases has been established at ICRISAT. The susceptible controls are grown at regular intervals to monitor the level of inoculums in the screening nursery in each season. The choice of breeding method for developing disease-resistant cultivars depends on the genetic nature of resistance sources. For wilt and sterility mosaic diseases, where good resistance sources are available, pedigree or mass selection has produced good results.

Pedigree selection within the landraces has been very effective in India and Africa for developing wilt resistant cultivars. In India, variety Maruti, a selection from ICP 8863 collected from Maharashtra State, is proving a boon to the farmers in the wilt-prone areas. In some districts, its adoption is as high as 60% (Bantilan and Joshi, 1996). A selection from a Tanzanian landrace (ICP 9145) has been adopted in 20% area of Malawi (Siliim, 2001). Since wilt and sterility mosaic diseases may occur in the same region, ICRISAT emphasizes to breed varieties resistant to diseases together. Large F₂ populations involving single, double, or three-way crosses are grown in the multiple-disease-sick nurseries. Individual plants resistant to wilt and sterility mosaic diseases are identified. To maintain their genetic purity, these plants are selfed with muslin bags. In subsequent generations, the evaluation for yield and other agronomic traits is done in disease-free fields, and the same material is sown in disease-sick fields to monitor the disease incidence.

In 1992, ICRISAT developed a widely adapted medium-maturing pigeonpea variety, ICPL 87119, through bulk-pedigree method. This variety demonstrated high level of resistance to wilt and sterility mosaic diseases and was also high yielding. In the All India Coordinated Trials, ICPL 87119 recorded 20% yield advantage over the control C 11. This variety is very highly popular in peninsular India.

For phytophthora blight, although considerable research has been done on standardization of glasshouse and field inoculation techniques (Kannaiyan et al., 1981), obtaining uniform disease reaction in field and glasshouse is still a problem (Reddy et al., 1990). The development of a number

of pathogenic races has further complicated this work. From the world collection, only a few lines, such as KPBR 80 and ICP 9252, have been identified with field resistance to P2 and P3 isolates, and this resistance is expressed only in adult plants.

Alternaria leaf spot [*Alternaria tenuissima* (Künzö ex Pers.) Wiltshire] is a disease frequently observed in the late-sown crops and in certain agro-ecological areas such as eastern parts (Bihar, Orissa) of India. Two resistant lines, ICPL 366 and DA 2, have been bred. Onim and Rubaihayo (1976) selected UC 796/1, UC 2113/1, ICP 8869, and ICP 12792 lines resistant to Cercospora leaf spot in Uganda. Line ICP 9177, a collection from Kenya, has shown immune reaction to powdery mildew (Raju, 1988). Some of the powdery mildew-resistant accessions such as ICP 8862 and ICP 7035 also have resistance to wilt and sterility mosaic diseases. Such materials are good source for multiple disease resistance breeding.

Wild relatives of the cultivated species are known to sources of useful genes. At ICRISAT, successful search for disease resistance has been made in the wild relatives. These include *C. scarabaeoides* and *C. sericeus* for sterility mosaic, and *C. platycarpus* for phytophthora blight and cyst nematode. The transfer of resistance from the wild relatives needs more resources and should be restricted in cases where the resistance in the cultivated types is lacking. For example, the resistance for wilt and sterility mosaic diseases is available in the cultivated types, which should be preferred in breeding. On the contrary, some *C. platycarpus* accessions have shown high level of resistance to P₃ isolate of phytophthora blight (Saxena et al., 1996c), a trait not available in the primary gene pool. Mallikarjuna and Moss (1995) transferred the phytophthora resistance to cultivated type using the embryo-rescue technique.

Information on the genetic control of pigeonpea diseases is restricted only to major diseases. Pal (1934) was the first to report that pigeonpea wilt resistance was controlled by multiple factors. Shaw (1936) confirmed the presence of two complementary genes for resistance. Joshi (1957) and Pawar and Mayee (1986) concluded that a single dominant gene determined resistance to fusarium wilt. Resistance to sterility mosaic disease was reported to be controlled by four independent loci, consisting of two duplicate dominant genes and two duplicate recessive genes. The expression of resistance of at least one dominant allele at locus 1 or 2 homozygous recessive genes at locus 3 or 4 are essential (Singh et al., 1983). Sharma et al. (1984) reported that two genes govern the resistance to sterility mosaic with multiple alleles for resistance to sterility mosaic diseases. Srinivas et al. (1997) reported two nonallelic recessive genes for resistance to race-1. A single gene controlled the disease reaction with three alleles for the race-2. In case of phytophthora resistance, the information is available only for P₂ isolate, and a single dominant gene controls the resistance (Sharma et al., 1982). A single recessive gene controls Alternaria blight resistance (Sharma et al., 1987).

4.7.3.1.3 Breeding for Insect Resistance

In pigeonpea, the use of cultivars resistant to the major insects would be a significant step toward the successful management of this age-old problem. Sadly, the success has been limited, despite large resources invested in this area. Breeding for resistance has been attempted for *Helicoverpa armigera* and *Maruca vitrata* using open-field screening methodology at ICRISAT. These programs started with germplasm screening under nonsprayed conditions to identify sources of resistance. A brief account of the constraints and achievements associated with breeding for resistance to major insects is given below:

Helicoverpa resistance breeding

At ICRISAT, extensive research has been conducted in the last 25 years for identifying lines with high level of *Helicoverpa* resistance. No truly resistant genotype was identified from more than 10,000 accessions screened. However, a few accessions with relatively less pod damage, classified by some as "tolerant" and by others as "resistant" were identified. These results were not

Table 4.6: Pod Borer Damage and Seed Yield of *Helicoverpa* Tolerant Variety Abhaya and Control BDN 1

Year/Trait	Abhaya		BDN 1 (Control)	
	Pod Damage (%)	Yield (t ha ⁻¹)	Pod Damage (%)	Yield (t ha ⁻¹)
1984	49.0	2.27	76.0	1.83
1985	11.6	1.84	33.4	1.44
1986	22.5	1.05	71.4	0.58
1987	70.6	2.73	94.2	1.54
1988	19.0	1.48	48.1	0.89
Mean	34.54	1.87	64.62	1.25

Source: Compiled from various ICRISAT reports.

consistent in the expression of resistance level over seasons and locations. In addition, intra-accession variability for compensative reproductive regrowth following pest damage further adds to the low heritability of the pod borer resistance. The variable insect population pressure in different years has also been a complicating factor.

