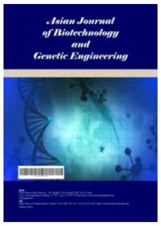

Asian Journal of Biotechnology and Genetic Engineering

4(3): 35-47, 2021; Article no.AJBGE.72979

A Comprehensive Review on Breeding Technologies and Selection Methods of Self-pollinated and Cross-Pollinated Crops

Adil Hussain[1*], Kamran Arshad[1], Jareer Abdullah[1], Ayesha Aslam[1], Aqsa Azam[1], Muhammad Bilal[1], Muhammad Asad[1], Ameer Hamza[1] and Muhammad Abdullah[1]

[1]Department of Plant Breeding and Genetics, University of Agriculture, Faisalabad, Pakistan.

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

Editor(s):
(1) Dr. Tsygankova Victoria Anatolyivna, Institute of Bioorganic Chemistry and Petrochemistry of National Academy of Sciences of Ukraine, Ukraine.
Reviewers:
(1) Vijay Dalvi, DCM Shriram Ltd., India.
(2) Samir Rabie Elsayed Abo-Hegazy, Cairo University, Egypt.
Complete Peer review History: https://www.sdiarticle4.com/review-history/72979

Review Article

Received 22 June 2021
Accepted 27 August 2021
Published 30 August 2021

ABSTRACT

The basis of crop improvement is the existence of genetic variability in plant material. A breeder exploits it in several different ways to create new crops varieties which are capable of outperforming their ancestors in the expression of various economic characters like yield, quality, resistance to diseases, and tolerance towards drought conditions. Breeders obtain their purpose by using different breeding technologies and selection methods. This review categorizes all the breeding technologies into two main portions of selection methods of self-pollinated crops and that of cross-pollinated crops. The principal methods by which new varieties of self-pollinated crops originate are selection and hybridization. Self-pollinated crops can also be developed by pure-line selection methods. Dirk and Penjamo-62 of wheat, IR-6 of rice, and Beechar of barley are the cultivar introductions in Pakistan. Using these methods, most of our crop varieties like wheat, cotton, sugarcane, maize, clover, and several other crops can be originated. The second portion of this review explains breeding methods of cross-pollinated crops. The methods used in the breeding of cross-pollinated crops or crops such as cotton and sorghum which have both self and cross-pollination are not as clearly defined as the methods used in the breeding of self-pollinated crops. In

**Corresponding author: E-mail: mr.tarar1122@gmail.com;*

addition, these methods tend to vary with the particular crop with which the breeder is working. Principal methods by which varieties of cross-pollinated crops can be originated by selection and hybridization. The selection method for cross-pollinated crops consists of mass selection, pure line selection, progeny selection, line breeding, and recurrent selection methods. While hybridization includes intervarietal and interspecific crossing and utilization of hybrid vigors. The whole concept gives an amazing figure to the new crop researchers in modern breeding technologies and selection methods.

Keywords: Breeding technologies; selection methods; self-pollinated crops; cross-pollinated crops.

1. INTRODUCTION

As humans first started to realize the true potential and importance of plants some 12,000 years ago, they started to utilize plants near them as a permanent food source. They started to settle in communities as they no longer needed to migrate in search of a constant food supply because they were able to harvest food at home through agriculture. They started to grow different types of wild plants to prepare different foods [1]. But this never remained the same as the human population began to rise at exponential rates. People were relying on wild-type plants that were not able to meet the needs of a growing population. Hence they started to grow food plants on much wider scales to meet their needs. They observed that some plants performed better than others in terms of some important physiological and quality parameters such as productivity and tolerance for certain types of stresses. They selected those particular plants and started to breed in order to get their desired crop [1]. But these crude and labor-intensive practices were not enough. Natural calamities such as droughts, diseases, and an exponential increase in crop insect pests resulted in famines in many regions of the world. It was until the nineteenth century when modern sciences paved way for the development and invention of modern plant breeding techniques. This was the start of the era of the green revolution. The green revolution is actually an amalgam of major advancements in the field of agriculture with the help of scientific approaches. It included new selection methods based on genetic and physical trait analysis of plants along with the use of chemical fertilizers and insecticides. Through these achievements during the green revolution, various developing countries were able to properly feed their populations and a balance between global food consumption and supply was attained which ultimately helped in the maintenance of global food security [1]. Developing countries witnessed a stark increase in crop production volumes in the past fifty years. This happened despite the increasing land values and scarcity [2]. The population had doubled but the total productivity of cereal crops increased three times with only an increase of thirty percent in cultivated area. People started to invest more in modern technology to adopt modern agricultural practices [2]. The modern world has a rapidly growing population and it is estimated that the world population is going to increase many times in the coming years. It has the potential to reach as much as 9 billion. To feed this population in order to maintain food security is very essential and we have to find sustainable ways for this purpose. Currently, scientists are working constantly on the improvement of existing varieties by developing new lines and cultivars every year [3]. To meet such targets new technologies such as recombinant DNA technology is used. In this technology, we use genome editing and sequencing to produce genetically modifies organisms GMOs. It is clear that GMOs are produced more easily as compared to conventional breeding but it has their own consequences. Many states do not allow GMOs and thats why we have to focus more on modern selection procedures in crop plants in order to achieve our targets [3]. Many items present in our daily kitchen routine are directly developed through conventional plant breeding. Some new cultivars and varieties which are thought to be a product of genetic recombination are actually produced from conventional selection procedures. These include Seedless kinnow, watermelon, apriums, and pluots. [4]. If we compare hundreds of new crop varieties are developed are released in the commercial market every year in order to maintain a sustainable supply of nutrients to the ever-growing population. It also enhances consumer choice and availability. Conventional plant breeding is composed of various procedures like selecting the superior parents with our desirable characters and quality traits and breeding them to develop a more efficient plant variety. This also involved the domestication of wild plants as early humans had to domesticate wild plants in order to gain their desirable yields [4]. Conventional plant breeding includes selection methods that are unique to crops with different types of modes of pollination. For example, in the case of self-pollinated crops included selfing or inbreeding is carried out. Pure lines are developed from repeated selfing of crops. High yield and quality traits such as tolerance for some abiotic and biotic stresses are desirable. Also resistance against certain diseases and disorders as well. Crop selection study programs are usually based on pure lines. Development of pure lines is possible through inbreeding for 5-6 generations. This produces inbred homozygous lines which are suitable for full-scale evaluation for commercial purposes [5]. This whole process usually takes 11-13 years to practice crosses necessary for commercial release of the variety. Segregating populations are also used to identify traits that are of particular interest. Pure line development is helpful in providing a permanent population which allows phenotyping of traits that are actually related to the same genotypes at different environmental conditions and times [5]. One of the most efficient and easy methods for developing homozygous pure lines for self-pollinated crops in a short period of time is known as double haploid technology (DH). DH lines can be through a culture of microspore and megaspore which is followed by doubling of chromosomes. Other methods include recombinant inbred lines (RILs) and near-isogenic lines(NILs). These lines can be produced through introgressions or repeated selfing of hybrids. The pedigree method is also a useful method of selection in plants with self-pollination [5]. By the collection of the crop, pedigrees can be used to help maximize genetic gains in the field of crop breeding and also allows the efficient management of the genetic resource [6]. Databases on large scales have been developed as a form of research tool for many groups of crops such as oats, rice, and wheat [6]. Backcross breeding is a method that is often used for cross-pollinated crops. For example, eggplant is among popular vegetables and it belongs to the Solanaceae family. Some wild relatives have remarkable resistance against biotic and abiotic stresses and there are not many attempts to transfer them to the cultivated commercial varieties [7]. Recent studies and experiments have resulted in the development of 30 first backcross (BC1) generations along with fifty hybrid combinations through the transfer of climate change tolerance genes [7].

