Principles of Plant Genetics and Breeding

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Blackwell Publishing

BLACKWELL PUBLISHING
350 Main Street, Malden, MA 02148-5020, USA
9600 Garsington Road, Oxford OX4 2DQ, UK
550 Swanston Street, Carlton, Victoria 3053, Australia

First published 2007 by Blackwell Publishing Ltd

5 2010

Library of Congress Cataloging-in-Publication Data

Acquaah, George.
Principles of plant genetics and breeding / George Acquaah.
p. cm.
Includes bibliographical references and index.
ISBN-13: 978-1-4051-3646-4 (hardback : alk. paper)
ISBN-10: 1-4051-3646-4 (hardback : alk. paper)
1. Plant breeding. 2. Plant genetics. I. Title.
SB123.A334 2007
631.5′233—dc22
2006004754

A catalogue record for this title is available from the British Library.

Set in 10/12pt Galliard
by Graphicraft Limited, Hong Kong
Printed and bound in UK
by TJ International Ltd

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International plant breeding efforts

Purpose and expected outcomes

The purpose of this chapter is to discuss the plant breeding efforts at international institutes and their impact on world food supply. Most of their efforts are directed at developing countries. Modern plant breeding is significantly responsible for the tremendous success of the agriculture of developed economies. It takes tremendous amounts of resources – human and financial – to undertake modern plant breeding research for developing new and improved cultivars for producers. The research infrastructure of most developing countries and the political support available limit the effectiveness of local scientists in addressing crop improvement needs. Because of lack of economic markets in developing countries, the multinational corporations that dominate the commercial seed market in developed countries find it unattractive to invest in the improvement of crops that are of importance primarily to developing countries.

Consequently, plant breeding efforts in developing countries depend on philanthropic organizations and the international agricultural centers they aid, for a significant support of their local breeding programs.

After studying this chapter, the student should be able to:

1 List all the International Agricultural Research Centers and indicate their mandate crops.
2 Discuss the contributions of the International Agricultural Research Centers to world crop improvement.
3 Discuss the role of the International Agricultural Research Centers in germplasm collection and maintenance.
4 Discuss plant breeding efforts by national programs in developing countries.

Brief overview of plant breeding in developed countries

The purpose of this very brief overview is to provide a basis for contrasting plant breeding in developed countries with those in developing countries. Plant breeding in developed economies is conducted in both the public and private sectors. In the USA, the land grant university system ensures the training of professional plant breeders, whereas its researchers actively engage in plant breeding research, resulting in the development of new technologies and the development of new plant cultivars. Public sector agricultural research is well funded by the government at both state and national levels, and primarily has a not-for-profit philosophy. Researchers use both conventional and modern technologies in their research.

Private sector research in plant breeding is significant in most developed economies. It is dominated by multinational corporations and is primarily for profit. Examples of such entities are Monsanto, Novartis, and Du Pont. These entities focus on high value crops (e.g., corn, wheat, rice, soybean) that are grown widely over the world. Unlike the public sector, patent rights protect the inventions of private corporations. Even though patents exist in the public sector as well, access to such protected materials is often much easier than access to those in the private sector. The issue of intellectual

Soybean

Soybean research is conducted at IITA. Breeding objectives include improved capacity to fix nitrogen without inoculation, high yields, and resistance to shattering. In 2001, CGIAR spent about 0.4% (representing US$1.3 million) of its commodity investment budget on soybean improvement.

Potato

Potato research is conducted at CIP, where breeding objectives include disease resistance (e.g., to *Phytophthora infestans*). The budget for the program is about 4.8% (representing US$14 million) of the CGIAR commodity investment budget.

Industry highlights

Plant breeding research at ICRISAT

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Introduction

The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) has a global mandate for the improvement of chickpea (*Cicer arietinum* L.), pigeonpea (*Cajanus cajan* (L.) Millsp.), groundnut (*Arachis hypogaea* L.), sorghum (*Sorghum bicolor* (L.) Moench), and pearl millet (*Pennisetum glaucum* (L.) R. Br.) (Fig. 1). These crops are grown in about 100 million hectares globally, predominantly under rainfed conditions by resource-poor farmers of the semiarid tropics.

