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Review Article

Speed breeding to accelerate crop improvement

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Abstract

Global food security has become a major issue as the human population grows and the environment changes, with the current rate of improvement of several important crops inadequate to meet future demand. Crop plants have extended generation times, which contributes to the slow rate of progress. However, speed breeding has revolutionized the entire world by reducing generation time and speeding up breeding and research programs to improve crop varieties. In the absence of an integrated pre-breeding program, breeding new and high-performing cultivars with market-preferred traits can take more than ten years. After the first cross with parental genotypes, a large amount of time, space, and resources are committed to the selection and genetic advancement stages during the early stages of breeding. Speed breeding has the ability to shorten the time it takes to develop, market, and commercialize cultivars. Crop improvement in the face of a fast-changing environment and an ever-increasing human population is a major concern for scientists around the world. Current crop enhancement projects are progressing at a rate that is insufficient to meet food demand. Crop redesign is urgently needed for climate resilience, as well as long-term yield and nutrition. Crop progress is slowed significantly by the long generation time required by crop plants during the breeding process. Speed breeding is now being used on a large scale to shorten generation time and support multiple crop generations per year as a solution in this approach. Researchers are now using an integrated approach to improve breeding efficiency, combining speed breeding with current plant breeding and genetic engineering methods. Speed breeding is a promising approach for achieving nutritional security and sustainable agriculture by shortening breeding cycles for food and industrial crop enhancement. Speed breeding is a methodology that allows plant breeders to improve crop production by adjusting temperature, light duration, and intensity to boost plant development. It uses an artificial source of light, which is kept on continuously, to activate the photosynthetic process, which leads to growth and reproduction much earlier than normal. This will assist in meeting the demands of the future's rising population. This can be accomplished using a variety of technologies, including genotyping, marker-assisted selection, high throughput phenotyping; gene editing, genomic selection, and re-domestication, all of which can be combined with speed breeding to allow plant breeders to keep up with a changing climate and growing human population.

Introduction

Crop production must increase to meet the food needs of the world human population; yet, changing environmental conditions make this task difficult. Climate change, also known as the "climate catastrophe," is causing the Earth to become warmer and drier [1]. Drought-related economic losses in agriculture have cost the world $29 billion over the last decade [1]. Water demand for agriculture is expected to double by 2050, with freshwater availability declining by up to 50% as a result of growing climate variability. Food security demands immediate investments in this area, notably in the development of high-yielding crops that are climate resilient and use water more effectively and efficiently than their current counterparts [2]. By 2050, the current rate of crop improvement will be insufficient to feed the world's growing population. In the face of drought stress, which results in severe crop yield losses, higher, more stable, and sustainable crop production is necessary.

The global population has been growing for several years and is expected to grow by at least 25% geometrically, yet food supplies are still limited [3]. Traditional or conventional breeding methods will not be sufficient to meet the demands of future generations, so breeders and cultivators are constantly under pressure to improve crop production and develop new

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varieties of crops that are of higher quality and yield higher yields that should be of superior quality in every respect, including nutritional value, disease resistance, and climatic changes. Before an improved cultivar is issued, it must go through several generations of cycling and evaluation. To introduce and assess many traits of interest, this lengthy procedure is required. However, a process known as 'speed breeding' for rapid generation advancement has been successfully implemented in agricultural plants to achieve rapid rates of crop improvement. Unlike in the past, plant breeders now have breakthrough technology that can help them overcome future crises and improve crop types.

Some of the methods that are now being used include the development of automated high-throughput phenotyping technology systems that help to boost selection strength and precision [4]. Another option is to use 2nd and 3rd generation sequencing platforms, which allow breeders to use more economical DNA markers. It helps in gene discovery and analytical breeding technologies, both of which attempt to boost production quantity and quality [5]. Although all of these technologies help to produce the best results, one of their limitations is that they only produce one or two generations per year, which poses a problem for crop production in terms of quantity. However, this limitation has been alleviated by the 'speed breeding' protocol, which uses light and temperature control systems to produce at least six generations of crops per year [6].

