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Market-Driven Plant Breeding for Practicing Breeders

Springer

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Foreword 1

Agriculture in India has been essentially a production-driven system for the past many decades, as it is in many developing countries. As we struggled to feed a growing population, the emphasis was producing more at affordable prices. Faced with shortages, the country had to focus on increasing production, and rightly so.

But the situation has also been changing simultaneously. With the rapid increase in per capita income in India from Rs. 25,987 in 2004–2005 to Rs. 1,28,829 in 2020–2021 at current prices (source: Ministry of Statistics & Programme Implementation GOI, World Bank and IMF World Economic Outlook: https://statisticstimes.com/economy/country/india-gdp-per-capita.php), the purchasing power of the common man has increased considerably. This is expected to grow by 58% in the next 5 years. The recent 15-year period has witnessed consumer preferences leaning towards private markets. In many fields, modern digital technology and big data analytics have made it possible for businesses to offer tailor-made products to suit consumer needs in different market segments. Food cannot lag behind.

The bottom of the pyramid still needs a large volume of food at affordable prices, thereby continuing the need for our agriculture to focus on higher yields and stress tolerance. However, the need for differentiated food products for the population with higher incomes has become markedly evident in the last 10–15 years, thereby propelling the need for market-driven agriculture, which meets the needs of different market segments.

In this context, market-driven plant breeding is essential to support market-driven agriculture. I am very happy that this book is coming out at a crucial juncture in the development of agricultural research, which is gearing itself to meet future challenges posed by food and nutrition security, climate change, changing food baskets, depletion of natural resources, stagnant yields, farm mechanization, digital transformation of agriculture, and other similar changes.

The stupendous achievements of plant breeding in improving crops have been laudable. The world in general—and India in particular—has hugely benefited by the advances in plant breeding and plant biotechnology. But, if we observe closely, the most successful crop varieties are those which met either felt or latent needs in the market. While some varieties may have succeeded mainly due to marketing efforts, most of them have succeeded because they fitted well—by design or by accident—with the needs of the customer.

Farmers are running a production system that is aimed at meeting the requirements of the consumers. In the value chain of a crop, the players include farmers, primary and secondary processors, traders, and the consumer. Each of them has his/her own expectations or requirements, which may be different from others. Understanding and incorporating these requirements for maximizing the synergistic impact of the germplasm is important. It is critical that breeders stay connected to the markets, which in their entirety include farmers and consumers, as well as the players in the value chain in between.

If the breeders are developing seed varieties for export markets, the farmers, consumers, and value chain players in those countries become the customers. Similarly, if the breeding is aimed at improving crops to make them suitable for export purposes, either as agricultural produce or as processed food, breeders need to understand the requirements of those market segments and tailor the varieties accordingly.

We cannot ignore the role of the society in acceptance of technologies, especially those which are used in agriculture and the manufacture of food. Hence, it is also a politically sensitive subject. Plant breeders and biotechnologists need to always keep in mind the social acceptance of their products. In this context, social scientists play an important role. It may be necessary for seed technology scientists to consult social scientists while developing technologies or products that are different from the traditional ones.

It is important that breeders in both the public and the private sectors keep the market requirements in mind. In the private sector, the planning process takes care of some of this aspect, as the companies are closely connected to the markets of farmers. They are still not fully connected, however, to the ultimate consumers, food companies, and exporters. This gap needs to be bridged by forming collaborative breeding programs with the food industry. The seed industry should also participate in consumer surveys conducted to understand the likely future trends in consumption. This is a highly dynamic area and needs constant monitoring.

As the CEO of a seed company, I always spent considerable time with breeding teams when they were setting up the objectives of their breeding programs. This is a crucial part of the preparation of our research teams to cater to the needs of the market. Breeders need to visit markets regularly and interact with farmers, processors, and exporters to understand the trends. Within the organization, whether public or private, there should be an institutionalized process of connecting markets to the breeders. The formation of teams for each crop, which bring together marketing and seed production personnel with the breeders of that crop, helps in this process, as observed by me during my career in the seed industry. Functions should not operate in silos.

Biotechnology has had—and will have—a huge impact on breeding strategies and possibilities. As human endeavor advances its efforts to find answers to ever-new challenges that come up, there will be greater technological developments in the future. They will facilitate market-driven plant breeding in a more precise and quicker fashion. However, it is the plant breeder who needs to have that "eye" for the continuously changing market requirements, so that he/she can utilize the new technological tools for a well-directed research effort.