The field screening for *Helicoverpa* resistance has resulted in the identification of some genotypes with noticeable ovipositional nonpreference but a change in insect behavior under no choice conditions restricted its use in host-plant resistance breeding (Reed and Lateef, 1990). Antibiosis, another potential resistance mechanism against *Helicoverpa*, also could not be used effectively in breeding due to undesirable level of the chemicals. Since different plant types are equally susceptible to *Helicoverpa*, the "plant type" approach for reduced damage also did not work. The transfer of moderate level of resistance from germplasm to agronomically superior genotypes was successfully achieved through hybridization and selection (Table 4.6). The released pigeonpea variety 'Abhaya' in India, tolerant *Helicoverpa*, could not make any impact due to severe pod damage in the years of high insect pressure and its susceptibility to fusarium wilt disease.

Maruca vitrata resistance breeding

Maruca vitrata (Geyer) is a serious insect pest of tropical legumes. In Sri Lanka, yield losses due to *Maruca* damage in pigeonpea range up to 100%. Field screening of 271 short-duration accessions revealed a large variation for *Maruca* damage to flowers and pods. On average, the *Maruca* damage in determinate accessions was higher (66 to 75%) than that of nondeterminate (41 to 50%) accessions (Saxena et al., 1996b). To purify the genetic stocks, pedigree selection for resistance to *Maruca* damage was carried out for four generations of unsprayed field plots. Some determinate and nondeterminate selections showed significant yield advantage over controls (Table 4.7). Under insecticide-free conditions in comparison to controls, the yield losses under nonsprayed conditions in the resistant selections were smaller (Saxena et al., 2002a). The resistance to *Maruca* was conditioned through yield compensation mechanisms. Poor larval growth and any other interference in the normal growth cycle of larvae feeding on the resistant line were possible reasons that may have contributed to resistance (Sharma et al., 1999). Saxena et al. (2002a) showed that by using the *Maruca*-resistant genotypes, it is possible to reduce the number of insecticide sprays for economic yields.

Breeding for Resistance to Other Insects

Although podfly (*M. obtusa*) causes considerable yield losses in long-duration pigeonpea, little efforts have been made to breed resistant genotypes. The resistant selections such as GP 3/3, SL 21/2, ICP 7151, and ICP 8102 were identified in germplasm screening, and they exhibit 5 to 10% damage under unsprayed field conditions, whereas in the susceptibles, up to 50% damage was recorded (Singh et al., 1990). Lal et al. (1986) suggested that by selection for shorter reproductive duration (less time from flowering to maturity), the podfly damage could be significantly reduced or escaped. So far, no breeding program has been undertaken to develop podfly-resistant cultivars.

In Kenya, Omanga and Matata (1987) observed genotypic differences to pod-sucking bug (*Clavigralla* spp.) damage. The selections 423/85 and 423/20 identified from local landraces had some level of resistance to the pod-sucking bug. The research on this aspect was not pursued further, and this resistance needs to be stabilized and quantified before using in the breeding program.

Table 4.7: Performance of Pigeonpea Lines Selected for Resistance to the Legume Pod Borer, *Maruca vitrata*, Maha Illuppallama, Sri Lanka, 1996-1997 Rainy Season

Genotype	Days to Flower [†]	Days to Maturity*	Seed Yield (t ha ⁻¹)		Yield Loss (%)
			Sprayed	Unsprayed	
Determinate					
MPG 537-M1-2-1B	62	109	2.39	2.01	15.9
MPG 537-M1-2-5B	59	108	2.07	1.83	11.6
MPG 537-M1-2-M4	60	107	2.09	1.86	11.0
MPG 537-M1-2-M13	57	107	2.37	1.53	35.4
MPG 537-M1-2-M16	58	107	2.09	1.62	22.5
ICPL 87 (control)	63	119	2.36	0.60	74.6
Mean (n = 15)	60	108	2.12	1.52	28.3
SE (var)	± 1.4	± 1.4	± 0.23		
SE (spray)	—	—	± 0.08		
SE (var→spray)	—	—	± 0.32		
Nondeterminate					
MPG 664-M1-2-M2	63	109	2.41	1.99	17.4
MPG 664-M1-2-M13	65	110	2.64	2.19	17.1
MPG 664-M1-2-M22	69	111	2.25	1.67	25.8
MPG 664-M1-2-M23	69	110	2.90	1.68	42.1
MPG 664-M1-2-M27	67	110	2.22	1.92	13.5
UPAS 120 (control)	66	115	2.32	0.670	68.9
Mean (n = 15)	66	110	2.50	1.42	
SE (var)	± 1.5	± 1.1	± 0.20		
SE (spray)	—	—	± 0.08		
SE (var→spray)	—	—	± 0.29		

* Under unsprayed conditions.

Source: Saxena (1999).

