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Review Article

Plant Breeding: An Art and Science of Modifying Plants for Human Benefits

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Abstract: Plant breeding is one of the oldest human practices dated back to 10,000 years ago, with people selecting plants that have been more prolific and beneficial. The success of plant breeding matched the rise of civilizations, albeit the general public has not acknowledged this. It may be due to a misunderstanding of what plant breeding entails. Plant breeding developed over time never lost its essence as an art and science of modifying plants for human benefits. The review discussed the evolution of plant breeding concepts and procedures separated arbitrarily into selection based on phenotypes, breeding values, and genotypes. The phenotype would continue to be essential in the present and future, regardless of how large the pool of genetic information has grown in recent years.

Keywords: plant breeding; phenotypes; genotypes; breeding values

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1. Introduction

Plant breeding is considered one of humanity's most long-running and constant endeavors. The progress of plant breeding matched the growth of human civilizations. The shift from a nomadic lifestyle of early men to inactive lifestyles that needed adequate food supplies and to sustain such lifestyle relied on individuals that recognized and improved agro-economic traits of crops that met their requirements. These were pioneer plant breeders that employed relatively simple plant breeding methods compared to modern breeding techniques. The availability of plant resources to meet human and cattle demands prompted the lifestyle change. The beginning of human civilizations has occurred around 10,000 years ago. As a result, it is assumed that plant breeding practices began at least 10,000 years ago, intending to choose the most prolific and valuable plant species to meet human and animal requirements.

Plant activities were crucial for human civilizations' existence because they generated improved varieties that were high yielding. Plant breeders were successful in creating high yielding cultivars from wild plants. Even though such wild plants were not high yielding but harbored traits that enabled them to flourish in the wild. These wild plants also play a vital role in crop improvement in the present era. Even today, plant breeders use wild plants as donors of genes that could improve the stress tolerance of cultivated plants. The critical attribute employed in selection was an adaptation based on the breeder's model, or ideal.

Even though plant breeding had a crucial influence in the evolution of many human civilizations, the general public does not see it as a major undertaking. Plant breeding has received less attention than advances in medicine, engineering, electronics, transportation, space exploration, and other fields. However, if more energy is dedicated to establishing appropriate food sources, advancement in other human pursuits would be hampered. For example, in the United States, fewer than 2% of the population is active in agricultural crop production, which offers enough varied crop species to supply the rest of the population's food, feed, fibre, and fuel demands. As a result, energy and resources may be diverted into activities that benefit society (e.g., medical and space research).

One of the reasons why plant breeding has received so little credit and recognition is because there is a lack of broad knowledge of what plant breeding entails. There are considerable variances in what characterizes plant breeding even within the plant breeding field. Several authors have proposed what they believe are the goals of plant breeding. Breeding, for example, is the development of man's will [1]; plant breeding, on the other hand, is the genetic adaptation of plants to man's service [2]; and plant breeding is a precise science in at least two aspects. First, it draws on information and techniques from various fundamental scientific disciplines. Next, its contributions in developing crop varieties, mutants, hybrids, clones, and so on [3]. Plant breeding can be defined as the application of techniques for taking advantage of the genetic potential of plants [4]; and plant breeding is the science, art, and business of improving plants for human benefits [5, 6] (Figs.1).

Figures 1: Representative pictures of plant breeding field.

Although the writers' goals for plant breeding varied, one consistent element is that plant breeding encompasses the art and science of modifying genetic systems to create superior cultivars. The shifts in emphasis are due to the different time frames in which plant breeding goals are considered. These goals vary from manipulating plant evolution through intentional selection by humans [1] to developing proprietary cultivars in a highly competitive sector [6]. The relative role of art vs science in plant breeding has shifted considerably over the last 100 years, with a more significant focus on science. Beginning around 10,000 years ago with the domestication of wild species, there have been numerous significant periods in the history of planting. This has been arbitrarily partitioned for debate in the evolution of plant breeding methods based on the major selection methods and the data available to breeders; selection based on phenotypes, breeding values, and genotypes. Because each of the three stages has a specific time and overlaps with the others, these are not discrete stages. Each stage, however, has been critical, despite the vastly differing time constraints.

