Speed Breeding in Cereal Crops: Accelerating Genetic Improvement for Rapid Agricultural Advancement

ABSTRACT

The global demand for food is rising due to population growth, climate change, and evolving consumer preferences. Traditional plant breeding programs typically require a decade or more to develop and release new crop varieties. Speed breeding is a cutting-edge technique designed to expedite genetic improvement by significantly reducing the seed-to-seed cycle. This review explores the principles, applications, and potential of this method in accelerating agricultural advancement.Originating from NASA's experiments for food production in space, the approach has evolved into a highly efficient strategy for speeding up breeding cycles in cereal crops. By manipulating light, photoperiodic regimes, temperature, and humidity within controlled environments, it is possible to achieve up to six generations of photo-insensitive crops and two to three generations of other crops per year. This rapid generation turnover provides a unique opportunity for accelerated genetic mapping, trait stacking, and enhanced genomic selection.Speed breeding complements modern breeding technologies such as genome editing, high-throughput genotyping, and CRISPR, facilitating quicker development of crop varieties with improved traits. Its applications extend to boosting transgenic pipelines and understanding critical physiological traits in crops. Furthermore, it aligns with breeding methods like single plant selection and single seed descent, offering a more efficient path to desirable outcomes.However, challenges remain, including the need for specialized infrastructure, the impact of genotypic variations, and potential stress responses due to accelerated conditions. Despite these hurdles, speed breeding represents a promising tool in the quest for food security and resilient agricultural systems. This review examines its potential to transform plant breeding, reduce cultivar development times, and contribute to rapid agricultural advancement in a changing world.

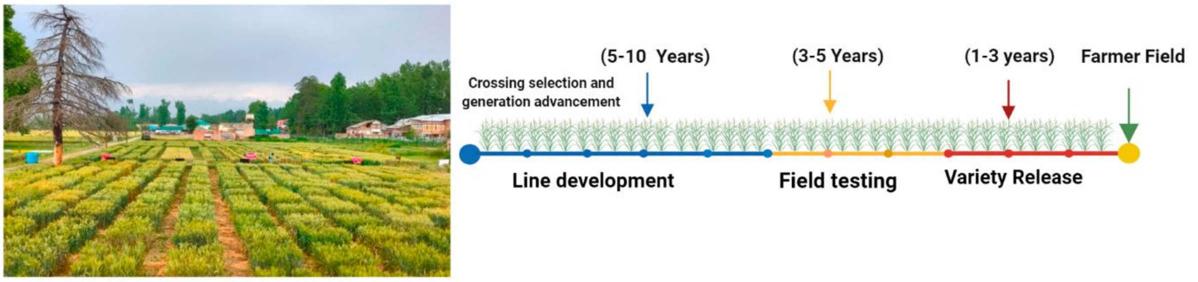
Keywords: *genome-editing, genotyping, CRISPR, Transgenic, Speed breeding, genomic selection*

1. INTRODUCTION

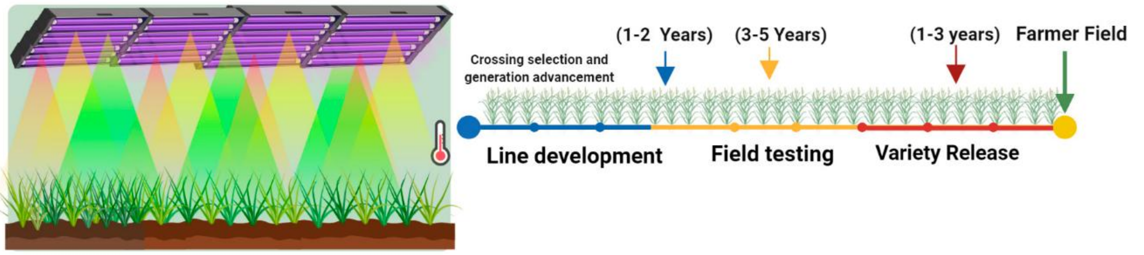
Speed breeding (SB) offers a revolutionary approach to plant breeding, allowing researchers to significantly accelerate the development of new crop varieties [1]. At its core, SB involves manipulating growth conditions such as light intensity, photoperiod, temperature, and humidity to shorten the time from seed to seed, enabling rapid breeding cycles. This approach is critical in addressing the challenges posed by a rapidly growing global population, which is projected to reach nearly 9.9 billion by 2050, and the looming threats of climate change, including rising temperatures, more frequent floods, and droughts.Traditional plant breeding, which involves selecting complementary parental genotypes, crossing them, and selecting the best progeny for advancement, typically takes a decade or more to produce new cultivars [2]. SB, however, accelerates the breeding process by focusing on techniques that speed up the generation cycle [3]. These methods include single-seed descent (SSD), rapid generation cycling (RGC), fast generation cycling (FGC), and rapid generation turnover (RGT), each designed to reduce the time required for flowering and seed development.