Some of those aspects find detailed explanation in this book. I have no doubt that the book will be extremely useful for breeders involved in crop improvement programs. The authors have made a tremendous effort to incorporate significant knowledge, which makes the book a "must have" asset in your portfolio. This results from their vast experience in the field, and from their ability to convert all that knowledge into useful guidelines for breeders, business managers, policymakers, marketing professionals, and other stakeholders. This is the first book of its kind in this field. I am confident that many agri-input industry professionals will benefit from it.

I congratulate the authors for bringing out this invaluable book.

Federation of Seed Industry in India (FSII) Ram Kaundinya
New Delhi, India

Foreword 2

It is a privilege and pleasure to write the foreword for this book. I consider it futuristic in the present-day context, where plant breeding is becoming increasingly important to meet the demands for food and nutrition security for the ever-increasing global population, which is expected to reach nine billion by 2050. During my Master's degree program in Plant Breeding (at the GB Pant University of Agriculture and Technology, Pantnagar, Uttarakhand, India) in the early 1970s, I considered plant breeding to be the same in public sector institutions and in private sector seed companies. However, over the years, after working with private sector seed companies (during my career with ICRISAT, the International Crops Research Institute for the Semi-Arid Tropics, Hyderabad, India), my perception has changed. The discussions and deliberations for the formation of the ICRISAT-Private Sector Hybrid Parents Research Consortia (HPRC) were highly educative. I was able to understand the importance and the need for commercial or market-driven plant breeding to be different from the public sector plant breeding efforts.

Broadly speaking, plant breeding can be defined as "fast-track evolution of economically important plant species to develop improved varieties, which produce better quality and quantity of the produce for food, feed, and fodder to enhance quality of life in human beings."

Working in an International public sector research and development (R&D) institute, (i.e., ICRISAT), plant breeding was considered a public good activity that produces International Public Goods (IPGs), including early-generation and advanced-generation breeding materials, which could then be shared with both public sector institutions and private sector seed companies, for them to further develop and release the breeding materials as improved crop cultivars (varieties/hybrids) to the farming community.

The private sector translates public goods from publicly funded research institutions into private sector assets, which can earn profits for their companies. Plant breeding in the private sector is different from that in the public sector for the following considerations: (1) market-oriented approach; (2) profit-driven goals; (3) speed and cost-effectiveness of the breeding efforts; (4) farmer-centric, targeted trait development; and (5) clarity of end-user needs in the selection of traits. While efforts in the public sector aim at releasing a variety, the private sector plant breeders' efforts continue to be invested on seed production and on placing the seed in the market at the right time and place, and at a price that is affordable to the targeted farmer. The private sector has an effective network of seed producers, as well as seed distributors, in the marketing system. That is how they succeed in marketing the varieties or hybrids that they produce. The private sector has also invested in strategic research and development as and when needed, including in biotechnology, so that they can always stay ahead of the competitors.

The book on *Market-Driven Plant Breeding* has been well conceived, and the chapters in the book are well thought out; they cover the most critical aspects of commercial plant breeding programs. In the past four decades, we have seen large investments by the private sector seed companies not only into basic and strategic research, but also on practical, adaptive, and applied research. Many new disruptive technologies that include cutting-edge technologies are being deployed from both information technology and biotechnology spheres. These new-age research methods and technologies have tremendously helped both the speed and accuracy of plant breeding, and the return on investment has been very good.

The ten chapters in the book cover a range of highly relevant aspects and issues, as they relate to market-oriented plant breeding. A major consideration in market-driven plant breeding is the need to retain productive staff for a long time because plant breeding is a long-term investment, and it will need committed staff to ensure that the products are delivered on time to the farmer. Despite the efforts by the private sector seed companies to retain committed and high-performing plant breeders, a high attrition rate and poaching within the industry have been common. Many private sector seed companies are investing in continuous training and in upgrading the skills of their plant breeders. That effort must be strengthened further under the Foundation for Advanced Training of Plant Breeders (ATPBR). The effort should also ensure that, in addition to the staff in many private sector companies, ATPBR can also train the public sector plant breeders. This book can be an effective instrument in such efforts.