2. BREEDING METHODS OF SELF-POLLINATED CROPS

Selection and hybridization are the fastest and easiest way to improve self-pollinating crops. Several cultivars of different crops, including Dirk and Penjamo-62 of wheat and IR-6 of rice, were introduced in Pakistan. Among our varieties of major crops and some other crops also came through these breeding technologies [8]. For example, our recent wheat breeding programs are introducing economical varieties through screening nurseries and yield tests, while individual plants are being segregated and parents are being selected through hybridization of crossing blocks [8]. All the breeding methods applicable for self-pollinated crops are listed below:

2.1 Pure-line Selection Method

Pure-line selection method is the method of selection of a single best plant based on phenotype from a heterogeneous population to produce individuals (plants or animals) having the same phenotype and genotype. This is applied in self-pollinated crops but sometimes it is also used for making inbreds and also in cross-pollination crops. Production of pure lines is an important step in breeding most crop plants. There are different major types of pure line breeding i.e Double haploid lines (DH), Recombinant inbred lines (RILS), and near-isogenic lines (NILS) [9]. DH lines are produced through microspores and megaspore culture followed by chromosomes. The other two are produced through repeated selfing. DH is the most quicker method but it has a drawback also as it depends upon the genotype. So thats why another method of the pure line is developed which is the fast generation cycling system (FGCS). It is more versatile as it is less dependent on genotype [9]. The pure line family method has been purposed for the high yielding cultivar. This PLF method consists of isolating individuals from a population and then sefling the big generation of each plant to a desired level of homozygosity. Single plant from each generation is isolated and then tested after repeated selfing. And the lines with superior performance are selected and evaluated. PLF method is the most faster method for cultivar development and would produce more superior lines as compared to other progeny methods [9]. In Iran, on eggplant, the pure line method was practiced. Five species of the eggplants were examined and separated.

About three years were given to this practice. In the first year, plants were selected based on certain specific characters, in the second year those plants were planted in an augmented way [10]. And in the third year, the plants were examined in randomized complete block design and were evaluated. The ten plants of good quality and quantity were selected at the end [10]. Evaluation of Japonica rice was done with the help of the pure-line method. Many Thailand companies appreciated farmers for the cultivation of DoA1 and DoA2 varieties. Recently changes are made in Japonica rice with the pure-line method. By repeated selfing, the japonica rice with the best cooking quality and yield is produced in the Phan districts whereas the DoA2 is best suited to Kamphaeng districts [11]. Kala jeera, Machankanta, and Haladichudi are three popular landraces and are near extinction due to impurities and less production. These are also in more demand of the consumer. The molecular marker-assisted pure line combined with the farmers resulted in the best high-yielding pure lines of Kala jeera, Machankanta, and Haladichudi. The high promises are shown by the pure-line method for the refinement of the elite landrace of rice [12]. The pure-line method is also used in Asteraceae (the largest family of angiosperms) for genetic analysis. For the sake of studying plant diversity, it is important to understand the molecular genetics of that plant, but due to allohexaploid and self-incompatibility, it was very difficult to evaluate. And there was high genome heterogeneity which was the major obstacle in understanding molecular biology [13]. The diploid species Chrysanthemum C.seticuspe was subjected to Agrobacterium-mediated transformation. And then through repeated selfing, a strain GojO-O was developed which proved favorable for genetic analysis and very helpful for genetic improvement in Chrysanthemum cultivars [13].