4.7.3.1.4 Breeding for Dwarfness

Realization of yield potential of pigeonpea cultivars is often restricted due to the damage caused by a variety of insects. In the absence of insect-resistant varieties and effective integrated pest management schemes, it seems that any attempt to increase pigeonpea productivity is unlikely to make an impact without the use of chemicals. Most cultivars at reproductive stage achieve the height of 2 to 3 m, which does not permit effective chemical sprays for controlling the insects. The introduction of dwarfing genes in productive backgrounds appears to be a logical approach for effective insect management to maximize yields. Saxena and Sharma (1995) reported 12 sources of genetic dwarfs in pigeonpea. Of these, D₁ has been utilized to combine yield and dwarfness in short, medium, and long duration groups. The height in dwarf inbred lines ranged from 70 to 80 cm and produced acceptable yields. Further breeding and selection is required to develop stable and productive genetically dwarf cultivars.

4.7.3.1.5 Breeding for High Protein

Protein content of pigeonpea *dhal* (decorticated split peas) ranges from 20 to 22%. However, a number of wild relatives of pigeonpea have protein content up to 32%. Three to four genes control the genetic variation for protein content in pigeonpea (Dahiya et al., 1977). A strong maternal effect in determining the seed protein content was reported by Dahiya and Brar (1977). Durga (1989) reported that the protein content was under additive and complementary gene effects. A breeding program was launched to enhance the protein content by transferring high protein genes from the wild relatives, such as *C. scarabaeoides*, *C. sericeus*, and *C. albicans*. Since these species have a number of agronomically undesirable traits including hard small seeds, bushy plant type, and low

yield, the breeding for combining protein with high yield and quality seed proved difficult and required large resources. In each segregating generation, large populations were grown and selections were made for these traits. Among the high protein agronomically superior lines, the seed size was correlated negatively (Saxena et al., 1987a) like in other food crops. From this gene pool a number of high yielding lines have been derived (Saxena et al., 2002b). It is estimated that by growing such lines in one hectare, about 350 to 450 kg crude protein could be harvested, with an advantage of 80 to 100 kg protein ha⁻¹ over the standard control. Biological evaluation of these lines using rat-feeding trials showed that high protein genotypes were nutritionally superior to the control cultivar (Singh et al., 1990).

4.7.3.1.6 Breeding for Vegetable Types

Pigeonpea pods picked still green are an excellent vegetable. Green pod is normally picked when the seeds have reached physiological maturity — that is, when they are fully grown but just before they lose their green color. It is currently an important market commodity in the Caribbean, Africa, and a few areas of India. Vegetable pigeonpea can be an excellent substitute when green pea (*Pisum sativum* L.) is unavailable. Although vegetable pigeonpea is not normally as sweet as green pea, it is preferred by some consumers and is usually less expensive. The traditional vegetable type is late maturing, produces green pods for a limited period, and pods and seeds are characteristically large. ICRISAT has bred a number of short-duration vegetable type lines from which fresh green pods can be harvested for a larger period to increase farmers' profitability. One such variety, ICPL 87091, has become very popular in India, Africa, and China. The vegetable pigeonpea seed is more nutritious than the dry seed because it has more protein, sugar, and fat than the mature seed (Table 4.8). In addition, its protein is easily digestible. Green seed contains considerably lower quantities of the sugars that produce gas in the intestine (flatulence). However, there are fewer minerals in the green seed than in the mature seed (Faris et al., 1987).

Table 4.8 Comparison of Some Nutritional Constituents of the Edible Portion of Dry Pea and Vegetable Pigeonpea on a Fresh-Weight Basis

Constituent	Green Pea	Vegetable Pigeonpea
Chemical Composition (g 100 g⁻¹)		
Edible portion (shelling %)	53.0	72.0
Moisture	72.1	65.1
Protein	7.2	9.8
Carbohydrates	15.9	16.9
Crude fiber	4.0	6.2
Fat	0.1	1.0
Mineral and Trace Elements (mg 100 g⁻¹)		
Calcium	20.0	57.0
Magnesium	34.0	58.0
Copper	0.2	0.4
Iron	1.5	1.1
Vitamins (mg 100 g⁻¹)		
Carotene (Vit. A 100 g ⁻¹)	83.0	469.0
Thiamin (Vit. B1)	0.1	0.3
Riboflavin (Vit. B2)	0.01	0.3
Niacin	0.8	3.0
Ascorbic acid (Vit. C)	9.0	25.0

Source: Faris et al. (1987).

Table 4.9 Pigeonpea Varieties Developed through Induced Mutations

Variety Name	Year of Release	Parent Line	Mutagenic Treatment	Trait Improved
Co 3	1977	Co 1	0.6% EMS	Yield
TT 5	1984	T 21	Fast neutron	Yield
TT 6	1985	T 21	Fast neutron	Seed size
TAT 10	1985	T 21	Fast neutron mutants crossed	Maturity
Co 5	1985	Co 1	16 Kr-rays	Yield

In comparison with pea, vegetable pigeonpea takes longer to cook and is not as sweet — but is much more nutritious. On a fresh-weight basis, vegetable pigeonpea has a greater edible portion, more protein, carbohydrates, crude fibers, fat, minerals, and more of some vitamins than green pea. Particularly noteworthy is their very high level of vitamin A and C.

4.7.3.2 Mutation Breeding

The initial crop improvement activities using induced mutations in pigeonpea were targeted to study the effective doses of various mutagens and induced genetic variation for various morphological traits. So far, 73 pigeonpea varieties have been released for India. Of those, only five were released through mutagenesis (Table 4.9). For EMS treatment, (0.6%) was found effective and variety Co 3 was developed. Another variety Co 5 was developed using 16 Kr of gamma rays. Two varieties, TT 5 and TT 6, were developed using fast neutron treatment. Besides high yield, TT 6 has 25% larger seed than parental line T 21 (Pawar et al., 1991). A variety TAT 10 was developed by mating two mutant pure lines derived from fast neutron treatment. This variety is high yielding and matures about 30 days earlier than the control. Bhatia (2000) postulated that in the new millennium, the use of traditional mutagens in developing cultivars will be restricted and considering the potential of this approach, future mutation research needs to be directed toward improving more difficult characters such as root traits, nodulation, host-pathogen interactions, photo-insensitivity, apomixis, and release of gene silencing in transgenics.