2. Phenotypic selection

Individuals' phenotypes result from a mix of genetic and environmental factors. Phenotypes are the visible initial traits, whether they are exhibited as a stunning decorative flower, maturity, plant size, insect resistance, or any other observable attribute. Individual phenotypes were the unit of selection for early plant breeders since phenotypic selection (also known as mass selection) was the most obvious selection method for desired kinds. To produce enough food for prehistoric civilizations, the selection was initially made for the more prolific phenotypes among the wild, weedy plant species. Eventually, the spectrum of features regarded in selection grew to include improved adaptability, preferred plant and seed kinds, increased insect resistance, and other traits deemed aesthetic or ceremonial.

Phenotypic selection is without a doubt the plant selection strategy that has been used in plant improvement for the longest time. It is an essential strategy that involves few resources and has shown to be beneficial in many situations. Making the shift from wild, weedy plant species to cultivated crop species is one of the most important contributions of phenotypic selection. In most cases, it most likely entailed minor, gradual alterations that, with the help of a few helpful mutants, eventually led to crop species reliant on humans for existence. Progress was not a continuous upward trend, but rather hundreds of generations of selection with cumulative effects that were typically beneficial. Because the relative heritabilities of the characteristics determine the success of the phenotypic selection, traits with higher heritabilities made more progress. The history of cultivated maize development may be used to show the impacts of phenotypic selection (*Zea mays* L.). According to current data, modern maize was developed 7,000 to 10,000 years ago in southern Mexico and northern Guatemala; teosinte species are the supposed parental variety that survived in the wild. Hundreds of generations of selection were necessary to shift from grassy-type plants with tiny seeds to the modern maize with kernels linked to large cobs. The long-term influences of phenotypic selection resulted in a prolific crop that greatly aided many civilizations spread over the regions.

According to Sturtevant [7], there were 189 different maize cultivars in the United States by the end of the nineteenth century. Some cultivars (for example, Reid Yellow Dent) were well-known due to awards won at local and national maize exhibitions, and they were commonly utilized because they were thought to be superior to other types. The creation of different cultivars, on the other hand, did not result in increased grain production. As a result, the phenotypic selection was quite effective for several characteristics except for grain production.

Phenotypic selection has been demonstrated to be successful for qualities with relatively simple genetic systems, i.e., traits with higher heritability [8]. The mix of genetic and environmental factors cannot be separated since phenotypic selection is dependent on individual selection. The genetic variance (Vg) and the environmental variation (Ve) influence the variance across phenotypes (Vp), and the heritability (H) may be represented as Vg/Ve. Phenotypic selection is more efficient for modest environmental impacts (e.g., maturity and kernel colour) than for grain yield, a more complicated genetic characteristic impacted by environmental factors all over the growing season. Even though phenotypic selection has been utilized for thousands of years, it continues to pique people's attention. Gardner [9], Abreu et al. [10], and Marquez- Sanchez [11], for instance, have proposed ways to improve phenotypic selection's efficacy, mainly by reducing the impacts of the environment on selection. Plant breeding programmes frequently employ phenotypic selection, and the results are comparable to those obtained when creating open-pollinated cultivars.

Phenotypic selection has the most extended history of any crop improvement technique; it was first used to improve weedy wild plants. It is still utilized in germplasm creation and breeding nurseries today. Phenotypic selection has undoubtedly played a significant role in developing our current germplasm supplies, and it is arguably one of plant breeding's finest achievements. While phenotypic selection will always have a function in plant breeding, its efficiency will be determined by the characteristics examined in the selection and the minimized environmental impacts [12]. Theoretical research in what variables may be managed to improve its efficacy continues [10, 11].