2.2 Mass Selection

It is the most primitive method of breeding for the production of desired varieties. In this method, the large number of seeds having desired characters are selected and then are bulked together to make a composite which is then grown in the field for producing varieties having desired traits. In sugarcane, this method proved very effective. The purpose of sugarcane breeding is to produce plants with Superior genotypes having superior quality traits than those which are in use currently [14]. To evaluate more efficient genotype this work contrasted the seedling ratoon with the conventional mass selection, with two methods which take into account BLUP (Best Linear unbiased prediction) of the family achieved in plant cane, Australian sequential selection by merit (BLUPseq), and sequential selection by merit (BLUPrel). 65 families were selected for crosses. Two replications were done in a complete randomized design [14]. Tests were conducted in Brazil. As a rule, the number of individuals selected from each generation was the same. 168 individuals marked from Mass selection. This mass selection provided the highest number of promising better genotypes. And BLUPseq was proved an effective method for superior genotype [14]. Scandinavian spring barley due to rainy and wet autumn sprouting damage occurs. It can be handled if dormant seeds are produced. So for the dormant seeds production, early generation selection is done with the help of mass selection. From the bulk population, dormant seed production proved very helpful for increased resistance against sprouting [15]. Providing resistance against sprouting is very helpful in barely standardizing water amounts. For handling and drying out the samples becomes easy by stopping germination. And mass Selection is a very effective method for genetic advancement [15]. Modern maize breeding programs gave rise to genetically uniform and homozygous progenies. But in the upcoming years, its yield could effect due to unpredictable climate changes. Maize is heterogeneous genetically so it is easy to produce new varieties of maize having better genetic diversity by the process of mass Selection [16]. For this purpose, a long-term participatory breeding/ on-farm conservation program was established in Portugal. Two varieties of maize were taken. The reason behind this strategy was to analyze the on-farm stratified mass Selection, agronomic practices, and molecular diversity of two historical varieties. In different locations, trials were performed [16]. The parental and new varieties were compared which showed good agronomic improvements. Through the molecular diversity, the analysis showed that both varieties mentioned good genetic diversity. That analysis proved the best quality traits evaluated progenies [16].

2.3 Hybridization

In self-pollinated crops hybridization is a process known as artificial cross-pollination among the genetically contrasting parents as a result new individual produces has a better combination of traits (Hybridization) [17]. Since the Neolithic era when plants domestication starts, plant hybridization is necessary to humans. For the wide range production of hybrid efficient methods of hybridization is necessary for self-pollinating crops [17]. Hybridization is a source of increase in genetic variability. It is considered one of the reasons for the disappearance of the rare plant but also consider a source of the creation of new species [18]. Earlier first spontaneous plant hybridization was found in 1716 in a letter written by cotton Mather in which crosses among Indian and yellow corn and also among gourds and squash occur that were grown simultaneously [19]. But later it is found that the first intentional artificial hybrid was done by Thomas Fairchild through a cross between carnation (Dianthus caryophyllus) and sweet William (Dianthus barbatus) [19]. The purpose of hybridization is to develop better quality plants, a combination of desirable traits from diverse parents, for the maintenance of genetic diversity and to maintain CMS lines pollinated by maintainer lines. The occurrence of natural hybridization may be replicated in a greenhouse by permitting the hybridization process to take place under controlled conditions. While artificial hybridization offers a way to explore the mechanism of genetic isolation and also testing of hybrid models evolution and introgression [20]. Due to the intense effect of hybridization on the genetics and ecology of engaged species, it is important to identify hybrid individuals as an initial step to describe the processes occurring in hybridizing populations. Chemical hybridization agents also use for heterosis. The role of hybridization will be minimal if the hybrid is less suitable than its parents. So the problem of hybrid fitness must be considered during the role of hybridization in evolution. In self-pollinated crops hybridization is achieved by the Pedigree method, Backcross method, and Bulk method [20].

2.3.1 Pedigree method

The pedigree method defines as a process used in self-pollinating crops for the genetic improvement in which selection is done from the segregating generations and also ancestor records of selected plants are maintained in each generation. At the end of the nineteenth century, the idea of the pedigree method was proposed and broadly applied in self-pollinating plants development programs, based upon the ancestry record between progenies over the selfing generations [21]. In 1891, Svalof uses the first pedigree method term. Although, it is a time-consuming procedure also for the selection procedure its adequacy is a bit restricted. The probability of using parentage data for the selection process may be in progeny evaluation in the experiments with replications [21]. Such an approach may be helpful, as long as breeders of autogamous bred are curious about choosing progenies that throughout homozygosis, assemble a better number of favorable alleles that link the finest additive genetic values (AGV), considering the focus is the establishment of lines [21]. The pedigree method may be helpful in the development of those traits which show suitable values for heritability and genetic advance [22]. In the pedigree method, selection starts from F2 generation and continues until homogenous lines are produced. Then next desirable F3 plants are selected. Similarly, in subsequent generations more desirable plants are selected and harvested individually [23]. However, breeding is a number game the more numbers manage, the more possibility of a finding of the right combination of genes. The size of the breeding program depends on the availability of resources. The pedigree method also depends on expected genetic variability in each generation on which several selections will be made. Expected genetic variability maximum at F2:3 generation and it reduce by half in every following generation [23]. At F6 maximum uniformity is achieved in the selected progenies. At F7 selected plants are grown to obtain a large number of seeds for yield and quality trails. Most breeders test for at least 5 years at five representative locations before the release for commercials use almost F8 to F12. At F10 to F13 seed multiplication is done for the distribution [24]. This method is mostly used when high heritability is present and resistance is control through polygene genes. It cannot be used in an environment where genetic variability is not express for the character of interest. It also requires more labor and land as compared to other inbreeding methods [25].