4.7.3.3 Population Breeding

In the self-pollinated crops, conventional breeding imposes restriction on the chance of recombination rates, retains tight and undesirable linkages, and restricts the number of desirable alleles at various loci that can be accumulated in the selected line. Pigeonpea, a predominantly self-pollinated crop with varying degrees of outcrossing, has populations with homozygous balance. Khan (1973) advocated the formation of composites for maintaining genetic variability, recombination breeding, and the selection of single plants for conventional breeding. He also emphasized that after three to four generations of random mating, these composites can be improved by a suitable system to provide a heterogeneous population, which can be released to the farmers as an open-pollinated variety.

To increase recombination by intermating of genotypes, a population-breeding program based on the dual population system (Rachie and Gardner, 1975) was initiated at ICRISAT. In the dual population method, a parent with an easily observable recessive marker is used. The F₂ is grown in isolation and plants with the recessive marker are harvested. In F₃, plants with the dominant marker gene are harvested, and in the F₄, plants with the recessive marker are taken. This alteration ensures that only cross-pollinated plants are advanced. This method did not produce good results. Onim (1981) tested two population improvement methods — stratified mass selection and mass selection with progeny testing in marginal rainfall areas. He reported 2 and 4% yield gain per cycle under stratified mass selection and mass selection with progeny testing, respectively. Singh et al. (1999) compared the relative efficiency of four population improvement schemes in increasing the

variability for yield and its component traits to the base population. Mean and genetic variation increased in all the selection schemes. Among the different population improvement schemes used, genetic variability was greater in selfed progeny selection and lowest in half-sib progeny selection.

4.7.3.4 Somaclonal Variability

The first attempt to exploit somaclonal variations for the varietal improvement in pigeonpea was made by Chintapalli et al. (1997). They regenerated plants from cotyledon explants of a short-duration brown seeded variety, ICPL 87. The regenerated R_2 plants exhibited considerable variability for floral morphology, plant height, seed size, and seed color. Tissue culture produced both dominant and recessive mutants. The promising selections were grown in field for pedigree selection for various agronomic traits. Field evaluation of 15 selected somaclonal variants exhibited large variation for yield, seed size, and seed color. The best selection, ICPL 99073, had white attractive seeds, with 25% increase in seed size and 30% more yield (Saxena, 2002).

4.7.4 Hybrid Breeding — The New Promising Technology

The genetic improvement research on various aspects of pigeonpea began in 1914, and new varieties, production packages, and resistant sources were developed. These achievements helped in increasing area significantly, but during the last several decades yield has remained unchanged, around 0.6 to 0.7 t ha⁻¹. This issue of yield plateau was considered a major challenge, and to achieve any breakthrough, plans were made to utilize genetically diverse germplasm including its wild relatives in hybridization programs in different mating and selection schemes. But the success in enhancing yield has been elusive. Unlike other legumes, pigeonpea flowers permit partial natural outcrossing, and this phenomenon was a bottleneck in maintaining purity of varieties. ICRISAT decided to make use of this limited outcrossing to exploit its hybrid vigor for developing high-yielding commercial hybrids. The effectiveness of hybrid breeding technology in any crop primarily depends on (a) the availability of grower-friendly male sterility-based seed production technology and (b) the presence of economic level of hybrid vigor for seed yield. Therefore, our initial research aimed at generating the crucial information on these two aspects.

4.7.4.1 Genetic Male Sterility Systems

Reddy et al. (1977) examined 7214 pigeonpea accessions and identified a male sterile variant based on anther morphology and pollen production with translucent anthers. The tetrads during microsporogenesis did not separate and gradually disintegrated in this natural mutant. It was due to persistence of tapetum and the intercellular wall of the two adjacent microspores (Reddy et al., 1978). Saxena et al. (1983) reported another source of genetic male sterility (GMS), characterized by brown and shriveled arrowhead-shaped anthers. Dunda et al. (1981) reported that male sterility was caused by breakdown of microsporogenesis at young tetrad stage, and it was accompanied by degeneration of the tapetum by vacuolation during the first division of meiosis. The anthers of GMS were completely devoid of pollen grains. However, male sterile plants set sufficient pods under open-pollination and thus established their potential in the hybrid breeding program. Each male-sterility source was found to be controlled by a single recessive gene.

The use of GMS poses practical limitations in the commercial seed production of hybrids, since it requires manual roguing of fertile plants from the rows of the female parent. This problem could be overcome to some extent if there were morphological seedling marker genes closely linked with the male sterile gene, as reported in lettuce (Lindquist, 1960) and watermelon (Watts, 1962). Singh et al. (1993) reported a possible linkage between translucent male sterile gene and temperature sensitivity. Under field conditions, they found that when the minimum temperature dropped below 10°C and the mean day temperature below 18°C, the male sterile plants shed all the floral buds,

Table 4.10 Plant and Seed Characteristics of Three CMS Lines Developed at ICRISAT Center, Patancheru

Trait	CMS 85010	CMS 88034	CMS 13092
Days to flower	64.0 ± 0.32	77.9 ± 0.61	135.5 ± 0.38
Plant height (cm)	66.3 ± 0.80	113.8 ± 1.92	182.4 ± 0.73
Primary branches	15.4 ± 0.26	16.5 ± 0.89	12.6 ± 0.47
100-seed mass (g)	9.2 ± 0.11	10.9 ± 0.15	12.6 ± 0.12
Seeds pod ⁻¹	3.2 ± 0.09	3.1 ± 0.06	4.9 ± 0.03
Growth habit	Determinate	Indeterminate	Indeterminate
Plant spread	Semi-spreading	Semi-spreading	Compact
Flower color	Yellow with light red streaks	Yellow	Yellow with red streaks
Stem color	Green	Green	Purple
Pod color	Green with brown streaks	Green with brown streaks	Green with purple streaks
Seed color	Brown	Brown	White

Source: Adapted from Saxena (2001).

whereas in the fertile segregants, the pod setting was normal. Unfortunately, this important work was not continued.