3. BREEDING VALUES

The basis of modern plant breeding was laid by the discoveries of Mendel's genetic principles in 1900 and Darwin's [13] idea of natural selection. Plant scientists have been researching hybrids formed from parents with different phenotypes and the retrieval of parental phenotypes in the F2 and backcross generations for 150 years before the identification of Mendelism in 1900. Because the principles of heredity were unknown, numerous explanations for the phenotypes detected in crosses and their segregating populations were proposed, reliant on the attributes assessed and the species under investigation. In most cases, the biologist's main goal was to obtain basic information on the inheritance of features and how they were sexually transferred from parents to their offspring, rather than plant improvement or cultivar creation. Kolreuter, on the other hand, is regarded by Dunn [14] as one of the founders of contemporary plant sex research and scientific plant breeding. Kolreuter was an early hybridizer who made substantial biological contributions to plant sex research, but he is not among the founders of modern plant breeding, in my opinion. Some pioneer hybridizers studied hybrids and their segregating generations in great detail. Still, unlike Gregor Mendel, none was able to produce a comprehensive hypothesis for the transfer of features from parents to offspring. Different ideas for the inheritance of features arose due to this failure. Still, in most cases, the proposed inheritance patterns were not satisfying to those who proposed them, including Darwin when establishing his theory of natural selection. Unfortunately, Darwin was not aware of Mendel's inheritance ideas published in 1865. Darwin and Mendel were contemporaries, and it would have been fascinating to see how the conclusions from Mendel's experiments might have influenced Darwin's rationale in establishing his theory of natural selection if Darwin had known about Mendel's rules of heredity. It took nearly 50 years for Darwin's and Mendel's study to come together after Mendel published his genetic experiments on the garden pea (Pisum sativa) [15].

During the nineteenth century, plant breeders and biologists did not access Mendel's findings; therefore, the phenotypic selection was stressed in adapted and unadapted landrace cultivars. The selection was effective for many qualities but less effective for others, such as yield and quality, due to the wide genetic diversity accessible in landrace cultivars. However, some people believed that selecting plants based on their progenies would be more successful than selecting individuals themselves. In 1859, Vilmorin of France suggested and implemented the progeny test to improve sugar beet size, shape, and content [16]. It is unknown how frequently Vilmorin's concept was implemented in the late 1800s, but Hopkins [17] employed a similar approach, subsequently known as the ear-to-row selection, to alter the chemical composition of maize grain. Even though the progeny test and ear-to-row procedures were developed before the knowledge of Mendelism, they are still in use, with certain adjustments to improve the performance of the progeny test methods [18].

The renaissance of Mendelism and Darwin's theory of natural selection provided the genetic basis for crop improvement. Still, other ideas discovered in the early twentieth century also significantly affected the development of plant breeding methods. The ideas were pretty diverse in origin, but they were unified with Mendelism and Darwin's theory of natural selection, leading to a better understanding of the heritability of various traits considered in selection. It also broadens how appropriate experimental procedures could be employed to determine the comparative importance of genetic and environmental effects on the expression of traits and individual breeding values. All plant breeders recognize the need for good experimental design and statistical analysis in determining the quality of their data for successful selection. Since Fisher [19] first introduced experimental design and statistical analyses, researchers have continued to improve and refine the concepts of experimental design and statistical analyses to reduce experimental error and improve the precision of our breeding value estimates. Following the finding of Mendelism, it was quickly discovered that the inheritance of our most essential economic qualities was not as straightforward as some of the features researched by Mendel, Bateson, Devires, and others [15]. To investigate the cumulative impact of a higher number of genes on trait expression, other analysis techniques were required. During the first half of the twentieth century, genetic studies were divided into two categories: 1) more traditional genetics, which emphasized segregation and gene expression for many major genes, and 2) quantitative genetics and population genetics and biometrical genetics, which emphasized at allele frequencies and their influences on the inheritance of complex traits. Although classical genetics has been useful in understanding how genes partition and express themselves, knowledge of quantitative trait inheritance has had a more decisive influence and direction on formulating and implementing plant breeding techniques. Mendel's genetic experiments conclusively demonstrated that parents convey genes rather than their genotypes to their offspring. Plant breeders were quite engaged in genetic studies between 1900 and 1930, especially for features that could be categorized based on the phenotype of the progeny [14]. However, many of the qualities of importance to plant breeders (such as productivity) were not accessible to Mendelian studies. Fisher [20] created a framework for studying increasingly complex features by formulating ideas and analyses. He discovered that the genotypic value of a progeny was decided by the average effects of the parent's alleles; that is, the additive effects were passed down from parents to their progeny. The mean value of its progeny as a divergence from the population means might be used to evaluate the breeding values of the parents [21]. The study of complex trait inheritance was made possible by combining the principles of Mendel and Darwin, which have served as the cornerstone of plant breeding for the past century. A foundation for quantitative trait inheritance was built, and natural selection ideas were applied, except that plant breeders regulated the direction of selection in the desired directions.