2.3.2 Backcross method

In the backcross method, F_1 is crossed with one of its parents. As many plant varieties lack in some characters, the deficient character present in the recurrent parent is introgressed through a cross with a parent in which that character is present (donor parent), for this backcross method is used. This method was proposed by Harian and Pope in 1922 [26]. The backcross method is very helpful in the transfer of desirable characteristics such as tolerance or resistance to disease [26]. The characteristic may be a trait, gene, or chromosome segment. Progenies are selected for the characteristic of interest in the successive generations and then backcrossed with the recurrent parent [27]. This method is useful for genetic improvement and also very helpful to dissect the genetic architecture of quantitative traits as it can separate a gene, in different genetic backgrounds. The backcrossing method also uses in conjunction with quantitative trait locus detection which helps in increase of quantitative trait locus (QTL) mapping effectiveness [27]. If the trait of interest is governed by dominance, almost for seven seasons backcrossing rounds are involved. If the trait of interest is governed by a recessive gene, then nine or more seasons are involved. For the success of the backcross method, the transferred trait may retain efficient and adequate backcross should be made for retrieving desirable traits of recurrent parents. For the transfer of any desired characteristics such as a variety 1 (recurrent parent) is well adapted and high yielding but deficient to resist against some diseases [28]. Variety 2 (donor parent) is low-yielding but has resistant to that disease, governed by a dominant gene. The first cross between V1 and V2. Hybrid F1 is produced. F1 is backcross with V1 to decrease the proportion one-half of V2. This progeny is known as BC1F1. This progeny produces homozygous recessive recurrent parent allele and heterozygous dominant donor parent alleles [28]. The homozygous recessive allele plant is discarded and selected plants are heterozygous for gene of interest 75% recurrent parent and 25% donor parent genotype. The BC1F1 progeny plant seeds are selected and backcross to the V1 parent, this progeny is known as BC2F1. The same process repeated in BC3F1 to BC6F1. Now heterozygous plants contain most of the original recurrent parent. Now from BC6 generation plants of RP with disease-resistant plants self-pollinated grow separately. In BC6F2 individual plants, progenies grow and V1 disease-resistant plants are selected [29]. In BC6F3 individual plants, progenies grow and homozygous progenies which are resistant to disease and similar to V1 are growing in bulk. Next year replication yield trails of the new variety development are done with Variety 1 as check. After yield trails, seed multiplication is done in the next year [29]. While in the case of donor parent disease-resistant trait is governed by a recessive gene, after the first backcross, and after two subsequent backcrosses, F2 plants are grown for the identification of disease-resistant plants. Variety1 (recurrent parent) is cross with Variety2 (donor parent). F1 progeny is produced [30]. F1 is backcross with a recurrent parent, BC1F1 generation is produced carrying 50% homozygous dominant (RR) and 50% heterozygous (Rr). The BC1F1 progeny is self fertilize to identify these two genotypic classes. This progeny is known as BC1F2 segregates as 1(RR), 2(Rr), and 1(RR). The homozygous recessive plant is selected and backcross with the recurrent parent [30]. All plants of BC2 are heterozygous, so they are again backcrossed with recurrent parent and BC3 progeny produce. It consists of 50% homozygous and 50% heterozygous plants, so the selfing of BC3 progeny plants is done. This progeny is called BC3F2. The homozygous recessive plants are selected and again backcross with a recurrent parent, BC4 progeny produce are heterozygous [31]. It again backcrosses with a current parent, BC5 progeny produce consist of 50% homozygous and 50% heterozygous plants. Again do selfing of BC5 plants [31]. A disease-resistant plant similar to Variety 1 is selected and grows separately. In BC5F23 Individual plants selection is achieved. In next year do yields trails. Then next year seed multiplication is done [31].

2.3.3 Bulk method

In the bulk method, F2 and subsequent generations are grown in bulk. Nilson-Ehle first uses a bulk method in 1908. The first two parents are cross, F1 produces. F1 and subsequent generations mostly up to F5 are grown in bulk. No selection is done during these generations while it is considered that the plants suitable to the environment will survive [32]. The bulk method depends on nature, so natural selection will occur. It allows the elimination of fewer fit plants. We must grow bulking generations in such an environment that is similar to that required for the resulting cultivars. In the next year, individual plants which have desirable characteristics are selected and grown in a row. The best lines are selected next year for yield trails. After yields, seed multiplication is done for the distribution of seeds to farmers [32]. This method is an economical way of producing homozygous lines after hybridization. The advantage of the bulk method is its simplicity, less land, and labor requirements. Also, it is one of the less expensive methods of inbred lines production. This method also provides the opportunity for natural selection and when require bulk populations also can be subjected to a disease outbreak or different stresses to skew progeny in the desired direction [33]. Sometimes breeders may combine the bulk method with other breeding methods. Breeders grow F2 and F3 progeny in bulk and use the pedigree method for the grown of later generations. One of the limitations of the bulk method is that each generation requires to be grown in the intended production area to get the advantage of natural selection [33].

3. BREEDING METHODS OF CROS-POLLINATED CROPS

The crops which are both self-pollinated and cross-pollinated like cotton and sorghum, the breeding methods in those crops are not obvious. Along with these methodologies also varies the breeders activity. So the breeding method in cotton may be different from sorghum, maize, millet [34]. On the other hand, the basic methods from which cross-pollinated crops may originate are categorized into these groups. A) selection d) hybridization [34]. All of these are described as:

3.1 Selection

For cross-pollinated crops, usually, three methods of selection are used that are; Mass selection, Progeny selection, and Recurrent selection.