4.7.4.2 Cytoplasmic Male Sterility Systems

The development of cytoplasmic male sterile (CMS) lines in pigeonpea would effectively overcome the seed production inefficiencies of GMS-based hybrids and their female parents. The first attempt to develop a CMS line in pigeonpea was made by Reddy and Faris (1981) by crossing a wild species (*C. scarabaeoides*) as female parent with the fertile F_1 hybrid plants of *C. cajan* and *C. scarabaeoides*. The resulting BC_1F_1 was fertile, but in BC_1F_2 some male sterile plants were identified, but due to accompanying female sterility, this material was not pursued further. Aryanayagam et al. (1995) crossed *C. sericeus* as a female parent with pigeonpea. The F_1 plant was partially male sterile and the subsequent backcross populations segregated for male sterility. The reversion of some plants from complete male sterility to full or partial fertility further complicated the selection and stabilization of this trait (Saxena and Kumar, 1999). Intensive selection and backcrossing for five generations, however, resulted in the identification of three stable CMS lines (Table 4.10).

Recently, CMS lines have also been developed from the materials derived from the population having cytoplasm of *C. scarabaeoides* (Saxena, 2002). This source has shown greater stability in the expression of male sterility over locations and seasons. The identification of some male sterile segregants in the populations of crosses involving *C. cajanifolius* has also been reported (Saxena, 2002).

Environmental Effects on CMS

Experiments conducted at ICRISAT have revealed that expression of male sterility in CMS lines derived from *C. sericeus* cytoplasm is influenced by environment. The factors responsible for this sex reversal are still unclear. In a recently conducted trial involving environment-sensitive CMS selections (Table 4.11), it was observed that the CMS lines expressed complete male sterility in the month of August, when sown in mid-June. However, in the month of September, when day length and mean temperature started declining, a proportion of the male sterile plants turned fertile and produced normal pods and seeds. It was also observed that the amount of pollen produced by these plants differed grossly from plant to plant. Further, toward mid-February, when day length and mean temperature increased, these "converted fertiles" reverted back to male sterility. Seeds produced from such plants give rise to male sterile plants without any abnormality. Similar environmental effects have also been recorded in some F_1 crosses made to study the fertility restoration.

Table 4.11 Phenotypic Expression of Male-Fertility Fertile and Sterile Plants in the Environment-Sensitive CMS Lines of Pigeonpea Evaluated at ICRISAT during Rainy Season 2000-2001

Line No.	Ratio of Fertile to Sterile Plants				
	September 17	September 28	October 10	November 11	February 15
103	0:14	3:11	9:5	9:5	0:14
111	0:17	6:11	6:11	6:11	0:17
114	0:12	5:7	5:7	5:7	0:12
115	0:14	8:6	8:6	8:6	0:14
120	0:16	8:8	8:8	8:8	0:16
121	0:34	27:7	27:7	27:7	0:34
122	0:26	9:17	9:17	9:17	0:26
131	0:27	19:8	19:8	19:8	0:27
132	0:26	20:6	20:6	20:6	0:26
133	0:21	13:8	13:8	13:8	0:21
134	0:26	15:11	15:11	15:11	0:26
135	0:26	15:11	15:11	15:11	0:26
137	0:27	10:17	10:17	10:17	0:27
140	0:21	11:10	11:10	11:10	0:21
141	0:17	6:11	6:11	6:11	0:17
142	0:24	12:12	12:12	12:12	0:24
143	0:15	4:11	7:8	7:8	0:15

Source: Saxena (2002).

The influence of environment on the expression of CMS and its fertility restoration is not uncommon in crop plants. Kaul (1988), while reviewing male sterility in crop plants, quoted a number of such examples from vegetable, cereal, and legume crops. Among the environmental factors, photoperiod and temperature have been reported to influence pollen sterility, microsporogenesis, tapetal development, and seed set. He concluded that the stability of expression is not only fertility restoration and male sterility gene specific, but it depends on the presence or absence of other genes.

4.7.4.3 Fertility Restoration of CMS Lines

Identification of genotypes, which, when crossed with CMS lines, produce fertile F_1 hybrids, is a vital component of a three-parent hybrid breeding technology. This activity was initiated soon after developing CMS lines, and of the 291 combinations tested, only 7 fully restored the male fertility. For identifying new fertility restorers, the germplasm resources available in ICRISAT's gene bank are being used. Since most germplasm accessions are heterogeneous due to partial outcrossing, the F_1 hybrid progenies segregated for fertility restoration and other agronomic traits. Pure lines with 100% fertility restoration have been developed through selection from such germplasm (Saxena, 2002).