ICRISAT
Patancheru, India

C. L. Laxmipathi Gowda

Preface

Plant breeding, the science of altering heritable patterns of economically important traits of plants to increase their value, is broadly defined as purposeful manipulation of plant genotypes to create desirable phenotypes for the benefit of mankind. A science-driven, inventive process of genetically improving plant varieties culminates in cultivar development and crop improvement, via improvement of the seed. It encompasses the creation of multi-generation, genetically diverse populations on which human knowledge and selection skills are applied to generate genetically altered plants, with precise new combinations of desirable traits. Commercial-scale plant breeding is a multifaceted process in which new crop varieties are continuously developed to enhance their yield and agronomic performance over the prevalent varieties. Plant breeders exercise planned and extensive selection practices to identify top performing plants with desired trait combinations, while minimizing inadvertent unintended changes.

In our current times, there is a pressing need to reorient plant breeding to create "smart" crop varieties that yield more with fewer inputs, which are also resilient to climate change. In addition, plant breeding helps to achieve food security and sustainability through the development of high-yielding, climate-resilient, nutritious, improved crop varieties; it thereby addresses the challenges posed by the needs of a growing global population, shrinking genetic diversity, and uncertain environmental conditions.

Both public and private sector organizations have contributed significantly to the development of improved varieties, which have had a strong positive impact on the economic well-being of its stakeholders (farmers, vendors, seed producers, marketing personnel, researchers, etc.), as well as on employment, environmental protection, and biodiversity conservation. Over the last three to four decades, there has been a significant increase in plant breeding activities in the private sector across the globe. On the one hand, this reflects the integration of advanced technologies into conventional plant breeding processes, the need for intellectual property protection of new plant varieties, and the globalization of seed trade. On the other hand, it is a consequence of shrinking or stagnant budgets devoted to applied plant breeding in the public sector.

Historically, the private sector has developed effective and efficient mechanisms to translate public sector research and innovations into commercially viable plant breeding products, delivered through seeds and/or other planting materials. Further, more recent efforts in the private sector have been devoted to efficient utilization of technological tools, as well as wider geographic and commodity coverage, involving greater fiscal commitment towards strengthening R&D capabilities to produce appropriate innovations. Those efforts have made it a front runner in the acceleration of plant breeding programs, development of improved varieties, and dissemination of improved varieties through scalable, high-quality seed delivery systems.

The outcomes sought and successes achieved by plant breeding in the future will be measured in terms of sustainable improvements in agricultural production of food, feed, fiber, fuel, and other plant products that meet the needs of society. Since plant breeding research in the private sector is driven by ROI (Return on Investment) and changing market preferences, plant breeders need to work very efficiently to deliver targeted outputs, under stricter timelines and clearly defined budgets, so that new varieties become available in the shortest possible time. To do so effectively, private sector plant breeding needs to respond quickly to changes in the market requirements and to spot new opportunities for improved plant varieties and hybrids as they occur. And despite the growing private sector involvement in plant breeding, presence of the public sector will continue to be crucial in the areas of plant breeding education, pre-breeding, new germplasm development, and conservation.

Over the past 30–40 years, private sector investments in R&D have increased substantially, and so has the requirement of skilled plant breeders. To build the capability in human skills required for crop improvement in the future, a new generation of plant breeders must be trained. In India, the private sector engages a major part of the existing workforce of plant breeders, but it needs trained plant breeders in greater numbers to augment breeding capabilities, and thus meet the growing demand of food, as well as plant-derived products, for an ever-increasing population. The current availability of skilled breeders is inadequate to fully capitalize on the benefits from available plant genetic resources.

To meet the growing need for plant breeders at regional, national, and global levels, it is essential both to train the existing workforce in the best practices and to develop a stream of highly skilled breeders to serve the growing needs of the industry. Plant breeders must be trained with an integrated set of capabilities to build and sustain effective regional, national, and global plant breeding capacities. Structured education and training are the traditional methods to identify and develop breeders. There is a need to update plant breeding education programs, both to meet the current needs of a rapidly expanding job market and to provide the requisite knowledge and skill for the future.

The authors have attempted to elucidate the finer aspects of plant breeding practices, as carried out in a commercially driven seed business, based on their collective experience over a substantial period of working in both the public and private sectors, nationally and internationally. This book encompasses their accumulated understanding of a lifetime, as it relates to practical and successful plant breeding.