Controlled-environment (CE) growth facilities are essential to SB, allowing researchers to precisely control environmental factors [4]. By manipulating day/night temperatures, light spectrum and intensity, and photoperiod duration, SB enables rapid phenotyping, trait evaluation, and mapping population development. The advent of advanced LED lighting systems has played a crucial role in optimizing light conditions, triggering faster flowering, and promoting quicker generation turnover [5]. Photoperiod extension and stress-induced growth acceleration further contribute to this rapid pace [6].SB has demonstrated its versatility across a range of crops, from long-day species like wheat and lettuce to short-day crops like rice and cotton, as well as day-neutral crops like amaranth [7]. Its applications extend to enhancing genetic gain through gene editing, high-throughput phenotyping, genomic selection, and marker-assisted selection (MAS). Additionally, SB can overcome some of the challenges associated with double haploid (DH) technology, like low germination rates and poor vigor.

By reducing the breeding cycle from 8-10 years to a fraction of that time, SB significantly enhances the speed at which new cultivars are developed and commercialized. This rapid generation turnover not only accelerates breeding outcomes but also reduces costs and space requirements in the process. Moreover, SB can help tackle pressing issues such as food security, environmental sustainability, and climate resilience by promoting the development of crops with higher yields, improved nutritional quality, and enhanced tolerance to biotic and abiotic stresses [8]. Speed breeding represents a pivotal advancement in plant breeding, offering a suite of techniques to expedite the generation cycle and drive rapid agricultural progress [9]. This review explores SB's historical development, its various applications, and the impact it can have on future food security and sustainable agriculture.Since the 1940s, plant breeders have increased the speed of plant lifecycle turnover through techniques like single-seed descent and shuttle breeding [10]. In recent years, they have further shortened these cycles by manipulating controlled-environment (CE) growth conditions [11]. A range of approaches aimed at expediting the plant breeding cycle within controlled environments has emerged under the banner of speed breeding (SB) (Figure 1) [12].



(a) Timeline of conventional breeding



(b) Timeline of Speed Breeding

Figure 1:Timelines of varietal development with (a) conventional breeding and (b) speed breeding [10]

2. PRINCIPLES OF SPEED BREEDING: ACCELERATING CROP DEVELOPMENT

Traditional breeding methods for developing new crop varieties are often slow and may not meet the exponentially increasing demand for food production [13]. However, with technological advancements and recent breakthroughs, researchers and breeders can now expedite the development of new varieties. Speed Breeding (SB) is a key technique in this regard, employing controlled environments to promote rapid and accelerated transitions from the vegetative to the reproductive stage in high-density planting (HDP) (Figure 2)[14].

2.1 Principles of speed breeding

Speed breeding (SB) is a cutting-edge approach in plant science that aims to accelerate the development of crop varieties by manipulating growth conditions to reduce the time from seed to seed [15]. The core principle of SB is to optimize the environment in which plants grow, allowing researchers and breeders to expedite the breeding cycle, sometimes achieving several generations within a single year [16]. This technique has emerged as a vital tool to meet the growing demands for food production and to address the challenges posed by climate change, increasing population, and limited arable land.

One of the key principles of SB is the control of photoperiod, which is the duration of light exposure that plants receive in a 24-hour period [17]. By extending or reducing the length of daylight, SB can manipulate the time it takes for plants to transition from the vegetative to the reproductive stage. Long-day crops, such as wheat [61] and barley, respond to extended light periods by flowering earlier, while short-day crops, like rice and soybean, can be induced to flower by reducing the light exposure [18]. This flexibility allows SB to accelerate the growth cycle of various crops, leading to rapid turnover and quicker generation cycles[19].