4.7.4.4 Special Features of Hybrids

4.7.4.4.1 High Yield

Since in any pulse crop no commercial hybrid is available, the release of the world's first pigeonpea hybrid, ICPH 8, in 1991 is a significant milestone (Saxena et al., 1989, 1992c). This hybrid was developed by crossing a GMS line (MS Prabhat DT) and a fertile inbred line, ICPL 161. It has nondeterminate vigorous growth, high yield, and early maturity, and escapes drought and major diseases. Evaluation from 100 yield trials in different agro-ecological zones showed ICPH 8 to be superior to controls UPAS 120 and Manak by 30.5 and 34.2%, respectively. (Table

Table 4.12 Zonal Weighted Mean Yields of the World's First Pigeonpea Hybrid ICPH 8 in Different Zones in India over the Years

Zone	Years	No. of Trials	Yield (t ha ⁻¹)			% Increase Over	
			ICPH 8	UPAS 120	Manak	UPAS 120	Manak
Northwest Plains	6	36	2.85	2.10	2.34	35.0	31.0
Central	4	30	1.56	1.16	0.93	32.9	52.5
Southern	4	30	1.42	1.22	1.26	23.6	27.3
Northwestern Hills	1	2	1.56	1.50	1.19	4.3	31.0
Northeastern Hills	1	1	1.68	1.15	—	45.6	—
Western	1	1	2.06	1.41	1.59	45.6	29.5
Overall Mean		100	1.99	1.53	1.35	30.5	34.2

Source: Saxena et al. (1996).

4.12). Punjab Agricultural University, Ludhiana, India developed pigeonpea hybrid PPH 4 in 1993 (Verma and Sidhu, 1995), which outyielded the control T 21 by a margin of 47.4% on the basis of eight multilocation trials conducted over two years. In the All India Coordinated Trials, this hybrid exhibited 32% superiority over the best national check, UPAS 120. Another hybrid, CoH 1, was released in 1994 by Tamil Nadu Agricultural University, Coimbatore, India. It recorded 32% higher yield over control VBN-1 in 17 trials (Murugarajendran et al., 1995). Two more hybrids, AKPH 4104 and AKPH 2022, were released in Central India and they recorded 35 to 64% superiority over the controls.

4.7.4.4.2 Faster Growth Rate

Inherently, pigeonpea is a slow growing crop, particularly in the early stages of growth. This makes it a less efficient crop as far as competition with weeds is concerned. Hybrids produce seedlings with greater vigor. The differences in growth vigor begin to appear during the early seedling stage and become more pronounced with time. This attribute of hybrids makes them more suitable for sole cropping than varieties, as it enables them to establish quickly and utilize light and water resources more efficiently. It was observed that in comparison to the pure line cultivars, the 1-month-old seedlings of hybrid ICPH 8 produced 43.9% higher shoot and 42.8% higher root mass, and such differences were maintained subsequently. Increasing spacing from 60 cm × 20 cm (83,000 plants ha⁻¹) to 75 × 20 cm (66,000 plants ha⁻¹) did not affect the yield (Saxena et al., 1996a).

In cereals and some legumes, a considerable proportion of the genetic variation in yield is accounted for differences in partitioning of photosynthates. By contrast, variation in pigeonpea yield is due to the differences in crop growth rates. Hybrids are higher yielding mainly due to their higher crop growth rates than the pure line varieties. The higher crop growth rates can be achieved by agronomic manipulations, such as increasing plant population and changing sowing time, but this does not necessarily result in increased yield because of its negative effect on partitioning. On the contrary, hybrids exhibit higher crop growth rates while maintaining their partitioning at least at the same level as that of pure line varieties (Chauban et al., 1994) and, thus, produce high yield. Hybrids have also shown significant improvement in the density of pods and seeds per pod. Higher crop growth rates of hybrids eventually result in both higher biomass production and seed yield.

4.7.4.4.3 Greater Drought Tolerance

Traditionally, pigeonpea is grown under rainfed conditions and is subjected to both intermittent and terminal droughts. Short duration pigeonpea has lesser root mass than the traditional medium- and long-duration types and, thus, is more prone to this stress. Incorporation of tolerance to drought is an important requirement if short duration is to succeed under rainfed conditions. Screening for drought tolerance using a soil moisture gradient with line source sprinkler irrigation showed that

hybrids performed well not only under optimum soil moisture conditions but also under drought stress, and that it might be related to the vigor of their root systems, which enables them to have a greater access to stored soil water (Saxena et al., 1996a). Lopez et al. (1996) attributed superiority of the hybrids to their increased ability to maintain relatively high water content than pure line varieties. It therefore appears reasonable to assume that in pigeonpea hybrids we may not only achieve higher yield potential but also a greater ability to adapt to drought, a trait that is otherwise difficult to improve through traditional breeding efforts.

4.7.4.4.4 Greater Adaptation

In most field crops, hybrids in general show wide adaptation and stability of yield across the environments. At most locations, the hybrid ICPH 8 outyielded the control, and it expressed greater stability in performance when compared across the environments.

Hybrids also promise to address disease control. A joint evaluation of wilt- and sterility-mosaic-resistant, pure line cultivars and hybrids in disease-free and disease-sick fields indicated that in the disease-sick nursery, both the hybrids as well as inbred controls were comparable in disease reaction, with less than 1% wilt and sterility mosaic disease incidence in both groups. Large differences, however, were observed in the expression of hybrid vigor under disease-free and disease-sick conditions. Although a general yield reduction was observed in all the genotypes when evaluated under disease-sick field, the expression of heterosis for yield was three times greater than disease-free conditions. Hybrid vigor conveys an extra degree of resilience that enables plants to produce under severe disease pressure when compared with nonhybrid cultivars. Lopez et al. (1996) also reported higher adaptability of hybrids in comparison to inbred cultivars. It is also postulated that, besides genetic factors, the ability of hybrids to produce greater root and shoot biomass throughout its growth cycle imparts greater ability not only to utilize greater amounts of available nutrients, but also to tolerate yield-limiting stresses such as drought, water logging, and disease resistance. The high level of recovery in yield from various stresses also contributes to increased adaptation of the hybrids.