Plant breeders must precisely estimate the comparative breeding values of the progenies being studied to be skilled in identifying elite cultivars. This notion holds in both fundamental research investigations determining the relative relevance of additive and nonadditive genetic influences of progenies in recurrent selection experiments and practical breeding programmes assessing progenies derived from F2 populations of superior line crossings. As a result, excellent experimental plot methodologies are critical for reliable comparisons. To isolate and evaluate the relative relevance of genetic influences, environmental effects, and experimental error, Fisher [19] introduced the ideas of randomization, replication, and repeatability. The ANOVA generates a tabular representation of progeny data collected across replications and conditions. The ANOVA may be used to measure heritability and anticipate genetic response to future selection, and estimate components of variance for experimental error, genotypic and environmental variability. Plant breeding was arguably the first major field to recognize the need for reliable experimental data and to calculate estimates of the experimental error to assess if variations between progenies are statistically significant. Effective evaluations between progenies are required if plant breeders generate cultivars that are genetically superior to those already in use. Plant breeders have always welcomed fresh ideas in experimental strategies (e.g., Latin squares, lattices, alpha, beta, etc.) and analysis (e.g., stability studies) to improve their capacity to find elite genotypes.

The concept of using hybrids as crop cultivars, predominantly in cross-pollinating crop species, was another item that influenced and inspired substantial plant study during the twentieth century. Shull [22] eloquently summarized the process of creating maize hybrids: establish inbred lines by self-pollination; make F1 crosses between inbred lines; analyze F1 crossings to evaluate relative yields, and choose the best cross for distribution to farmers. The inbred-hybrid notion was first met with skepticism, but during the 1930s and 1940s, the concept was thoroughly tested, and growers quickly adopted hybrids. Hybrid maize cultivars now account for practically all maize cultivars planted in major producing areas. The fascination with hybrids sparked a flurry of research into the genetic basis of heterosis and how genetic systems may be improved to boost heterosis expression [23, 24, 25]. Since, Shull [22] first proposed the notion of hybrid maize, it has been tested and commercially employed in a variety of plant species [23].

One of the primary causes driving productivity gains in the twentieth century was the notion of assessing the breeding values of parents through progeny testing. According to most research, genetic enhancements in inbred lines and hybrids account for 50 to 60% of maize grain yields [26, 27, 28]. Although not as substantial as in other crop species, progress has been made in yield and resistance to pests, drought, acid soils, and other factors [29]. In future plant breeding programmes, breeding values will continue to play an essential role in selecting parents for generating breeding populations.

4. Genotypic selection

Genotypes are indirectly considered the core unit of natural or artificial selection. Individual genotypes have remained the unit of selection throughout millennia of domestication, phenotypic selection, breeding value evaluation, and now when molecular genetics is used to select parental genotypes and create GMOs. Of course, the effectiveness of genotypic selection is governed by the trait's heritability, which is dictated by how the environmental flux influences genotype expression. In the early twentieth century, Plant geneticists examined and mapped mutant genes that could be categorized based on their phenotypic segregation. Plant size, leaf orientation, awns vs awnless, ear shape, endosperm kinds, and other features were deemed Mendelian type traits in their inheritance. These genetic investigations were helpful in determining chromosomal arrangements, but they didn't immediately help develop new cultivars.