ICRISAT has assembled over 104,000 accessions of these crops (17,258 chickpea, 13,632 pigeonpea, 15,419 groundnut, 36,774 sorghum, and 21,594 pearl millet) through donations by various genebanks and national programs and joint explorations. These valuable genetic resources preserved in ICRISAT's genebank at Patancheru, India have contributed significantly in

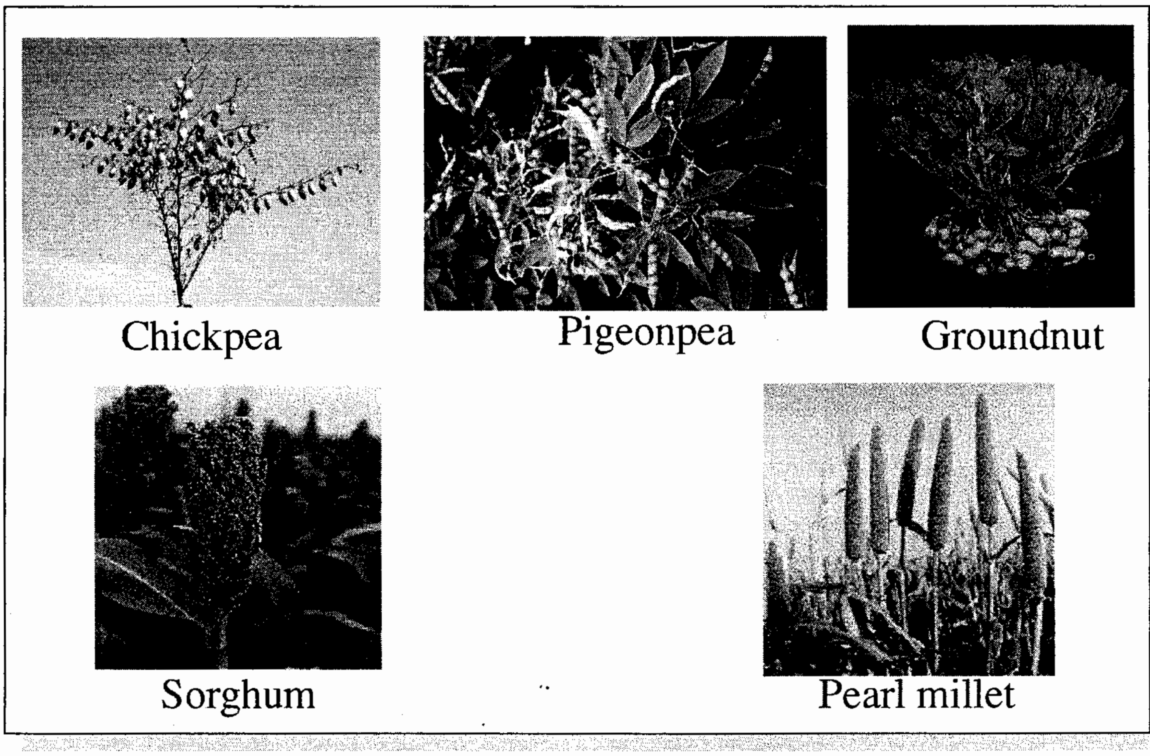

Figure 1 The five mandate crops of ICRISAT.

strengthening breeding programs of ICRISAT and the National Agricultural Research Systems (NARS) globally. Close to 1.2 million samples of these crops have so far been distributed to the NARS and ICRISAT scientists.