3.1.1 Mass selection

In 1961, Gardner defined it as the selection of several phenotypically superior plants or seeds from the field population, harvesting and bulking their produce together for sowing the next years crop and repeating this process till desired characters are achieved. It is followed both in self-defective and cross-pollinated crops [35]. It is the simplest and oldest method of crop improvement. Mass selection is an example of selection from the abiologically variable population in which differences are genetic in origin. The Danish biologist, W. Johansen, is credited with developing the basis for mass selection in 1903. Mass selection is often described as the oldest method of breeding self-pollinated plant species. However, this by no means makes the procedure outdated [35]. As an ancient art, farmers saved seed from desirable plants for planting the next seasons crop, a practice that is still common in the agriculture of many developing countries. This method of selection applies to both self-and cross-pollinated species, provided there is genetic variation. The purpose of mass selection is population improvement by increasing the gene frequencies of desirable genes. Selection is based on plant phenotype and one generation per cycle is needed. The improvement is limited to the genetic variability that existed in the original populations (i.e., new variability is not generated during the breeding process) [35]. The goal in cultivar development by mass selection is to improve the average performance of the base population. Some breeders use mass selection as part of their breeding program to rogue out undesirable plants, thereby reducing the materials advanced and saving time, and reducing the cost of breeding. Cross-pollinated species tend to focus on population improvement rather than the improvement of individual plants, as is the focus in breeding self-pollinated species [35]. In addition to methods such as mass selection that apply to both self-pollinated and cross-pollinated species, there are specific methods that are suited to population improvement. In self-pollinated crops, a mass-selected variety is homozygous but heterogeneous, because it is a mixture of several pure-lines [35]. In cross-pollinated crops, such varieties are a mixture of homo and heterozygotes and are heterogeneous, because they consist of several homo- and heterozygous genotypes [35]. Several economically important crop species have mating systems that involve a mixture of self-and cross-pollination. A naturally reproducing population of such a species differs from those produced under either strict autogamy or allogamy in that it consists of a mixture of individuals with different histories of selfing and, therefore, different coefficients of inbreeding [36]. these differences contribute to the phenotypic variance of the population. The effect of artificial selection is more complex than in either of the above cases [36]. Mass-selected varieties have wide adaptation and are more stable against environmental changes due to heterogeneity which provides better buffering capacity. In other words, mass-selected varieties have a broader genetic base than pure lines. They exhibit more or less stable performance. However, adaptability is more in cross-pollinated crops than in self-pollinated species [37]. They are composed of several pure lines in self-pollinated crops and several homos and heterozygous genotypes in cross-pollinated crops. Hence there is heritable variation in the mass-selected varieties, besides environmental variation. The heritable variation provides them a good buffering capacity [37]. Selection is effective in the case of mass-selected varieties of self-pollinated crops due to the presence of heritable varieties. However, further selection in the mass-selected varieties of cross-pollinated crops may lead to inbreeding depression [37].

3.1.2 Progeny selection

For cross-pollinated crops, inheritance of a trait cannot be followed by methods of classical genetics because of heterozygous random mated populations. Thus, Hardy Weinberg law applies and genotype frequency in the gene pool of cross-pollinated crops can be altered through selection [38]. Direct selection of individuals among population proved successful and also have no adaptation fear but have limitations i.e lacks variability [39]. As variability is the base for selection, and progeny selection, one of the oldest methods of crop improvement depends upon the variability in a population. It is commonly practiced for cross-pollinated crops, however can be used for inbreeding (self-pollinated) crops too [40]. Progeny selection involves the selection and evaluation of progenies for superior performance, leading towards inbreeding and consequently lost in vigor. However, it has been an important method of breeding cross-pollinated crops for more than 70 years, which involves the selection of superior progenies and the elimination of inferior ones. Then the selected progenies for superior characters are incorporated in composite population which is called line breeding [41]. In progeny selection, individual plants are selected on the phenotypic basis from a heterozygous population and are grown. Unlike pure lines, varieties developed through progeny selection are less uniform but more stable and resistant to environmental stresses due to a broader genetic base [42]. Progeny selection is a continuous process from choosing an unimproved landrace/local variety and then selecting individuals throughout progenies for almost six or more years until a desirable superior cultivar is obtained. After that selected off-springs, which are few in number are tested for performance and bulked. Progeny selection takes almost 08 to 10 years for releasing a variety [42].

3.1.3 Recurrent selection

Recurrent selection is the predecessor to the progeny selection method, involved in cross-pollinated crops which is a cyclic process of selecting inbreeding individuals among progenies aiming to increase the gene frequency for desirable traits in a population. Selected individuals, after selfing and reselection, can be inbred for the production of hybrids or synthetic varieties [43]. With excessive variability in the population, improvement in the frequency of quantitative traits can be achieved in sub-populations as compared to the preliminary population [44]. Based on approaches of selection, which could be phenotypic or marker-assisted recurrent selection vary in efficiency [45]. Although a specific method of recurrent selection is efficient for a specific experiment but not for others, as selfed progeny recurrent method is more efficient for yield improvement in maize [46]. In general, selected plants from the open-pollinated population are evaluated for superior characters after selfing and enter in the recurrent selections cyclic process which includes the following methods:

3.1.3.1 Simple recurrent selection

The simple recurrent method is effective in maximizing the gene frequency for highly heritable characters with a negligible reduction in variability [47].

1st Year

1. Individual plants selection on a phenotypic basis
2. Selfing of the individuals selected in step (1)
3. Evaluation of superior plants

2nd Year

1. Superior progenies were grown individually
2. Intercrossing
3. Compositing seeds from intercrossed progenies

3rd Year

1. Composite sowing
2. Repeat procedure of 1st year

4th Year

1. Grow progenies individually
2. Repeat procedure of 2nd year

Referred to as 1st recurrent cycle.

3.1.3.2 Recurrent selection for GCA

In this method, progeny is test-crossed with a tester parent having a broad genetic base, which is randomly mated for the estimation of GCA (General Combining Ability) of the plants. As the tester is common, progenies selected based on the superior performance of individuals crossed with the tester would have high GCA [47]. This method predicts the performance of inbreeds in their early stages, 1st or 2nd generations of inbreeding.

1st Year

1. Individual plants selection on a phenotypic basis
2. Selfing of the individuals selected in step (1)
3. Test cross the males to the random female tester

2nd Year

1. Superior plants of test crosses are collected separately
2. Replicated yield trials
3. Select superior progeny

3rd Year

1. Selfing of selected progeny
2. Inter-crossing the superior test cross progeny
3. Bulking the seeds of inter-crosses equally

4th Year

1. Composite plantation separately
2. Repeat the steps (1) and (2) of 1st year

5th Year

1. Repeat the procedure of 2nd year

6th Year

1. Repeat the procedure of 3rd year

Recurrent selection for GCA can be used in concentrating genes for superior GCA, resulting in isolation or it can be used to improve agronomic characters resulting development of synthetic variety.