Speed breeding has the ability to develop crop varieties in a smaller duration of time. It is an artificial environment with increased light duration to provide extended day light, which helps in the manipulation of photo-insensitive crop life cycles. A new variety takes 8-10 years to produce using traditional methods, but with speed breeding, the generation cycle can be shortened (2- 3x times). Speed breeding methods are available for several plant crops that function on the chromosomes and are provided with ideal light quality, light intensity, and proper temperature to boost photosynthesis and increase growth and breeding. At least six generations of distinct species are produced as a result of this process. Speed breeding does not necessitate the use of specialist labs; it can be done in ordinary settings [7]. Speed breeding provides various advantages over conventional approaches, including the ability to accelerate backcrossing, pyramiding characteristics, and transgenic pipelines. Speed breeding can be done in smaller regions, and researchers who do not have access to bigger areas can set up smaller speed breeding units [8]. To speed crop development under controlled temperature and light conditions, speed breeding has been integrated with numerous different methods.

Selecting complimentary parental genotypes with desired traits, followed by crossings and a succession of selection and advancement of superior progenies to produce candidate cultivars that meet market demands, is the traditional strategy of breeding a new crop variety [9]. Higher yield potential and nutritional quality, as well as increased tolerance to biotic and abiotic challenges, are all important breeding goals in agricultural cultivar improvement projects [9]. In any crop improvement program, the following breeding procedures can be distinguished in the following order: (a) selection of desirable parents with complementary traits to combine; (b) crosses involving the selected parents and the development of progenies; (c) selection and genetic advancement of the best progenies based on target traits; (d) screening of the best progenies in multiple target production environments to identify the best performing; [8].

Most crop cultivar development efforts use these conventional breeding techniques. In the absence of an integrated pre-breeding program, however, traditional breeding processes can take more than ten years to produce and release an enhanced variety [10]. However, current methods such as doubled haploid breeding [11] and speed breeding can minimize the length of each crop breeding cycle [12]. Speed breeding is a collection of strategies that involves manipulating the environmental conditions in which crop genotypes are produced with the goal of speeding up flowering and seed development to get to the next breeding generation as soon as feasible. Through quick generation development, the approach reduces breeding time and resources. Global climate change and population growth have posed a danger to global food security by increasing demand for larger quantities and higher quality food. Crop breeding attempts to meet this growing need, but the long breeding cycle required to generate any acceptable cultivar is a severe restriction. As a result, breeders have long desired to reduce the crop duration in each generation of a breeding cycle. Speed breeding is a new technology that aims to shorten the agricultural breeding cycle and accelerate crop improvement through rapid generation advancement. Growing crops in a speed breeding-specific growth chamber speeds up research on adult plant phenotyping, crossing, mutants, and transformation.

Speed breeding protocols are currently being developed for several crops [6]. Unlike twofold haploid technology, which uses haploid embryos to produce entirely homozygous lines, speed breeding is suited for a wide range of germplasm and does not require special in vitro culturing equipment [6]. The premise of speed breeding is to accelerate the rate of photosynthesis by using optimal light intensity, temperature, and daytime duration regulation (22 h light, 22°C day/17°C night, and high light intensity), along with annual seed harvesting to minimize the generation period [13]. Flowering is controlled by the intensity and wavelength of light [14]. The speed of yield increment in most crop breeding efforts is insufficient to meet the increased food demand induced by a rapidly growing global population. The very long crop duration limits the development of improved crop varieties in plant breeding. The rapid development of better plant varieties is one strategy to alleviate food scarcity issues and increase food security. Through rapid generation advancement, speed breeding shortens the breeding cycle and accelerates crop research. Speed breeding can be done in a variety of methods, one of which is to lengthen the duration of plants' daily light exposure, paired with early seed harvest, to cycle swiftly from seed to seed, lowering generation times for some long-day or day-neutral crops. The objective of this paper was to

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assess the potential use of speed breeding techniques in a crop improvement system.