The crop improvement activities are conducted at ICRISAT's locations in India and Africa, and jointly with many national program scientists globally, wherever the mandate crops are cultivated. In African regions, the development of varieties in all five crops continues to be the primary objective, while in Asia (specifically for India), the present emphasis is towards development of varieties in chickpea, groundnut, and pigeonpea, and hybrids in sorghum, pearl millet, and pigeonpea. Towards this goal, ICRISAT develops segregating materials, populations, advanced breeding lines, and hybrid parents and supplies these to scientists in NARS, non-government organizations (NGOs), and the private sector for evaluation and selection at their locations and utilization in their breeding programs. Based on performance in local, regional, or national trials, varieties/hybrids are released or notified by the various national programs according to their own protocols and procedures.

Breeding objectives

The crop breeding priorities and strategies at ICRISAT have been dynamic, guided by a changing scenario of agriculture and development of new technologies, and are reviewed and revised periodically based on the feedback from NARS scientists, extension personnel, farmers, consumers, and industry. Improved yield potential (mostly for grain, but more recently also for fodder in sorghum, pearl millet, and pigeonpea) is the common and foremost important breeding objective in all crops. The other major objectives include genetic improvement of resistance/tolerance to diseases (*Fusarium* wilt (FW), *Ascochyta* blight, and *Botrytis* gray mold in chickpea; wilt and sterility mosaic in pigeonpea; rust, early and late leaf spots, and rosette and bud necrosis in groundnut; grain mold, anthracnose, and charcoal rot in sorghum; downy mildew in pearl millet), insect pests (*Helicoverpa* pod borer in chickpea; *Helicoverpa* and *Maruca* pod borers in pigeonpea; shoot fly, stem borer, midge, and head bug in sorghum), and abiotic stresses (drought and cold in chickpea; drought in groundnut; drought, salinity, and acidity in sorghum); adaptation (early maturity in chickpea, pigeonpea, and groundnut) and quality of grain (reduction in aflatoxin contamination in groundnut) and fodder (sorghum, pearl millet, pigeonpea).

Breeding methods and techniques

Conventional breeding methods

Chickpea A combination of the pedigree and bulk methods is generally used for selection after hybridization in this highly self-pollinated legume. The early segregating generations (F_2 and F_3) are invariably grown in FW-sick nurseries and the surviving plants (resistant to *Fusarium* wilt) are harvested as bulk. The selection of single plants starts from F_4 or later generations. Progeny evaluation is carried out in F_5–F_7 generations. High-yielding and nearly uniform progenies are bulked for replicated yield tests. The backcross method is used only occasionally to incorporate one or few traits from a germplasm line, sometimes a wild species, to a well-adapted variety. Rapid generation advancement in a greenhouse following a single-seed descent (SSD) method is generally used for development of recombinant inbred lines.

Pigeonpea Pigeonpea is a partially outcrossed crop (outcrossing up to 30%), and the breeding methods generally recommended for self-pollinated crops are used. Recurrent outcrossing and selfing within landraces has resulted in pigeonpea being heterozygous as well as heterogeneous for important agronomic traits. Such landraces contain a tremendous amount of genetic variability, which has been utilized very effectively to select/breed high-yielding pure-line varieties. Besides this, hybridization and pedigree selection is widely used. The limited natural outcrossing has been successfully exploited for increasing yield and stability through the development of commercial hybrids using genetic male sterility. Currently, cytoplasmic male sterility (CMS) is being used to develop and commercialize hybrids.

Groundnut Being a completely self-pollinating crop, the pedigree method is the most commonly used breeding method in groundnut. This allows breeders to practice selection for highly heritable traits such as plant type, pod and seed size and shape, and testa color in early segregating generations. Selection for quantitative traits such as yield and seed composition is made in later generations. SSD and recurrent selection have been used very sparingly. Only limited use of backcrossing has been made, particularly in situations where one of the parents is a primitive landrace or a compatible wild species.