3.1.3.3 Recurrent selection for SCA

SCA (Specific Combining Ability) means the specific gene combinations, that combine with genes of an inbred tester. Recurrent selection for specific combining ability is objected to isolate these specific gene combinations to reduce heterosis [47]. The same procedure of recurrent selection for GCA is applied, but the selection of an inbred tester should be very careful.

3.1.3.4 Reciprocal recurrent selection

In this method, different populations can be improved at a time by combining them with each other. Each population serves as a tester for the selected progenies from others. Combining ability is the base for this selection either it is GCA or SCA [47]. Improved populations by reciprocal recurrent selection can be used to develop a superior combined population with a broad genetic base.

1st Year

1. Individual plants selection on a phenotypic basis
2. Selfing of the individuals selected in step (i.)
3. Each plant from one population is test crossed with several plants from other populations randomly.

2nd Year

1. Superior progenies of test crosses are collected separately
2. Replicated yield trials for selected testcross progenies from each population
3. Select superior progenies

3rd Year

1. Selfing of selected progenies
2. Inter-crossing among progenies from each population separately
3. Bulking the seeds of inter-crosses from each population separately

4th Year

1. Composite plantation separately
2. Repeat the steps (i) and (ii) of 1st year

5th Year

1. Repeat the procedure of 2nd year

6th Year

1. Repeat the procedure of 3rd year [47]

3.2 Hybridization

Plant hybridization is the process of crossbreeding between genetically dissimilar parents to produce a hybrid. It frequently results in polyploid offspring. Following the cross-pollination, segregating Generations are grown, and pure lines are selected after homozygosity is reached. The objective is to Identify and select lines that combine desirable genes from both parents [48]. The selected lines are Evaluated by progeny tests to verify the presence of a desirable combination of genes. Hybridization is to obtain an assortment and recombination of desirable genes from the parent cultivars [48]. The reported advantage of haploid breeding is to obtain rapid homozygosis following hybridization, but the induction of mutations in the segregating progenies confounds the selection process and increases the difficulty of finding the segregants with the desired recombination of genes [48]. Hybridization might be Interspecific or Intervarietal:

3.2.1 Interspecific hybridization

The plant breeders purpose in making interspecific or intergeneric crosses is to transfer a gene not available in existing cultivars. The success will be affected by the genetic relationships among the species [49]. The system of classifying plants into species is based on the natural relationships between groups of plants as determined largely by their morphological and physiological characteristics. The classification was worked out to a large extent before the science of genetics was developed and without current information on the relationships existing among chromosomes and genes in different species. As a result of it is difficult to make generalizations regarding the breeding behavior in interspecific and intergeneric hybridization [49].

3.2.2 Intervarietal hybridization

The parents involved in hybridization belong to the same species; they may be two strains, varieties, or races of the same species. In crop improvement programs, intervarietal hybridization is the most commonly used. An example would be the crossing of two varieties of wheat (*T. aestivum*), rice (O. Sativa), or some other crop. The intervarietal crosses may be simple or complex depending upon the number of parents involved [49]. In a simple cross, two parents are crossed to produce the F_1. The F_1 is selfed to produce F_2 or is used in a backcross program, e.g., A x B → F1 (A x B). More than two parents are crossed to produce the hybrid, which is then used to produce F_2 or is used in a backcross. Such a cross is also known as a convergent cross because this crossing program aims at converging genes from several parents into a single hybrid [49].

3.2.3 Utilization of hybrid vigor

Observation says that the cross of two different varieties results in a hybrid having desirable characteristics than their parents and that is known by the term Heterosis / Hybrid vigor. A hybrid may have more desirable characteristics of growth, yield, reproduction than their parents by whom it is produced [50]. We just know the heterosis/hybrid vigor phenomenon but we are still not aware of the actual mechanism causing higher growth rate of hybrids than their parents. Heterosis is not caused by a single source but actually, its caused by a mixture of many mechanisms and that knowledge we just attain from systems of genetically model rice, cotton, maize [50]. Also, the studies showed that in tomatoes the heterosis is controlled by a single locus so the heterozygous type of tomato plant has a higher yield than homozygous plants. We are still working on the genetic basics of heterosis and in F_1 hybrids the combination of different genetic mechanisms produces the heterotic phenotypes [50]. Firstly, Hayes and Jones proposed heterosis/vigor hybrid in cucumber but it did not work because of production of hybrid cucumber seeds was costly. Also in tomatoes there occur less hybrid utilization because of a large amount of self-pollination [51]. There are some scientists Pearson, Jones, and Clarke utilized different genomic mechanisms in cabbage and onion for the reduction in selfing and production in pure line and hybrid seeds. After they get to know heterotic traits like growth, yield, stress tolerance, etc are good in F_1 hybrids [51]. Basically, the objective of heterosis is to get comparatively high plant growth, plant yield. Size, weight, and the number of fruits also matter in hybrid vigors objective. Hybrids show good desirable characteristics like fruit size, fruit weight also the number of fruits in heterosis as compared to their parents who also have those characters [52]. Heterosis was firstly described in 1912 as a high plant performance than others. Then hybrids were made to improve this strategy also known as hybrid vigor. Hybrid vigor simply means that the total higher output than that of parents which includes growth, size, number of fruits, efficiency, etc overall productiveness that really means [53]. The term heterosis is closely associated with the term hybrid vigor and that term heterosis is commonly being used for the enhancement of crops gross productivity. Different agents show their importance in heteroses like dominance/overdominance, heterozygosity, allelic / non-allelic interactions, epistasis, and maternal interactions, etc these help hybrids for the heterosis action [53]. In general, the efficiency of the plant in F_1 generation depends upon heterosis. Doshi and Shukla described in 2000 that the utilization of hybrid vigor in chili results in more heterosis effect in different character such a fruit volume, number of fruits per plant, fruit shape and that indicate a large number of hybrid seed production. This makes it possible to take that chili hybrid seed to a commercial level just because of their high heterosis effect in the yield of the chili plant [53]. We came to know that some crops such as maize, rice, sorghum showed high efficiency in yield production because of heterosis so this encourages the growth of hybrids [54]. Heterosis showed higher efficiency in traits that were related to productivity. Feyzian et al also observed the heterosis effect in melon which is related to the weight of fruit. So the heterotic effect in different plants is the result of some genomic effects like dominance, epistasis, super dominance. The plant growth, number of fruits per plant, fruit volume, the complete productiveness all depend upon some crosses and this is in control of many genes which reveal the heterotic effect in a plant [54].