2.2 Environmental Control and its Impact on Speed Breeding

Another fundamental principle of SB is the precise control of environmental factors within controlled environments, such as growth chambers or greenhouses [20]. These factors include temperature, light spectrum and intensity, humidity, and CO2 concentration. By fine-tuning these parameters, SB creates an environment conducive to rapid plant growth and development. The ability to manipulate temperature, for instance, enables researchers to simulate different seasons or climatic conditions, allowing for year-round plant growth regardless of external weather patterns [22].

Additionally, the light spectrum and intensity can be adjusted to encourage specific plant behaviors [23]. The use of LED lighting systems in SB allows for precise control of light wavelengths, enabling researchers to promote or inhibit certain plant responses [24], such as shade avoidance or accelerated flowering. This control over environmental conditions not only reduces the time to maturity but also enhances the consistency of plant development, leading to more uniform results and reliable breeding outcomes.Overall, the principles of SB revolve around creating optimal conditions for rapid plant growth, allowing for faster generation cycles and more efficient breeding [24]. By leveraging controlled environments and advanced technologies, SB has become a powerful approach to address the needs of modern agriculture and food production.

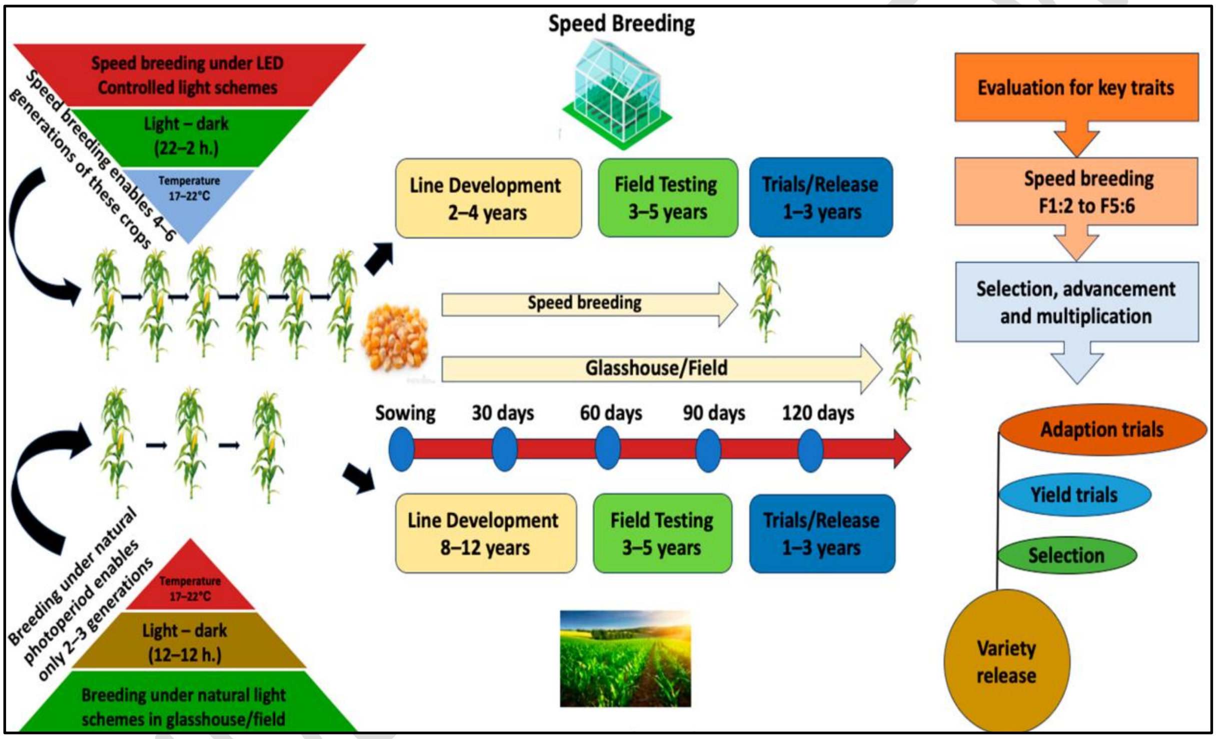


Figure 2: Speed Breeding for Crop Improvement vs conventional Breeding [38]