Role of speed breeding in enhancement of crop plants

The majority of plant species have bottlenecks in their applied research and breeding programs, requiring the development of technology to speed up plant growth and generation turnover. NASA's work in the early 1980s was an inspiration to all plant scientists. Researchers at the University of Queensland coined the phrase "speed breeding" in 2003 to describe a set of techniques designed to speed up wheat breeding. Over the last 100 years, traditional breeding programs around the world have produced numerous notable enhanced types. Despite this, development is gradual, in part due to the lengthy breeding cycle, which can take anywhere from 10 to 15 years from cross to cultivar release [15]. Combining large numbers of polygenic characteristics is a significant challenge [9]. While marker-assisted selection has proven to be an effective tool in crop improvement programs, it is most effective when targeting a small number of genes with a large effect, such as leaf rust resistance genes (e.g. Lr23) in bread and durum wheat [16] and Yr15 in durum wheat [16].

Speed breeding produces 3 to 9 generations per year against 1 to 2 generations per year with traditional selection methods [6]. As a result, speed breeding allows for the rapid production of homozygous and stable genotypes, as well as the rapid progress of generations, resulting in the development and release of novel cultivars [17]. In addition, for multiple trait selection, speed breeding technology works well with marker-assisted selection and high-throughput phenotyping approaches. Furthermore, marker-assisted selection may only be used if the target gene or QTL responsible for the desired characteristic is known. As a result, the marker-assisted selection is less viable for complex traits when the underlying genetic influences are unknown [18].

Genomic selection (GS) has recently surmounted the constraints of marker-assisted selection by estimating breeding values (EBVs), which provide an assessment of the genomic merit associated with all small or substantial impacts across the entire genome, using genome-wide markers [19]. The genomic selection also allows for simultaneous selection of several traits; nevertheless, despite the efficiency and promise of this breeding strategy, the costs of genotyping large numbers of selected candidates are currently too costly to encourage widespread usage. Furthermore, because genomic selection is often used for inbred lines [20], the rate of advancement is constrained by the time necessary to conduct crossings and generate genetically stable new selection candidates.

Several speed breeding-adapted phenotyping techniques have been established, allowing for the characterization and selection of important traits [21]. Plant breeders are interested in screening a wide range of traits in population development's early generations. This allows breeding programs to save time and money by reducing labor and field testing costs. A high-throughput, reproducible, and robust screening methodology is necessary to accomplish this. For genetic studies and plant breeding, improving existing phenotyping methods and inventing new methods for phenotyping traits are critical. High-throughput, rapid, cost-effective, and repeatable methods are required for traits that are highly variable not just in the field but also in the glasshouse. Speed breeding methods can also be used to synchronize the flowering of cultivated and wild individuals of crop species, increasing the amount of variety in breeding populations and accelerating the achievement of breeding goals. Optimizing the plant development environment (plant density, photoperiod, and temperature), genetic engineering targeting the flowering pathway, grafting juvenile plants to mature rootstocks, using plant growth regulators, and harvesting immature seed are all techniques for rapid cycling [21].

Integrated phenotyping with speed breeding as a tool for improving yield

Any breeding selection method starts with phenotyping. Modern plant phenotyping, on the other hand, evaluates complex traits related to growth, yield, and stress adaption with greater accuracy and precision at many scales of organization, from organs to canopies [22]. The assessment of complex plant traits such as growth, development, tolerance, resistance, architecture, physiology, ecology, and yield, as well as the basic measurement of individual quantitative parameters that form the basis for complex trait assessment, is a more recent and comprehensive definition for plant phenotyping [23]. The dynamic and local interaction of phenotypes with the spatially and temporally dynamic environment above and below ground gives rise to the plant phenotype. Plant biomass [24], root morphology [25], leaf features [26], and fruit traits are all examples of structural and functional aspects that can be directly quantified.