4.7.4.5 Hybrid Seed Production Technology

4.7.4.5.1 Isolation Specifications

The technology of producing hybrid seed must be simple and user-friendly. The production package should contain appropriate agronomical operational, insect management recommendations and information on post-harvest handling of the seed. An efficient seed production system that could provide quality seeds at economically viable costs is the backbone of such technology. Since outcrossing in pigeonpea is affected by insects, a safe distance is recommended so that the pollinating insects, carrying pollen grains on their body, could not fly to and pollinate the flowers of other lines. This is essential to produce genetically pure seed. So far, no isolation distance study has been conducted using male sterile lines of pigeonpea, and it is assumed that the information generated on isolation specifications of pure line cultivars could be utilized safely in producing seeds of pigeonpea hybrids and their parents.

The recommended isolation specifications for pigeonpea differ considerably on degrees of natural cross-pollination. Ariyanayagam (1976), citing the Food and Agricultural Organization (FAO), recommended a minimum isolation distance of 180 m and a maximum of 360 m, while Agarwal (1980) recommended distances of 400 m and 200 m for the production of foundation and certified seeds, respectively. Faris (1985) suggested that, for quality varietal seed production, two varieties must be separated by at least 100 m, while a distance of 200 m between varieties is essential if the seed is to be used by breeders. In India, the seed certification standards fixed with regard to isolation distance for varieties are 200 m for breeder seed and 100 m for both foundation

and certified seed (Tunwar and Singh, 1988). The experience at ICRISAT suggests that the FAO specifications are suitable for both the production of hybrid seeds and for maintaining male sterile and pollinator lines.

4.7.4.5.2 Male Sterile Lines

It is essential that male sterile stocks be genetically pure for uniform expression of heterosis. For GMS systems, the lines must be maintained in the heterozygote form by harvesting seeds from male sterile (*ms ms*) plants pollinated by fertile heterozygotes (*Ms ms*). To multiply male sterile lines, the seeds harvested from male sterile plants (*ms ms + Ms ms*) are grown in isolation. At flowering, at least one young bud from each plant is manually opened and its anthers checked for the presence or absence of pollen grains. The male sterile and fertile plants are tagged with different colored markers. At maturity, seeds are only harvested from the male sterile plants. Immature pods are removed from segregants plants, if necessary, to extend the period of pollen availability (Saxena et al., 1996a). For multiplying seed of CMS line, the female male sterile rows (A line) and their maintainer (B line) are grown in 6:1 ratio. Pod set on the "A" line is accomplished by insects, which help in mass pollen transfer from "B" line to "A" line.

4.7.4.5.3 Pollinators

The genetic purity of pollinators is also essential for uniform expression of hybrid vigor. To prevent genetic contamination, the pollinators must be grown in isolation and off-types, if any, should be rogued before flowering starts.

Generally, the full pod set is realized if one pollinator row is sown after every six male sterile rows. In the production of GMS-based hybrids, the first bud that appears on each plant in the female rows is examined, and the male sterile plants are tagged while the male fertile segregants are rogued before their flowers open. It is a time-bound operation, and if roguing is delayed, the quality of the hybrid seed is adversely affected. In the CMS-based hybrid program, the same (1 male:6 female) ratio is used, but in the female rows, identification and roguing operations are not carried out. This not only saves expensive labor but also helps in maintaining quality of the hybrid seed.

Since pigeonpea is a perennial plant, flowering on the male sterile plants continues until the potential number of pods are set on each plant. This could be due to lack of pollinating insects or nonsynchrony of flowering of the two parents. On the contrary, in the pollinator rows, the flowering terminates when the potential pod set is realized by selfing. To ensure adequate hybrid yields, flowering in the pollinator rows can be extended by periodically removing young, developing pods and frequent irrigation. In situations where the pollinating insects are inadequate or plant growth is variable, the recommended 1 male:6 female ratio may not be adequate for optimizing hybrid seed yield, and it may be modified to suit local conditions.

4.7.4.5.4 Economics of Seed Production

Seed cost plays an important role in the adoption of hybrids. In a detailed study conducted at Coimbatore using GMS system, 813 kg ha⁻¹ of hybrid seed was obtained in a single harvest, resulting in approximately 1:32 seed-to-seed ratio. The estimated cost of hybrid seed was Rs 21.87 (1 U.S.\$ = Rs 45) kg⁻¹. In this study, the roguing operation alone accounted for about 45% of the total production cost (Murugarajendran et al., 1990). In tropical environments with warm winters, pigeonpea produces several flushes of pods within a year, and the perennial nature of this crop can be exploited to produce quality hybrid seed at low cost by adopting multiple harvest systems (Saxena et al., 1992c). So far, no study has been conducted to determine the cost of hybrid seed production using the CMS system, but it is likely to be more economical than the GMS technology, because in the former the costly operation of roguing is eliminated.

4.8 TRADITIONAL AND NONTRADITIONAL USES OF PIGEONPEA

4.8.1 Food

Dhal (decorticate split peas) is the most acceptable form of pigeonpea consumption. It is made by dehulling and splitting the two cotyledons of dry seeds. In India, almost all pigeonpea produce (2.2 mt) is converted into *dhal* by more than 10,000 milling units scattered all over the country. White-colored, whole dry seeds of pigeonpea are used in various traditional foods and snacks in eastern Africa, western India, and Indonesia. In addition, a number of food items can be prepared from pigeonpea seed or flour. These include tempeh, fresh sprouts, ketchup, canned-dry seeds, and various extruded food products; such as snacks, noodles, etc. Immature or green seeds of pigeonpea can be used as a vegetable. They can be grown in backyards — or commercially, in large fields. Green pigeonpea is an important vegetable in the Caribbean. In Puerto Rico and the Dominican Republic, green seeds are canned for local consumption and for export. Frozen and dehydrated green seeds are also consumed in some countries.