The ten chapters in the book cover a range of topics from the evolution of plant breeding to recent trends, including contemporary regulations governing plant breeding. The range encompasses germplasm management; designing breeding programs for targeted deliveries; inbred line development and hybrid breeding; use of molecular technologies; product development; maintenance breeding; seed production research; and the role of breeders in related functions of the seed value chain. Each chapter contains detailed explanations, integrating knowledge and experience, for both potential and practicing plant breeders. Given the diverse experience of the authors, there is a diversity in approaches to their topics as well, and no attempt has been made to impose (or even arrive at by discussion) a consistency or uniformity of approach across the chapters.

The book highlights plant breeding in a competitive market-driven environment, and it describes the crucial aspects of the seed value chain. We earnestly hope that this book will prove to be a valuable source of practical knowledge, and thus help readers to effectively accelerate their plant breeding efforts in a market-driven world.

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Bangalore, Karnataka, India — Sharan P. Angadi
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Bangalore, Karnataka, India — M. J. Vasudeva Rao

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Thinking about writing a book and converting that idea into a book are two different sides of a coin. Writing a book is an emotional journey, and this experience is challenging as well as rewarding. The authors were inspired by their brilliant friends, colleagues, and family members to deliver their best experience in the form of this book. The authors wish to record thanks to the following (mostly unseen) contributors.

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Following authors have contributed specific chapters as mentioned against their names in the book:

Chapter 1. Plant Breeding: Its Evolution and Recent Trends - Aparna Tiwari

Chapter 2. Germplasm Management in Commercial Plant Breeding Programs - Surinder K. Tikoo

Chapter 3. Designing Plant Breeding Programs for Targeted Deliveries - M. J. Vasudeva Rao

Chapter 4. Inbred Line Development and Hybrid Breeding - Sharan Angadi

Chapter 5. Use of Molecular Technologies in Plant Breeding - Suresh B. Kadaru and Sadananda R. Ajanahalli

Chapter 6. Product Development in Market-Driven Plant Breeding - Surinder K. Tikoo

Chapter 7. Maintenance Breeding - Sadananda R. Ajanahalli

Chapter 8 Seed Production Research - Sadananda R. Ajanahalli

Chapter 9. Breeders' Role in Supporting Allied Functions in the Seed Business - Sadananda R. Ajanahalli

Chapter 10. Regulatory Aspects of the Seed Business in Relation to Plant Breeding - Sadananda R. Ajanahalli

—The Authors

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About the Authors

Aparna Tiwari is cofounder and Chief Executive Officer at the Foundation for Advanced Training in Plant breeding (ATPBR), where she leads professional training, technology liaising, awareness sessions, and other capacity building activities. She also serves as a conference secretary and coordinates 5F Farming national conferences annually. She has worked previously in various positions with the FAO (Food and Agriculture Organization), Monsanto India Pvt. Ltd., ICRISAT (International Crops Research Institute for the Semi-Arid Tropics), and the MGM–Institute of Technology. She obtained her MSc and PhD from the Wageningen University, The Netherlands, and her Bachelor's (BSc) from Banaras Hindu University. She has authored a book and published several research papers in peer-reviewed international journals and conferences.

Surinder Kumar Tikoo currently Cofounder and Director Research—Breeding and Development, Tierra Seed Science Pvt. Ltd., Pune, has five decades of experience as a successful vegetable breeder, teacher, and research and development manager. He has held global leadership positions over long periods in two private sector organizations, as well as spent 20 years with the Indian Council of Agricultural Research (ICAR) as a vegetables breeder, teacher, and research guide. He has developed several nationally and internationally released varieties and hybrids of tomato and okra, some of which are market leaders in their respective segments. He has served on several advisory committees of the Government of India and various professional bodies. Dr. Tikoo, a PhD from Bangalore University, has published over 50 research and review papers. He also holds one patent. He has been conferred the Lifetime Achievement Award for Excellence in Translational Research, jointly by the Society of Plant Biochemistry and Biotechnology and Springer.

Sharan Angadi is a plant geneticist and breeder who worked for 17 years in India, first with UAS, Bangalore, and then with the Indian Council for Agricultural Research (ICAR), contributing significantly to the genetic improvement of oilseed crops and horticultural crops. He then devoted 22 years to Pro Agro PGS and Nunhems Seeds, Netherlands, where he served as Head of Breeding for Asia Pacific and Global Coordinator for peppers, spanning several countries in Asia, Europe, and the Americas. He has particular experience in applying emerging technologies to viable commercial plant breeding. Dr. Angadi has a PhD from IARI, New Delhi; an MSc from Tamil Nadu Agricultural University, Coimbatore; and a BSc from UAS, Bangalore. After retirement, he continues to provide expert R&D advice to seed companies in India and abroad, besides serving on various expert bodies. The Asia and Pacific Seed Association (APSA) honored him with The Most Influential Plant Breeding Researcher for Horticultural Crops Award for the year 2021.