Phenotyping is the assessment of complex plant traits related to growth, development, and all other features that serve as the foundation for complex trait assessment. Because the temperature fluctuates throughout the year in every corner of the world, it has an impact on crop output, resulting in human misery due to a lack of food resources. Jack Christopher et al. [27] conducted an experiment on the Australian environment because there was evidence of a continual rise in temperature and decrease in rainfall in that region. As a result, an experiment was carried out to determine the efficacy of combining phenotyping and speed breeding to promote root adaptation in changing environments and water scarcity. By combining phenotyping and speed breeding, a multi-purpose approach was used to boost yield. Overpopulation development of more than 1000 recombinant inbred lines of wheat was advanced to generation within 18 months, according to the study's findings. As a result, our study provides a solid foundation for integrating genetic advances toward enhanced adaptability to water-limited conditions [27].

Gene editing in combination with speed breeding for crop improvement

Although traditional plant breeding has been successful in producing excellent crop varieties, genetic quality has

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decreased in the current era due to continual selection and long-term domestication of crops, and this is one of the limiting factors for crop quality development. In this era, genome editing technology has proven to be beneficial. Gene editing is a technology that involves making changes to the genes of a crop species to improve its yield. Felix Wolter, et al. [28] investigated the ability of CRISPR/Cas to generate directed genomic variation at many loci in their research. The CRISPR/Cas system opens new possibilities for genetic diversity. It can multiplex, which means that the number of targets can be changed at the same time. It addresses the actual issue, and a high-yielding variety can be produced; however, this process takes a long time and requires a lot of effort; therefore, combining genome editing and speed breeding has the potential to overcome this crisis, and multiple generations can be produced in a single year [28].

Boosting genetic gain by speed breeding and genomic selection

Shorter breeding cycles (the time between crossing and selecting progeny to use as parents for the next cross) and a reduction in the number of cycles required to develop new varieties can help breeders and researchers make faster progress. In crops including wheat, rice, and maize, recent improvements in breeding techniques such as genetic engineering, genomic selection, and doubled-haploid technology have shortened breeding cycles and enhanced genetic gain rates [15]. When these technologies are paired with speed breeding techniques, which allow for rapid generation advancement by cultivating plant populations under-regulated photoperiod and temperature regimes to quicken their growth and development, they can have an even bigger impact [28].

The rate of genetic gain in a breeding program can be represented by the breeder's equation, a model of the expected change in a trait in response to selection [29]. The equation can be written as $R = \frac{\delta g \text{ x i x r}}{L}$, where *R* is the change in the trait mean per year, δ g is the amount of genetic variation within the population, i is the selection intensity, r is the selection accuracy, and L is the length of the breeding cycle. Based on this equation, speed breeding protocols can improve genetic gain in crop improvement programs by increasing the number of plant generations cycled in one year, which can substantially reduce the length of the breeding cycle. This is particularly useful for crossing and line development before field evaluation.

Speed breeding and genomic selection are used to improve the genetic benefit. Researchers have shown that speed breeding and genomic selection can improve genetic benefits in a variety of crops. Meuwissen et al. [30] were the first to propose genomic selection. The fundamental benefit of using genomic selection is that it shortens the breeding cycle and creates higher-quality plant varieties in a shorter amount of time, improving genetic gain. Researchers have demonstrated that combining genomic selection with other modern breeding procedures can improve crop quality even more effectively. The recent development of 'speed breeding' procedures has the potential to drastically speed up breeding efforts for many crops by increasing generation in a shorter time frame [31]

Speed breeding to accelerate domestication

Plant domestication is the process of transforming wild plant varieties into crop plants via artificial means. Early hybridization is followed by a selective breeding approach in this procedure. Plant breeding is especially connected to polyploidy crops. It is a time-consuming technique, thus to address this issue, it has been integrated with speed breeding, which minimizes the time duration and number of generations of that crop that has been issued. Plant domestication proof has to be found in polyploidy plants like peanuts and bananas, in combination with rapid breeding. O'Connora et al. undertook a study to determine the feasibility of using the speed breeding approach in peanut breeding. In comparison to the regular breeding phase, this study reduces the time it takes to produce multiple generations in a shorter period [12].