One example is the opaque and floury maize kernel mutants. Although both mutants improved protein levels and quality, the negative consequences of decreased yield, grain quality, higher grain moisture, and susceptibility to plant and ear pests outweighed the benefits of higher protein levels and quality. To generate effective inbred lines and hybrids, long-term breeding operations were required to overcome the detrimental effects of the opaque and floury mutants [30]. In virtually every case, large mutant alleles have had a detrimental influence on production. After extensive breeding attempts, usable products with the mutant allele were generated [31]. Experiences with mutant alleles that have major effects on specific traits have rarely significantly impacted plant breeding. Mutant alleles have typically had deleterious effects on other important economic traits, and it wasn't until plant breeders were able to select for other modifying alleles to reduce the harmful effects of the mutant alleles. As a result, successful breeding strategies rely on genes and alleles that behave consistently in various settings. Genetic research was particularly important for determining the chromosomal organization of genes for most main agricultural plant species, even if the adoption of large mutant alleles had little influence on cultivar development. However, the structure of genes and chromosomes, as well as their chemical makeup, remained unknown. Although geneticists and chemists had discovered that genes created specific proteins, the nature of the gene and how specific proteins were made became the focus of intense research in the second half of the twentieth century. Watson and Crick [32] reported on the structure and chemical composition of the hereditary materials, which was a massive change in the study of genetics, similar to discovering Mendel's principles of heredity in 1900. From 1900 to 1930, extensive research by geneticists and plant breeders confirmed the particulate nature of allele segregation and applied the same ideas to the study of quantitative trait inheritance. Plant breeders had made tremendous success in establishing and executing breeding methods to generate genetically enhanced cultivars by 1950, thanks to a combination of Mendelian genetics, Darwin's principles of natural selection, the development of experimental design, and statistical analysis. During the 1930s and 1950s, it took approximately 50 years for sources of genetic information to be integrated for practical use by plant breeders. Another aspect that sparked substantial theoretical and fundamental study by 1950 was the inbred, hybrid idea with double-cross hybrids. Although there was considerable genetic research, the phenotypic level was the primary selection unit. Because experimental design and statistical analyses allowed for the determination of the relative relevance of environmental and genetic impacts and the parents' breeding values, the selection at the phenotypic level based on breeding values became more successful. Extensive phenotypic data was collected and evaluated on replicated progeny experiments repeated throughout the target conditions.

Since Watson and Crick's publication, a similar trend has emerged (1953). At the molecular level, extensive genetic investigations were undertaken to discover gene structure, functions, products, transmission, and so on, but there was one difference. Plant breeders were actively interested in genetic research after the revelation of Mendelism in 1900, both independently and in collaboration with geneticists. Plant breeders typically lacked the necessary technology and expertise for extensive molecular genetic analyses. Plant breeders had a limited role in genetic research due to the potential indicated by molecular geneticists from comprehensive information collected at the molecular level. Whereas, with the understanding of Mendelian genetics, support for plant breeding increased rapidly (especially after WWII), direct support for plant breeding decreased in many cases, both in terms of monetary support and staffs' positions: funds and staff's positions were side tracked to sustenance the affluent molecular genetic research. Plant breeding became a necessary matrix component for the potential use of information and products derived from molecular genetic studies. Still, it was not realized until later that if the benefits of information derived from molecular genetic studies were to be utilized, plant breeding became a core part of the matrix for the potential use of information and products derived from molecular genetics.

Molecular geneticists first concentrated on a few genes that had substantial impacts, akin to the early studies of Mendel's principles of heredity. However, it appears that inserting particular DNA pieces into a plant's genome and achieving the necessary expression was more challenging than anticipated. However, progress was made for characteristics that provided resistance or tolerance to some of the most significant pests in maize production. Resistance to certain herbicides for weed management and infestations by specific insect groups are two examples. These features have been widely used in some of the most important agricultural species [33]. Parallel to Mendelian genetic research, molecular geneticists recognized that if molecular genetics contributed to the long-term development of agricultural species, it had to focus on quantitative trait improvement. Quantitative trait inheritance at the molecular level was just as challenging as it was for Mendelian geneticists a century ago. However, with the sequencing of genomes of key crops, new techniques for identifying genes, and lower prices, theory and experimental information have been planned and utilized to find quantitative trait loci (QTLs) and incorporate the knowledge into breeding and selection strategies [34]. Plant breeding and selection will continue to be influenced by molecular genetics. New plant breeders with molecular genetics education and expertise will be more involved in breeding strategies, especially to enhance complex characteristics.