Suresh B. Kadaru has nearly 15 years of industry research experience in developing superior seed products for farmers, using modern breeding tools, technologies, and data analytics. He completed his BSc (Agri.) at Acharya NG Ranga Agriculture University, Rajendranagar, and his MSc (Biotechnology) from Tamil Nadu Agricultural University, Coimbatore, India. After completing his PhD in Agronomy and Applied Statistics from Louisiana State University, Baton Rouge, he worked as a Marker Data Analyst in Syngenta, USA, pioneering the application of molecular markers in plant breeding. Then relocating to India, he has provided functional leadership and served on the regional Seeds Product Development Leadership Team, which defines R&D strategies for maize and rice crops in the Asia-Pacific region. In addition to his publications, he has a joint patent and considerable training experience to his credit. He has received several internal awards in Syngenta for his markers assisted breeding work on rice and corn hybrids.

Sadananda R. Ajanahalli an expert in agricultural research and technology management, has more than 40 years' experience in the seed industry and in international and national public research institutions, including the International Maize and Wheat Improvement Center (CIMMYT), with whom he was associated as Maize Seed Systems Specialist for Asia. His various roles and responsibilities have included plant breeding, product development, and seed system management. After retiring from CIMMYT, he has pursued consultancy activities through the firm, AGREEVA. He has managed R&D in multinational and Indian seed companies for over 17 years and facilitated the development and deployment of Bt cotton hybrids (BGI & BGII) and maize hybrids in the shortest possible time. He has developed 47 hybrids and varieties in different field crops and served on various industrial bodies for biodiversity, variety protection, and biotechnology. Dr. Sadananda holds a PhD in Genetics from IARI, New Delhi.

M. J. Vasudeva Rao (PhD in Genetics, IARI; MSc in Plant Breeding, UAS, Bangalore) has spent 15 years as a plant breeder in the public sector, and then nearly 35 years in the private seed sector. While at ICRISAT, he won the Hari Om Ashram Award from ICAR for his work on *Striga* resistance in sorghum; he also did pioneering work on early-maturing groundnut. His responsibilities in multinational and national seed companies in India ranged from Breeding and Research Management to include supply chain, sales, marketing, and business opportunities. He last served as President, Agricultural Technology, at Metahelix Life Sciences Private Ltd. (a Tata enterprise). His contributions to plant breeding in developing successful new varieties and hybrids, new selection technologies, and in mentoring plant breeders have won him the Lifetime Achievement Award in Plant Breeding by the ATPBR (Foundation for Advanced Training in Plant Breeding). He has published extensively and served on many committees to promote the science of Plant Breeding.

Plant Breeding: Its Evolution and Recent Trends

1

Abstract

Plant breeding is the process of improving crops. It continuously addresses the evolving needs of consumers by introducing new genetic diversity through new products. The principles of plant breeding and tools of biotechnologies are being effectively utilized by breeders to improve crop performance; they do so by developing varieties with better nutritional content and agronomic traits (e.g., yield, disease resistance, etc.). Breeders work in close association with farmers as well as consumers to understand their preferences and priorities, and accordingly design and execute comprehensive breeding strategies to maximize revenue opportunities of all stakeholders through the new improved varieties. A successful breeder requires technical knowledge and acquires extensive experience over time. But breeding successes are often confined to a handful of experts, who know how to translate breeding challenges into opportunities, and how to take ownership of efforts to develop an improved variety, by minimizing total cost without compromising on productivity and quality of produce.

With the increasing need for food from a growing human population, it has now become indispensable for us all to learn from the best commercial plant breeding practices. This chapter aims to emphasize the need to train breeders with the knowledge and wisdom acquired from experienced breeders in a commercial setting.