Multiple disease resistance by speed breeding

Plant breeders are experimenting with new approaches to improve crop production quality to respond faster to changing climates and emerging diseases. Lee T. Hickey et al. [15] combined the two-row barley cultivar, Scarlett, with novel approaches for rapid trait introgression in a study. They developed 87 BC1F3:4 Scarlett introgression lines (ILs) in two years using four donor lines with multiple disease resistance and a redesigned backcross method that included phenotypic multi-trait screens as well as fast generation advanced technology 'speed breeding' [32].

Comparison of speed breeding with other breeding techniques

Plant breeding strategies that use existing genomic variation in plants to generate a variety in eight to ten years can reduce genetic variability in the genome of the plant. Traditional breeding methods cannot meet the ever-increasing food demand for grain crops. It is critical to enhance breeding processes to boost food production in less time. To increase agricultural traits, several conventional and molecular breeding strategies are applied. CRISPR/Cas9, CRISPR/Cpf1, prime editing, base editing, dcas9 epigenetic modification, and various additional transgene-free genome editing techniques have been created by molecular researchers. These genome editing technologies can precisely and quickly improve desired traits. Furthermore, by reducing the crop cycle, a newly developed breeding technology known as "speed breeding" has transformed agriculture.

Ensure global food and nutrition security is an age-old challenge made more difficult by accelerated population growth rates in poor and emerging economies, urbanization, extreme and changing climates, the need to reduce agricultural activities' environmental impact, and competing demands for food, feed, and fuel [33]. A few and declining number of plant and animal species and strains are used in global agri-food systems [34]. Shorter breeding cycles (the time between

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crossing and selecting progeny to use as parents for the next cross) and a reduction in the number of cycles required to develop new varieties can help breeders and researchers make faster progress. In crops including wheat, rice, and maize, recent improvements in breeding techniques such as genetic engineering, genomic selection, and doubled-haploid technology have shortened breeding cycles and enhanced genetic gain rates [15]. When these technologies are paired with speed breeding techniques, which allow for rapid generation advancement by cultivating plant populations under-regulated photoperiod and temperature regimes to hasten their growth and development, they can have an even bigger impact [17]

Plant breeding has played a critical role in ensuring food security and safety since the early 1900s and has had a significant impact on food supply around the world [35]. However, in recent years, worldwide food quality and quantity issues have arisen as a result of the excessive food demand for the fast-growing human population. Furthermore, extreme weather changes caused by global climate change are generating heat and drought stress, resulting in major crop losses for farmers all over the world [36]. Global epidemics, such as the Irish potato blight of the 1840s and the Southern corn leaf blight of the 1970s in the United States, were terrible events that killed millions of people owing to a lack of food [37]. The ratio of food production to consumption has declined significantly in recent years, while worldwide urbanization rates and demographic growth have soared. People choose to consume processed meals, which have a lower nutritional content, in this era of rapid expansion and progress. Traditional farming practices are intended to improve the nutritional value of various food plants. Recent scientific advancements have opened up a wide range of plant breeding options and novelties [38]. To meet the growing demand for plant-based products, the current yearly yield enhancement levels in main crop species (ranging from 0.8-1.2 percent) must be doubled [39] Figure 1.

Presently, farmers feed 10 times more people using the same amount of land as 100 years ago. The use of Mendelian rules for crop breeding transformed the profession. Crop development has changed dramatically in the last 150 years as a result of cutting-edge genetics [40]. Plant reproductive cycles have been shortened using a variety of techniques. Plant breeding has been proven to be accelerated using novel strategies developed in the last decade, including genomic selection, high-throughput phenotyping (HTP), and current speed breeding. Gene transformation has also been used to generate crops with desirable characteristics utilizing genetic engineering and molecular technologies [41]. Other strategies have been proposed to improve the breeding of commercially significant crop species, such as cisgenesis, intragenesis, polyploidy breeding, and mutant breeding, such as large-scale sequencing, genomics, quick gene isolation, and high-throughput molecular markers [42].