Sorghum A trait-based pedigree breeding approach is being used in sorghum, in which the families are used as the selection units for resistance response, and individuals within the resistant families are used as selection units for grain yield. Also, a simple, mass selection-based, recurrent method is being used to improve male-sterile (ms_3 and ms_7 genes) populations to develop trait-based gene pools. Simultaneous testcrossing and backcrossing the selected maintainer plants, along with selection for resistance traits and grain yield, in the trait-based breeding programs is carried out for the purpose of improving male-sterile lines for a specific resistance trait and high grain yield through heterosis.

Pearl millet Being a highly cross-pollinated crop (> 85% outcrossing), pearl millet provides an opportunity for exploitation of heterosis. Various forms of recurrent selection have been used to develop open-pollinated varieties (OPVs). The availability of several alternative CMS systems and their restorers has enabled large-scale commercial exploitation of single-cross hybrids in

India. Pedigree breeding has been used in populations developed by recurrent selection, albeit on a limited scale, to develop hybrid parents. Various forms of pedigree breeding have been extensively used in populations derived from hybridization between lines to develop hybrid parents. Backcross breeding has been extensively used in developing partially converted dwarf versions of several composites. Of course, backcrossing remains the only option to develop male-sterile line (A-line) counterparts of maintainer lines (B-lines).

Marker-assisted breeding

Marker-assisted selection (MAS) is being considered as a potential method to hasten and improve the precision and effectiveness of crop improvement. ICRISAT has established a high-throughput applied genomics laboratory and identified molecular markers for several important traits, such as the stay-green trait and resistance to shoot fly and *Striga* in sorghum, and downy mildew resistance and terminal drought tolerance in pearl millet. Research is underway to identify markers for root mass and resistance to *Ascochyta* blight, *Botrytis* gray mold, and *Helicoverpa* pod borer in chickpea; and FW resistance and fertility-restorer genes in pigeonpea. MAS has been successfully practiced for some traits. For instance, marker-assisted backcross breeding was used to incorporate resistance to downy mildew in the pearl millet single-cross hybrid HHB 67. Marker-assisted breeding for terminal drought tolerance in pearl millet is in progress.

Transgenics

Transgenics have been developed in pigeonpea and chickpea with resistance to *Helicoverpa* pod borer by using the *Bt Cry1A(b)* gene derived from the bacterium *Bacillus thuringiensis* and the soybean trypsin inhibitor (*SbTI*) gene. Molecular characterization and insect bioassays are in progress. Efforts are also being made to develop transgenics in chickpea for tolerance to abiotic stresses such as drought and low temperatures. Transgenics have been developed in groundnut for several genes such as those encoding for viral coat protein of Indian peanut clump virus (IPCV) and groundnut rosette assistor virus (GRAV), replicase of IPCV, *Bt Cry1A(b)*, and chitinase from rice. In cereals, transgenics have been developed for resistance to stem borer in sorghum and are currently under greenhouse testing.

Major accomplishments

Chickpea

1 Short duration varieties (85–100 days at Patancheru, 17.4°N) have been developed that can escape terminal drought and provide wider adaptability to the crop, e.g., ICCV 2 and KAK 2 in *kabuli* type and ICC 37 and JG 11 in *desi* type.
2 Super-early *desi* chickpea lines, ICCV 96029 and ICCV 96030, have been developed, which mature in 75–80 days at Patancheru. These lines are being extensively used in crossing programs as source of earliness by NARS in many countries.
3 High root biomass has been identified as an important trait for drought avoidance in terminal drought conditions. Lines with a greater degree of drought tolerance (e.g., ICCV 98901–98907) were developed by combining the large root traits of ICC 4958 with the few pinnules trait of ICCV 5680.
4 Most chickpea cultivars are susceptible to chilling temperatures at flowering. A number of cold-tolerant lines (e.g., ICCVs 88502, 88503, 88506, 88510, 88516) have been developed that are able to set pod at a low temperature.
5 Several varieties with high and stable resistance to FW, the most important root disease of chickpea, have been developed (e.g., ICCV 10, ICCC 37, JG 11).
6 Breeding lines with moderate to high levels of resistance to the important foliar diseases *Ascochyta* blight (e.g., ICCV 04512, ICCV 04514, ICCV 04516) and *Botrytis* gray mold (e.g., ICCL 87322, ICCV 88510), have been developed.
7 Sources of high-level resistance are not available for pod borer (*Helicoverpa armigera* Hubner), which is the most important pest of chickpea worldwide. Several breeding lines/cultivars have been developed with some level of resistance, e.g., ICCV 7, ICCV 10, ICCL 86102, and ICCL 86103. Further efforts are being made to combine different mechanisms of resistance identified in the cultivated and wild germplasm.