4.8.2 Animal Fodder and Feed

Pigeonpea plant and grains have been used as animal feed by Indian farmers for centuries. After harvesting pods, the plants are left in the field for browsing by domesticated animals. It produces about 20 to 25 t ha⁻¹ of edible dry forage and provides fodder at a time of the year when there is a deficit of energy and protein for the animals (Whiteman and Norton, 1981). Leaves can provide a good substitute for alfalfa in animal feed formulations, particularly in areas that are not suitable for growing alfalfa (Embong and Ravooof, 1978). The recovery of *dhal* ranges from 70 to 80% during milling. The remaining portion, consisting of seeds, broken, powder, and husks, produced as by-products, can also be used as animal feed. These are considered protein-rich concentrates for both ruminant and nonruminant animals.

4.8.3 Other Plant Products

Dried stems and branches provide excellent fuel for rural households in India. The heat value of pigeonpea wood is about half that of the same weight of coal (Panikar, 1950). Their straight branches are used in villages for roofing, wattling on carts, baskets, and temporary fences. Pigeonpea can also be used to produce lac and silk. Leaves are fed to silkworm (*Boroceras cajani*) in southern Madagascar (Watt, 1908). In the Philippines, China, and India, pigeonpea plants are used to cultivate (*Laccifera lacca*) a scale insect, which produces lac.

The curative effects of various pigeonpea plant parts find place in folk and ayurvedic medicines in India, Indonesia, China, West Africa, Madagascar, and the West Indies — for healing wounds, destroying internal worms, and curing lung diseases (Morton, 1976). Prema and Kurup (1973) reported that pigeonpea intake decreased cholesterol in rats. Also Ekeke and Shade (1985) found that pigeonpea caused reversion of sickle cells in patients suffering from sickle cell anemia.

4.9 LOOKING AHEAD

Pigeonpea remains a less-domesticated plant, even after centuries of cultivation since it has retained its unique characteristics such as perenniality, nondeterminate growth, low harvest index, and photothermal sensitivity. However, multiple uses and its role in sustaining productivity makes pigeonpea a favorite crop of small land holders. In the last few decades, a significant progress has been made in domesticating the crop by developing short-duration and determinate types, but a large scope for further improvement still exists.

In recent years, pigeonpea production in India has recorded a significant growth rate, and it is attributed to the development of short-duration and medium-duration disease-resistant varieties. Since the demand for pigeonpea is ever increasing, the attention needs to be focused on increasing its yield potential. The exploitation of heterosis and restructuring of plant type are two possible ways of achieving breakthrough in yielding ability. To achieve this goal, a complementary approach is to knit these two and other important elements together. In pigeonpea, the information gap needs to be filled for significant yield increases at the genetic level. Restructuring plants is a difficult task, and significant input from physiologists is essential. In the subtropical environments where plants have sufficient biomass, the inefficient partitioning is the major yield-limiting factor. In this context, it is postulated that if the intra-plant competition for photosynthates is increased by inducing synchrony in fertilization and pod set in the entire plant, it may help in releasing the stored assimilates from stem, roots, and other plant parts, and it might lead to quick grain filling and increased yield. In the tropical environments and post-rainy season pigeonpeas, where restricted biomass is the major production constraint, the hybrids are the answer because hybrids can produce about 25 to 30% additional biomass. The GMS hybrid technology in the past 25 years has conclusively demonstrated that the exploitation of hybrid vigor is feasible if the seed production difficulties are addressed adequately. The issues of developing high-yielding, CMS-based hybrids and their grower-friendly seed production technology also need further exploring. These include diversification and stability of cytoplasmic male sterility, breeding high-yielding diseases resistant 'A', 'B', and 'R' lines — and identification of heterotic cross combinations.

There have been debates in various international forums about the future of pigeonpea, because it has largely been treated as a regional crop, notwithstanding the multiple uses it offers. Among the factors contributing to its limited adoption outside India seem to be a lack of appreciable consumption due largely to different dietary habits, lack of adaptation into the cropping systems, and lack of appropriate appreciation of its diversified uses. However, with the recognition of its role in sustainability, development of new plant types amenable to mechanical harvest, resistance to major diseases, and extended adaptation from 30 to 45°N and S latitudes, it may be accepted as an alternative crop for diversification.

With the emphasis being placed on the intensification of agriculture, the crop will find increasing acceptance only if its yields can be improved both on per unit area and time basis. The development of short-duration cultivars and hybrids that can be commercially cultivated holds promise in this regard. The development of vegetable types has opened potential for encouraging rural enterprise and helping women obtain earning opportunities through canning and developing other marketable food items, such as noodles; fermented foods such as tempeh; and in sauces, as a substitute for soybean. The economic conditions in southeast Asia and frequent droughts are encouraging countries like Indonesia, China, and Myanmar to grow pigeonpea. The crop is being grown in Thailand for green manuring. In the U.S., there is increasing interest in growing pigeonpea crops for grazing during the lean season; the bushy dwarf types fit well into the production system likely to be followed there.

There are a number of other situations where pigeonpea can be successfully grown. Development of a pigeonpea simulation model can help in visualizing scenarios for assessing the profitability of the crop. This has been lacking so far, since such assessment required the actual conduct of trials at a considerable cost. The modeling tool can now be used for verification of potential, thus saving costs. However, a lot will still depend on how the crop will be consumed. In countries where people depend on meat as a source of protein, pigeonpea needs to be tried as animal fodder. Several studies have shown that it can be used for feeding poultry and pig. Other reports suggest using it for producing paper pulp, rearing lac insect, but definitive work needs to be undertaken in these areas. Some of these innovative uses will need to be explored if pigeonpea is to be made a truly global crop, which in turn is likely to attract more research investment for its improvement.

ACKNOWLEDGMENTS

The support provided by R.V. Kumar, M. Satyanarayana, and C.A. Selwin of Pigeonpea Breeding Unit in preparing this manuscript is acknowledged.

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