Plant genome improvement is insufficient for developing new plant varieties using traditional breeding approaches. Since the 1990s, molecular markers have been employed to identify superior hybrid lines to overcome this barrier in plant breeding procedures [43]. The artificial selection and breeding of this provided attribute by the plant breeder are required to improve plant phenotype for a certain desirable trait. In general, breeders focus on diploid or diploid-like qualities (maize and tomatoes) rather than polyploidy traits (alfalfa and potatoes), which have more complex genetics. Breeders prefer to use crops with shorter reproductive cycles, which allow

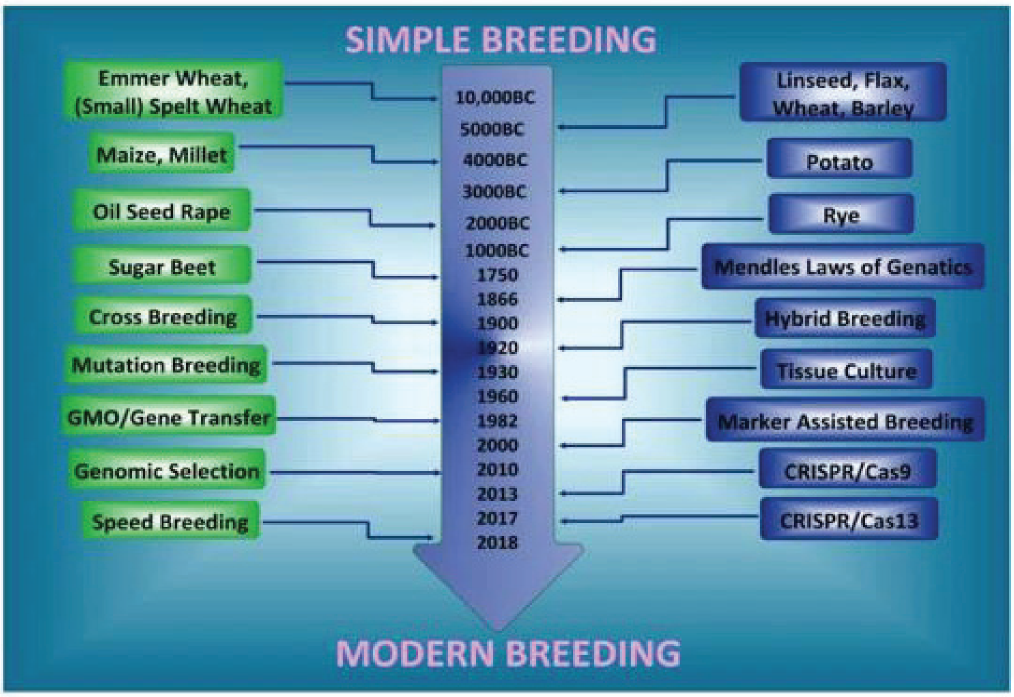

Figure 1: Historical milestones in plant breeding. For 10,000 years, farmers and breeders have been developing and improving crops.

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for the production of multiple generations in a single year, resulting in faster artificial breeding of desired phenotypes than crops that reproduce only once a year or perennial plants that reproduce only once every few years [44] Figures 2,3.

Conclusion

To feed the world's ever-growing population, food security in a changing environment is a serious concern. Plant breeding