Pigeonpea

1 Extra-early and early maturing (90–120 days at Patancheru, 17.4°N) photoinsensitive varieties/lines have been developed that made cultivation of pigeonpea possible in a range of environments. Extra-early lines (e.g., ICPL 88039) allow farmers to take two crops (pigeonpea and wheat) in a year.
2 FW and sterility mosaic are major pigeonpea diseases. A number of varieties with high resistance to FW and sterility mosiac have been developed and some of these have combined resistance to both diseases (e.g., ICPL 87119).
3 *Helicoverpa* and *Maruca* pod borers are the major insect pests. Sources of moderate resistance have been identified and a moderately resistant variety ("Abhaya") has been released.
4 The high protein trait was successfully transferred from wild species *Cajanus scarabaeoides*, *C. sericeus*, and *C. albicans* to the cultivated species without sacrificing grain yield or seed size (e.g., HPL 40).
5 Commercial hybrids were initially developed using genetic male-sterility systems (e.g., ICPH 8). These provided, on average, 30–35% more yield and greater stability in yield than the pure-line cultivars. Recently, three stable CMS systems have been developed and corresponding fertility restores have been identified to overcome the problems of hybrid seed production associated with genetic male-sterility systems. Efforts are being made to develop commercial hybrids using CMS systems.

Groundnut

1. Several drought-tolerant and high-yielding varieties have been developed, which perform well under rainfed conditions, e.g., ICGS 5, ICGS 44, ICGS 76, and ICG (FDRS) 10 for mid-season drought, and ICGS 11 and ICGS 37 for end-of-season drought in India and ICGV 86021 for end-of-season drought in Indonesia.
2. Varieties with high levels of resistance to rust and moderate levels of resistance to late leaf spot have been developed and released by national programs to farmers in Asia (ICG (FDRS) 10 and ICGV 86590 in India) and Africa (ICG (FDRS) 4 in Mali). Resistance to early leaf spot has been introgressed from wild *Arachis* species.
3. Varieties with field resistance to peanut bud necrosis disease, a widespread disease in Asia, have been developed (e.g., ICGS 11, ICGS 44, and ICGS 37). These varieties are generally resistant/tolerant to thrips, the vector of the disease. Some genotypes also show tolerance to the virus (ICGV 86031 and ICGV 86029).
4. Groundnut rosette disease (GRD) is endemic to Africa and its nearby islands. A short-duration GRD-resistant variety has been developed (ICGV-IS 96894) and released as "Samnut 23" in Nigeria.
5. The contamination of groundnut by aflatoxins is a serious problem in most groundnut-producing countries. Genetic variation has been identified for preharvest seed infection, *in vitro* seed colonization, and aflatoxin production. These resistances have been transferred to superior agronomic backgrounds, e.g., ICGV 88145 and ICGV 89104.
6. Short-duration varieties are required where the growing season is short, crops suffer end-of-season drought, early frost occurs, and in multiple cropping system. Using the thermal time concept, several short-duration and high-yielding cultivars have been developed (e.g., ICGV 86143 as "BSR 1" in India; ICGV 86015 as "Jayanti" in Nepal; BARD 92 in Pakistan; HL 25 in Vietnam; ICGV 93382 as "Sinpadetha 7" in Myanmar; ICGV 86072 as "BARI Groundnut 5" in Bangladesh; and ICGV 93437 as "Nyanda" in Zimbabwe). It has also been possible to combine early maturity with high-yield potential and tolerance to rust, late leaf spots, and low temperature in ICGV 92267.
7. Groundnut genotypes belonging to Spanish types have non-dormant seed, and rains prior to harvest in such genotypes can cause seeds to sprout in the ground, resulting in loss of yield and poor quality of produce. A fresh seed dormancy trait has been successfully introduced in Spanish types from Virginia types, and several short-duration Spanish cultivars with a fresh seed dormancy of 2–3 weeks have been developed, e.g., ICGVs 86155, 86156, 86158, 87378, 87921, and 93470.