1.1 Introduction

The world population has been growing continuously, necessitating a corresponding rise in the demand for food. By 2050, we may need to feed about 2.3 billion more mouths than we do today (FAO 2009). Much of the population growth is predicted to occur in urban areas, while urbanization already exerts a slowing effect on

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agriculture. While, on the one hand, food consumption per capita increases tremendously, on the other hand, skilled labor in rural areas is becoming scarce. This eventually poses a serious threat to food security. There are several other factors affecting food security, such as the following:

1. Currently over 50,000 edible plant species are available in the world, of which, only 30 species are grown, providing 95% of human dietary energy. Rice, wheat, maize, and potato are the four crops that provide more than 60% of the world's food energy intake. This dependence on a few selected crop species would be a serious threat for food security.
2. The global climate is undergoing severe changes, with rising incidences of unpredictable storms, shrinking the available area of arable farmland. Increases in global temperature have been disrupting the normal agricultural production patterns. This intensifies the difficulties of maintaining genetic resistances against pests, diseases, and weeds among crops.
3. There is a continuously growing demand for nutritious and quality food, mainly due to economic progress in the developing countries, such as China, India, Indonesia, Brazil, and Mexico.

In modern times, there are numerous questions related to food security, which breeders and agricultural experts need to address. For example,

1. Can the existing food systems suffice to feed the growing global population, which is projected to cross 9 billion by 2050?
2. Can agriculture generate more livelihood opportunities, which, in turn, can ease the mass migration to cities?
3. Can breeders achieve the expected increases in the rates of production?
4. Can all stakeholders of the agriculture system (i.e., public sector, private sector, farmers, consumers, government bodies) work in unison to promote the sustainable development of agriculture?

The answer to all these questions is affirmative, in that sustainable production can be achieved by using climate-smart farming techniques in efforts led by competent breeders, who aim to stabilize the food security via the development of crop varieties that are tolerant to pests, diseases, drought, waterlogging, and salinity (FAO 2013). Over the past few decades, advanced technologies, and introduction of enhanced seed varieties, with traits such as higher yield, improved nutritional quality, reduced crop damage, and disease resistance, have encouraged farmers to shift from the usage of farm-saved seeds to the use of value-added, innovative, commercial hybrid seeds. This shift has been possible with the advancements in plant breeding.

Plant breeding is an effective tool to make genetic changes in plants to achieve the desirable phenotypes. Plant breeding helps to develop improved varieties for resistance to biotic and abiotic stresses, improve crop productivity, and thus help stabilize the market and reduce price volatility, contribute to reduction of greenhouse gas emission, and help improve farmers' incomes. These are achieved, however, by skilled expert plant breeders, using innovative tools and exploiting the available pool of germplasm. Today's innovations in plant breeding use sophisticated science and technology that includes speed breeding, genomic selection, gene mapping, precision phenotyping, mutations, and marker-assisted breeding (MAB). Though plant breeders play a very critical role in crop improvement, their current set of skills and competencies may not be adequate to meet the current and future demands for improved varieties.

This chapter provides an overview of the plant breeding industry and elaborates the importance of plant breeding research to meet the needs of growing populations. It attempts to cover the evolution of plant breeding, along with the market forces that will drive the future direction of plant breeding research, which indicates the growing prominence of the private sector in plant breeding research to meet the trends of the future market. The importance of plant breeding is increasing and so is the need for competent plant breeders.

1.2 History and Evolution of Plant Breeding

Plant breeding has a very long history. If selection is considered as the beginning of crop improvement, then plant breeding began with the start of agriculture in human civilization. Every single person of those times was the first or primitive plant breeder. In the early years of plant breeding, variability was exploited by natural selection, which is still followed by farmers who use farm-saved seeds from selected plants for sowing. Over the years, this selection process has evolved into a very precise and efficient scientific body of knowledge, i.e., the science of plant breeding.

Agriculture is a continuous evolutionary process and so is plant breeding (see Table 1.1), where a few methods are basic and evergreen, to be always applied in any breeding program (such as introduction, selection, hybridization, mutation, etc.). A few others are still in the process of improvement and adaptation (such as genetically modified organisms, or GMO, and genomic selection), while some are in the fully mature phase (e.g., marker-assisted selection, or MAS, mapping). Experts have classified the history of plant breeding into four stages or eras: Pre-Mendelian, Mendelian, Post-Mendelian, and Modern (see Table 1.1 and Fig. 1.1; see also Flannery 1973; Palladino 1993; Diamond 2002; Davies 2003).