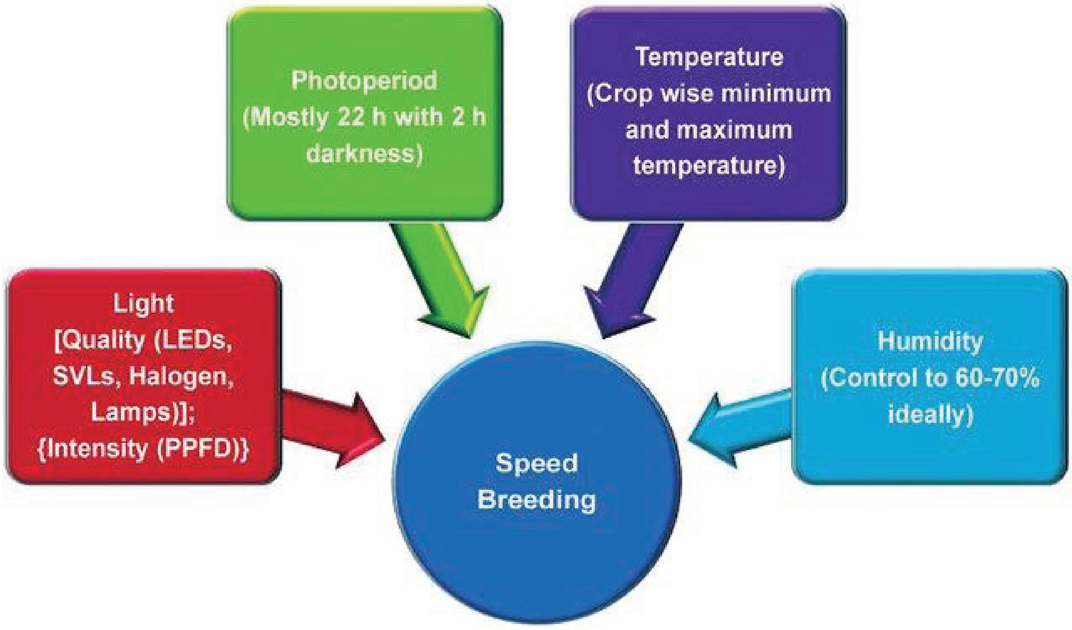

Figure 2: Key altering factor in speed breeding. Light: An appropriate spectral range (400-700 nm) can be achieved through light-emitting diodes (LEDs) or other lighting sources such as halogen lamps or sodium vapor lamps (SVLs). In addition to controlling light quality, light intensity should also be taken care of, so the recommended photosynthetic photon flux density (PPFD) of ~450-500 μmol/m 2 /s. Photoperiod: Normally recommended photoperiod of 22 h with 2 h of darkness in a 24-h diurnal cycle. Temperature: The optimal temperature regime (maximum and minimum temperatures) should be applied for each crop. Humidity: A reasonable range of 60-70% is ideal and for crops adopted in drier conditions, can apply a lower level.