Marker assisted selection will improve selection for quantitative traits such as yield, grain quality, and stress tolerance, but the resolution of gene interactions and the impact of environmental factors will be a major challenge; these are the similar issues that have plagued plant breeding throughout its long history. Molecular genetics has improved plant breeding by finding the best parents to use in breeding crosses, assigning genotypes to appropriate heterotic groups, and discovering essential alleles that help with complicated trait selection. The amount of genetic data available to plant breeders is several times more than in the past. Advances in computer software and technology have allowed for better inclusion of genetic data that may be utilized in selection. The proportional relevance of science in plant breeding has risen considerably due to the greater availability of knowledge. Plant phenotypes are still essential and will continue to be so in the future, even if plant breeders now have more genetic information than they had 50, 100, or 1,000 years ago [35].

5. Future Prospects

Plant breeding efforts, which began with the domestication of wild plants and continue today, have played a significant (though largely unrecognized) role in providing food, feed, fuel, and fibre for the development of human civilizations and the survival of the world's more than 6 billion population. If the world's population grows to 9 billion people by 2050, or roughly 37% more people than in 2010, we'll need to keep up these efforts. Some have prophesied that the rate of expansion of the human population will overrun their ability to supply their food demands from the time of Malthus at the turn of the nineteenth century. Genetic information has risen exponentially over the last 30 years, allowing for better phenotypic selection. Crop cultivation has a finite geographical area on the planet. Crop yields have increased, sustaining human requirements, notably for food. Crop yields per unit have grown in most cases during the last century [29].

Millions of people still lack appropriate and nutritional meals to live healthy lives due to political conditions, infrastructure, and distribution issues. Yet, adequate food supplies are accessible in many cases if appropriately used. Grain yields have risen as a result of several causes. According to Duvick [35], enhanced cultivar genetics were responsible for 50 to 60% of higher U.S. grain yields; comparable rates of 2.6 to 2.9 per cent growth each year have been observed in other maize producing areas [26, 27, 37]. Positively, it appears that additional genetic improvement may be sustained as more molecular genetic information is learned and combined with phenotypic selection, our selection efficacy will improve. It will be critical to maintaining improved crop yields per unit area in the future. During the final half of the twentieth century, the human and financial resources dedicated to plant breeding research have changed dramatically [29]. Since the revelation of Mendelian genetics in 1900, publicly funded academics have been at the forefront of fundamental research into the inheritance of characteristics and the application of this knowledge to cultivar improvement. Significant shifts in people and financial resources for plant breeding have occurred from the public to the private sectors by the year 2000. The economic potential of items produced from molecular research supplied in plant cultivars piqued the private industry's attention considerably. As a result, private support for plant breeding proliferated. In the public sector, however, resources committed to plant breeding have either diminished or been moved to the study of molecular genetics. Because of the discoveries in genetics and their commercial worth, this duality of public and private research resources has shifted during the twentieth century. This appears to be a pattern that will continue in the future.

Because of the competitive nature of private businesses, resources will be made accessible to compete in the marketplace. Even though the amount spent on plant breeding has risen dramatically over the last 30 years, the expenditures have yielded positive results [38]. Many nongenetic areas have made significant contributions to improving the efficiency of plant selection and determining breeding values for data taken at the phenotypic level [39]. Plant breeders, based on their past triumphs, will continue to play an essential role in providing suitable and high-quality field cultivars to satisfy our future demands, in our opinion. The proportional relevance of science to the art of plant breeding has risen as more genetic information has become accessible. Plant breeding will continue to rely heavily on the phenotypes of newer cultivars created with a stronger emphasis on science.

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