4. CONCLUSION

This review allows estimating the state of a functional factor in regard to the main breeding technologies and selection methods of self-pollinated and cross-pollinated crops separately. All these technologies and methods have a common objective the eliminate various defects that contribute to the low yield and poor quality of the end product. Important progress in crop breeding has been made in the development of varieties of better quality that can withstand the hazards of adverse weather, disease, insects, and unfavorable soil conditions. The whole chapter aims to provide an amazing figure of facts in terms of modern technologies which finally contribute to originate various crop varieties with desired results and traits.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Qaim M. Role of new plant breeding technologies for food security and sustainable agricultural development. Applied Economic Perspectives and Policy. 2020;42(2):129-50.
2. Pingali PL. Green revolution: impacts, limits, and the path ahead. Proceedings of the National Academy of Sciences. 2012; 109(31):12302-8.
3. Oliver MJ. Why we need GMO crops in agriculture. Missouri Medicine. 2014; 111(6):492.
4. Kaiser N, Douches D, Dhingra A, Glenn KC, Herzig PR, Stowe EC, Swarup S. The role of conventional plant breeding in ensuring safe levels of naturally occurring toxins in food crops. Trends in Food Science & Technology. 2020;100:51-66.
5. Yan G, Liu H, Wang H, Lu Z, Wang Y, Mullan D, Hamblin J, Liu C. Accelerated generation of selfed pure line plants for gene identification and crop breeding. Frontiers in Plant Science. 2017;8:1786.
6. Fradgley N, Gardner KA, Cockram J, Elderfield J, Hickey JM, Howell P, Jackson R, Mackay IJ. A large-scale pedigree resource of wheat reveals evidence for adaptation and selection by breeders. PLoS biology. 2019;17(2):e3000071.
7. Gramazio P, Prohens J, Plazas M, Mangino G, Herraiz FJ, Vilanova S. Development and genetic characterization of advanced backcross materials and an introgression line population of Solanum incanum in a *S. melongena* background. Frontiers in Plant Science. 2017;8:1477.
8. Abbas MA, Hussain T. General agriculture. Publishers Emporium; 2000.
9. Yan G, Liu H, Wang H, Lu Z, Wang Y, Mullan D, Hamblin J, Liu C. Accelerated generation of selfed pure line plants for gene identification and crop breeding. Frontiers in Plant Science. 2017;8:1786.

10. Nakwilai P, Cheabu S, Narumon P, Saensuk C, Arikita S, Malumpong C. Evaluation of japonica rice (*Oryza sativa* L.) varieties and their improvement in terms of stability, yield, and cooking quality by pure-line selection in Thailand. Sci Asia. 2020;46:157-68.
11. Bagheri M, Keshavarz S. Pure line selection from five Iranian eggplant (*Solanum melongena* L.) landraces.
12. Roy PS, Patnaik A, Rao GJ, Patnaik SS, Chaudhury SS, Sharma SG. Participatory and molecular marker assisted pure line selection for refinement of three premium rice landraces of Koraput, India. Agroecology and Sustainable Food Systems. 2017;41(2):167-85.
13. Nakano M, Taniguchi K, Masuda Y, Kozuka T, Aruga Y, Han J, Motohara K, Nakata M, Sumitomo K, Hisamatsu T, Nakano Y. A pure line derived from a self-compatible Chrysanthemum seticuspe mutant as a model strain in the genus Chrysanthemum. Plant Science. 2019;287: 110174.
14. Thiago ND, Perecin D, Xavier MA, Marcos GD, Daniel ND, Rubens LD. Methods of selection of seedlings in sugarcane breeding programs. RASSA Journal of Science for Society. 2021;3(1):61-9.
15. Reitan L. Early generation mass selection for seed dormancy in barley. InThird International Symposium on Pre-Harvest Sprouting in Cereals. 2019;244-250.
16. Alves ML, Belo M, Carbas B, Brites C, Paulo M, Mendes-Moreira P, Brites C, Bronze MD, Šatović Z, Vaz Patto MC. Long-term on-farm participatory maize breeding by stratified mass selection retains molecular diversity while improving agronomic performance. Evolutionary applications. 2018;11(2):254-70.
17. Yahaya MA, Shimelis H, Laing M, Mohammed MS, Mathew I. Methodologies for hybridization in predominantly self-pollinating crops: A review. Journal of Crop Improvement. 2020;34(2):268-89.
18. López-Caamal A, Tovar-Sánchez E. Genetic, morphological, and chemical patterns of plant hybridization. Revista chilena de historia natural. 2014;87(1): 1-4.
19. López-Caamal A, Tovar-Sánchez E. Genetic, morphological, and chemical patterns of plant hybridization. Revista Chilena de Historia Natural. 2014;87(1): 1-4.
20. Yahaya MA, Shimelis H, Laing M, Mohammed MS, Mathew I. Methodologies for hybridization in predominantly self-pollinating crops: A review. Journal of Crop Improvement. 2020;34(2):268-89.
21. Nunes JA, Ramalho MA, Ferreira DF. Inclusion of genetic relationship information in the pedigree selection method using mixed models. Genetics and Molecular Biology. 2008;31:73-8.
22. Belete YS, Kebede SA, Gemelal AW. Heritability and genetic advance in Ethiopian mustard (*Brassica carinata* A. Brun). International Journal of Plant Breeding. 2011;6(1):42-6.
23. Niazi IA. Description of new high yielding forage Avena Sativa L. cultivar Super Green Oats. Journal of Agriculture and Food. 2021;2(1):17-25.
24. Salwa MM, Abou-Zaid GA, El-Refaey RA, Sarhan AD. Selection efficiency of pedigree method in early segregating generations of faba bean (*Vicia faba* L). Egypt. J. Plant Breed. 2017;21(5):469-478.
25. Swarnapriya R. Breeding Approaches for Biotic Stress Resistance in Vegetables. InPlant Breeding-Current and Future Views 2021 May 5. IntechOpen.
26. Briggs FN. The use of the backcross in crop improvement. The American Naturalist. 1938;72(740):285-92.
27. Hospital F. Selection in backcross programmes. Philosophical Transactions of the Royal Society B: Biological Sciences. 2005;360(1459):1503-11.
28. Hebard FV. The backcross breeding program of the American Chestnut Foundation. Journal of the American Chestnut Foundation. 2006;19:55-77.
29. Ullah S, Bramley H, Daetwyler H, He S, Mahmood T, Thistlethwaite R, Trethowan R. Genetic contribution of emmer wheat (*Triticum dicoccon* Schrank) to heat tolerance of bread wheat. Frontiers in plant science. 2018;9:1529.
30. Reddy BV, Rattunde HF, Stenhouse JW. Breeding sorghums for insect resistance. Plant resistance to insects in sorghum. Patancheru 502 324, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics 1997;25: 115.
31. Sabesan T, Saravanan K. Breeding Procedures for Developing Insect-Resistant Crops. In Experimental Techniques in Host-Plant Resistance 2019. Springer, Singapore. 2019;285-293.