Toward the latter part of the seventeenth century, Marcello Malpighi and Nehemiah Grew contributed substantially to early understandings of plant anatomy and reproduction, which marked the beginning of scientific forays into plant breeding. Marcello Malpighi was the first scientist to describe the plant structures and the generation of seeds in 1675, which was elaborated further to identify the parts involved in the germination and growth of young plants.

The discovery of the laws of inheritance by Mendel toward the end of the nineteenth century accelerated the innovations in crop improvement. The scientific basis of these laws allowed the creation of combinations of beneficial traits among parent plants more precisely and efficiently than before. Later, the discovery of DNA structure in 1953 by Watson and Crick increased the knowledge of genetic material

Table 1.1 The four stages or eras in the history of plant breeding

"Pre-Mendelian" - before 1900

- 9000 BC - First evidence of domestication
- 1717 - first artificial hybrid Fairchild's mule by crossing Carnation and Dianthu (Sweet william variety)
- 1801 - Lamarck's theory of inheritence of acquired characters
- 1859 - Darwin's "Origin of Species" published - has details on inbreeding, sterility etc.
- 1866 - Mendel's Laws of Inheritance - "recombination", "segregation", "dominance"

"Mendelian" - 1900 - 1920

- 1899 - Terms "allelomorph", "homozygote", "heterozygote", "F1" and "F2" (Bateson)
- 1900 - deVries' Mutation Theory
- 1902 - Pure line theory (Johannsen)
- 1903 - Embryo culture (Hannig)
- 1906 - Term "Genetics" (Bateson)
- 1906 - Multiple Factor Hypothesis (George Yule)

"Post Mendelian" - 1921 - 1950

- 1928 - Mutagenic effects of X-rays in barley
- 1929 - 10 chromosomes in maize identified
- 1931 - Cytological proof of crossing-over
- 1933 - Cytoplasmic male sterility in maize discovered (Rhoades)
- 1944 - DNA identified as the hereditary material
- 1945 - Recurrent selection method(Hull)
- 1946 - Reciprocal (half-sib) recurrent selection
- 1950 - Ac-Ds system of transposable elements in maize (McClintock)

"Modern" - 1951 to present

- 1952 - Use of multi lines in oats (Janssen)
- 1953 - method of developing multilines in Wheat outlined (Borlaug)
- 1953 - Structure of DNA (Watson and Crick)
- 1956 - G for gene hypothesis for host-parasite resistance (Flor)
- 1964 - Developed high yielding semi dwarf varieties of wheat which resulted in green revolution (Borlaug)
- 1965 - First applied Single Seed Descent (SSD) method in oats (Graphius)
- 1968 - Developed the concept of crop ideotype in wheat (Donald)
- 1970 - World's first cotton hybrid for commercial cultivation in India (Patel)
- 1970 - rDNA technology (Berg, Cohen and Bayer)
- 1976 - World's first rice hybrid (CMS based) for commercial cultivation in China
- 1983 - First GE transgenic plant – tobacco - in USA (Fraley et al.)
- 1987 - World's transgenic cotton plant in USA (Monsanto)
- 1991 - World's first pigeon pea hybrid (ICPH 8) (GMS based) for commercial cultivation in India
- 1994 - "FlavrSavr" tomato, first GM food produced for the market (Calgene, California)
- 1994 - GMO, Insect resistant cotton
- 1995 - BT corn developed
- 1996 - Glyphosate Resistant Crop® soyabean
- 1997 - Terminator gene allowing germination of seed for one generation only (Monsanto, USA)
- 1998 - Identification of traitor gene, which responds to specific brand of fertilizers and insecticides
- 2000 - Marker Assisted Selection Barley resistant to yellow dwarf virus
- 2004 - Glyphosate Resistant Crop® wheat developed
- 2010 - Genomic selection
- 2012 - CRISPR-Cas9 (Gene editing)
- 2018 - Speed breeding

substantially. Targeting the DNA to restructure plant anatomy through mutation breeding became the center of research in plant breeding around 1960. In 1983, with the development of recombinant DNA or GM (Genetic Modification) technology, modern plant breeding techniques, such as genomic selection, became a reality. During the same period, the "Green Revolution" (from 1960 to 1980) was noted bringing about remarkable increases in the production of wheat and rice. The establishment of CIMMYT (International Maize and Wheat Improvement Centre) in 1966 and IRRI (International Rice Research Institute) in 1960 contributed