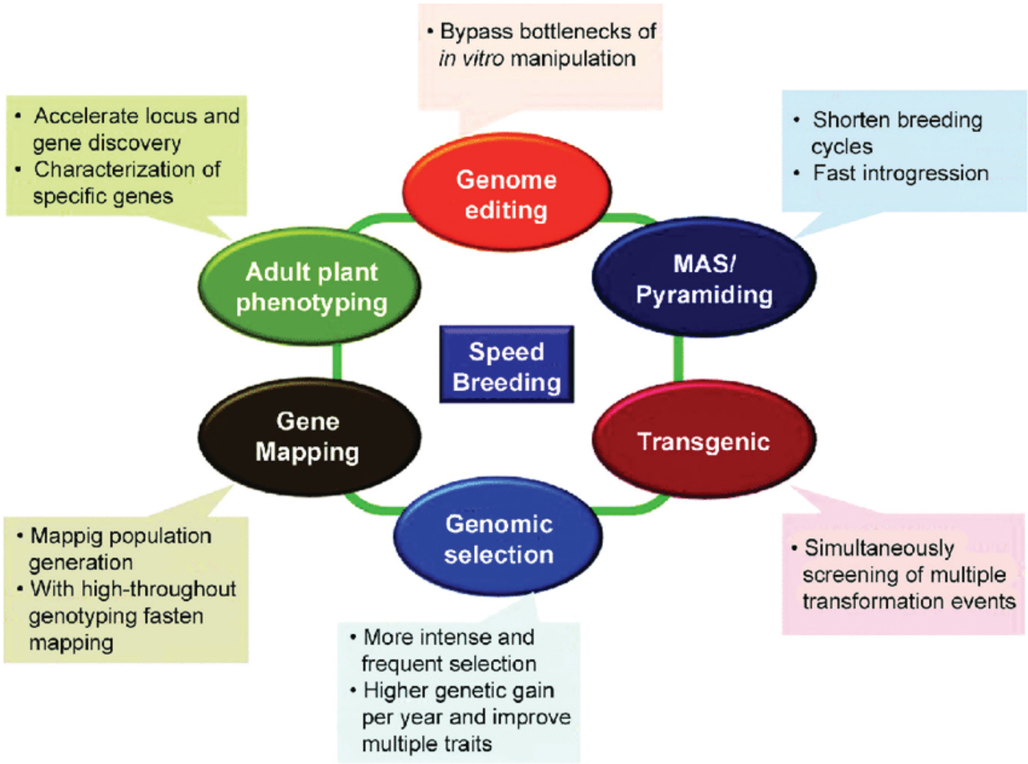

Figure 3: Speed breeding coupled with other breeding methodologies.

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advances in the form of breakthrough approaches are the ultimate solution for developing high-yielding, disease-resistant, and nutritious cultivars in a short period. Crop development is critical for improving crop yield to fulfill global food demands. Plant breeders and scientists are working hard to generate superior crops with higher yields, better nutritional compositions, pest and pathogen resistance, and climate resilience. To improve a crop, traditional breeding plays a vital role, which is a lengthy and tedious procedure that involves producing and studying huge populations of crops over several generations, frequently in conjunction with fatal gene co-integration.

The rate of yield increment in most crop breeding programs is insufficient to meet the increased food demand caused by a rapidly growing global population. The very long crop duration limits the creation of improved crop types in plant breeding. A new cultivar can take one or two decades to develop due to the numerous stages of crossing, selection, and testing needed in the generation of new plant varieties. The rapid development of better plant varieties is one strategy to alleviate food scarcity issues and increase food security. To improve agronomic qualities in crop plants that are linked to production, quality, and tolerance to biotic and abiotic challenges. Genetic selection, mutagenic breeding, somaclonal variations, whole-genome sequence-based techniques, physical mapping, and functional genomics tools were among the traditional and molecular approaches used. Recent advancements in genome editing technology, such as programmable nucleases, clustered regularly interspaced short palindromic repeats (CRISPR), and CRISPR-associated (Cas) proteins, have ushered in a new era of plant breeding. Plant breeders and researchers around the world are using modern strategies such as speed breeding, genome editing technologies, and high-throughput phenotyping to improve crop breeding efficiency.

Speed breeding is a form of protocol that can be used to increase agricultural yield by altering the light duration, intensity, and temperature-controlled zone, as well as the generation of disease-resistant varieties and lowering salt sensitivity in crops. The photosynthetic process is improved via speed breeding, resulting in faster crop development. In comparison to traditional breeding, this approach allows for the release of several generations of the same crop in a shorter amount of time. Speed breeding is a revolutionary technique for rapidly creating new long-day plant cultivars by lowering the generation time. Speed breeding is a cutting-edge technique for growing plants in several generations per year. To address food security challenges, more generation times each year are required. By lowering the amount of time, space, and resources invested in the selection and genetic progression of superior crop varieties, speed breeding can hasten the production of high-performing cultivars with market-preferred features. Plant breeders may now offer enhanced crop types more quickly thanks to this technology. For effective incorporation of speed breeding into a crop development program, streamlined operations that reduce labor and lost-cost facilities are essential.

Furthermore, combining speed breeding with conventional, marker-assisted selection, and gene editing breeding procedures can help to improve the selection of elite genotypes and lines with innovative features like improved yield and nutritional quality, as well as biotic and abiotic stress tolerance. The most suitable selection strategies are compatible with rapid breeding. However, in many developing countries, particularly in public plant breeding programs, the adoption of speed breeding is limited due to a shortage of skilled plant breeders and plant breeding technicians, as well as a lack of the necessary infrastructure and reliable water and electricity sources. There is now a lack of regulatory and financial support from the government to launch and continue speed breeding in public plant breeding programs. To accelerate the production, testing, and commercial release of crop varieties, speed breeding must be combined with other breeding techniques as well as cost-effective high-throughput genotyping and phenotyping. In general, plant biologists can scale up their crop improvement research by combining speed breeding with genetic tools and resources. Speed breeding protocols that reduce plant production times can help accelerate breeding and research to meet rising demand.

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