Sorghum

1. Several high-yielding varieties have been developed and released in several countries in Africa and Asia for rainfed, drought-prone areas. Some varieties are popular in many countries (e.g., ICSV 112 in Zimbabwe, Kenya, Swaziland, Malawi, and Mozambique; ICSV 111 in Cameroon, Chad, and Nigeria). Some varieties have been bred for dual purposes (grain and stover), e.g., ICSV 112 and ICSV745. A variety NTJ 2 is highly popular for its "roti" making quality.
2. Several ICRISAT-bred improved hybrid parents have been extensively used by both public and private sector research organizations to develop and market hybrids in Asia. More than 30 hybrids, based on ICRISAT-bred parents, have been released in India and China. Notable among them are JKSH 22 in India, and Lio Za 4, Longsi 1, Jinza 12, and Gilaza 80 in China.
3. *Striga*, an obnoxious obligate parasitic weed is one of the most important biotic yield constraints in Africa, although less important in Asia. Several *Striga*-resistant varieties (e.g., "Framida" in Burkina Faso and Ghana, "SAR 1" in India) and seed parents (e.g., ICSAs 579, 583, 584, 588, 592) have been developed.
4. Grain mold is an important disease of sorghum in Asia and Africa. Many grain mold-resistant varieties have been developed. Among them, PVK 801, besides being grain mold resistant is a dual-purpose variety with a good quality stover.
5. Shoot fly, stem borer, and midge are the major insect pests of sorghum. Midge-resistant white grain varieties in tan color background (e.g., ICSV 745, PM 13654) have been released in Australia. Several grain mold-resistant (e.g., ICSAs 300, 369, 400, 403, 404) and shoot fly-tolerant (e.g., ICSA 419 and ICSA 435 for rainy season, ICSA 445 and ICSA 452 for post rainy season) CMS-based seed parents have been developed.

Pearl millet

1. About 60 OPVs – 40 in Asia and 20 in African regions – have been developed primarily for grain yield and downy mildew resistance. The most popular OPVs include WC-C75 and ICTP 8203.
2. Several hybrids and hybrid parents have been developed with resistance to downy mildew, ergot, and smut. ICMH 451, the first ICRISAT-bred hybrid developed in 1986, covered an area of over 1.0 million ha by the mid-1990s. Later ICRISAT developed and disseminated a wide range of breeding materials and over 90 male-sterile lines for use by NARS and the private sector in hybrid development. Of the 70 pearl millet hybrids released in India, about 60 are based on ICRISAT-bred A-lines or on A-lines developed by the public and private sectors from ICRSAT-bred germplasm.
3. Alternative and more stable CMS sources were identified and characterized. The A_1 CMS system was not associated with susceptibility to downy mildew, ergot, and smut. Using the stable A_4 CMS system, it was also shown that it is possible to quickly develop male-sterile populations for use in breeding interpopulation hybrids.
4. Topcross, three-way, and interpopulation hybrids forms were identified to have numerous advantages over single-cross hybrids, in terms of seed production economy and reduced vulnerability of downy mildew, ergot, and smut diseases. Topcross hybrids were suggested to be the most efficient route to combine the high-yield potential of improved seed parents and the adaptation of landrace-derived populations.