32. Morais Júnior OP, Breseghello F, Duarte JB, Morais OP, Rangel PH, Coelho AS. Effectiveness of recurrent selection in irrigated rice breeding. Crop Science. 2017;57(6):3043-58.
33. Miladinović J, Vidić M, Đorđević V, Balešević-Tubić S. New trends in plant breeding-example of soybean. Genetika-Belgrade. 2015;47(1):131-42.
34. Abbas MA, Hussain T. General agriculture. Publishers Emporium; 2000.
35. Acquaah G. Principles of plant genetics and breeding. John Wiley & Sons; Mar 12, 2009.
36. Gokidi YU, Bhanu AN, Singh MN. Marker assisted recurrent selection: an overview. Adv Life Sci. 2016;5(17):6493-9.
37. Bos I, Caligari P. Selection methods in plant breeding. Springer Science & Business Media; 2007 Oct 26.
38. Degefa I. Plant breeding methods: In brief for student. International Journal of Agriculture and Agribusiness. 2019;3:156-203.
39. Chaudhry MR. Cotton breeding: Developments and opportunities. In33rd International Cotton Conference. 2016; 16-18
40. Jennings DL, Iglesias C. Breeding for crop improvement. Cassava: Biology, production and utilization. 2002;149-66.
41. David Luckett and Gerald Halloran, chapter 4, plant breeding, 22-24
42. Jennings DL, Iglesias C. Breeding for crop improvement. Cassava: Biology, production and utilization. 2002;149-66.
43. Jennings DL, Iglesias C. Breeding for crop improvement. Cassava: Biology, production and utilization. 2002;149-66.
44. Al-Taweel SK, Azzam CR, Khaled KA, Abdel-Aziz RM. Improvement of stevia (stevia rebaudiana Bertoni) and steviol glycoside through traditional breeding and biotechnological approaches. Sabrao J. Breed. Genet. 2021;53:88-111.
45. Arshad K, Hussain A, Aslam A, Azam A, Asad M, Bilal M. Genetic Analysis of Drought Resistance in Maize Using Physiological, Morphological and Molecular Markers. Asian Journal of Biotechnology and Genetic Engineering. 2021;29:1-0.
46. Sajjad M, Khan NU, Gul S, Khan SU, Bibi Z, Ali S, Ali N, Khan SA. Maize improvement through selfed progeny recurrent selection across different environments. Pak. J. Bot. 2020;52(2):541-9.
47. Degefa I. Plant breeding methods: In brief for student. International Journal of Agriculture and Agribusiness. 2019;3: 156-203.
48. Wright H. Commercial hybrid seed production. Hybridization of crop plants. 1980;161-76.
49. Hadley HH, Openshaw SJ. Interspecific and intergeneric hybridization. Hybridization of crop plants. 1980:133-59.
50. Goulet BE, Roda F, Hopkins R. Hybridization in plants: old ideas, new techniques. Plant physiology. 2017;173(1): 65-78.
51. Yu D, Gu X, Zhang S, Dong S, Miao H, Gebretsadik K, Bo K. Molecular basis of heterosis and related breeding strategies reveal its importance in vegetable breeding. Horticulture Research. 2021; 8(1):1-7.
52. Tamta S, Singh JP. Heterosis in tomato for growth and yield traits. International Journal of Vegetable Science. 2018;24(2): 169-79.
53. Herath HN, Rafii MY, Ismail SI, JJ N, Ramlee SI. Improvement of important economic traits in chilli through heterosis breeding: a review. The Journal of Horticultural Science and Biotechnology. 2021;96(1):14-23.
54. Angui CM, Koffi KK, Issali AE, Zoro BI. Assessment of hybrid vigour, dominance effect and hybrids regeneration potential in the genus Citrullus. Heliyon. 2020;6(9): e05005.

Peer-review history:
The peer review history for this paper can be accessed here:
https://www.sdiarticle4.com/review-history/72979