3. CEREALS: ACCELERATING BREEDING THROUGH SPEED BREEDING TECHNIQUES

Researchers in cereal breeding are continually seeking innovative approaches to reduce the time needed to produce homozygous lines after hybridization, enabling faster development of new cereal varieties [25]. One technique involves harvesting immature wheat seeds 15 to 20 days after anthesis, treating them with hydrogen peroxide (H_2O_2) at low temperatures, and thereby accelerating germination [26]. This method has allowed for obtaining four to six generations of wheat in a single year, greatly reducing the traditional breeding cycle.Following this lead, other researchers extended the duration of H_2O_2 treatment to further improve wheat germination rates at low temperatures, thus shortening generation times by 12 to 23 days, depending on the cultivar. Similar results were observed with air-dried wheat seeds harvested after 21 days of anthesis, achieving over 90% germination.

In rice breeding, Japanese scientists have made significant advancements with a biotron breeding system (BBS) that uses controlled environmental conditions—temperature, photoperiod, and CO_2 levels—combined with techniques like embryo rescue and tiller removal [28]. This system has reduced the generation interval of popular rice cultivars, like ‘Nipponbare,’ by up to three months. The BBS has enabled breeders to achieve two-month generation cycles, yielding four to five generations of rice per year [28].Speed breeding has been applied successfully to wheat for rapid trait screening, including disease resistance, root structure, plant height, and flowering time [29]. This technique has also been used to identify drought tolerance in barley and to develop disease-resistant barley lines through a modified backcrossing method and Genomic approaches for improving drought tolerance in wheat [60]. In sorghum, embryo rescue and direct germination of immature seeds can reduce the breeding cycle [30]. Oats also benefit from a longer photoperiod and mineral supplements, which hasten anthesis for a higher generation turnover [31].These techniques represent a promising shift towards faster and more efficient breeding in cereals, allowing researchers to respond more rapidly to the demands of food production and crop resilience.

4. SPEED BREEDING IN RESEARCH AND CROP IMPROVEMENT

Speed breeding (SB) has revolutionized the field of plant breeding by significantly accelerating the development of various breeding materials and research outcomes [32]. Its applications are vast, encompassing the creation of biparental and more complex mapping populations, trait pyramiding, expediting backcrosses, phenotyping of adult plant traits, mutant studies, and genetic transformation experiments.SB has proven particularly powerful when combined with advanced techniques such as gene editing, high-throughput phenotyping and genotyping, genomic selection (GS), and marker-assisted selection (MAS) [33]. By integrating these modern methodologies with SB, breeders can fast-track crop improvement and tackle multiple objectives simultaneously.One key advantage of SB is its ability to reduce costs and space requirements by allowing plants to grow at high densities [34]. This is especially beneficial for producing a large number of inbred lines. Additionally, SB addresses some limitations associated with double haploid (DH) technology, such as low germination rates, poor vigor, and distorted growth.

For genetic mapping, recombinant inbred lines (RILs) derived from several generations of self-fertilization provide benefits over DH due to the increased meiotic events during repeated fertilization, leading to a higher recombination frequency [35]. This advantage is crucial for detailed genetic analysis and trait mapping. Likewise, the advancement and evaluation of segregating generations can be efficiently conducted through single seed descent (SSD) under SB conditions. This process is faster and more cost-effective than traditional pedigree breeding methods. Moreover, SB has demonstrated a significant impact on generation turnover, achieving a rate three times higher than conventional shuttle breeding methods. This capability allows researchers to compress breeding timelines, facilitating rapid cultivar development and enabling a more agile response to emerging agricultural challenges. Speed breeding offers a versatile and efficient approach to advancing crop breeding and research [36]. Its capacity to accelerate breeding cycles, combined with modern genetic techniques, makes it a powerful tool in the quest for rapid agricultural improvement and food security [38].

5. APPLICATIONS OF SPEED BREEDING IN CROP IMPROVEMENT

Applications of Speed Breeding (SB) extend beyond crop improvement, offering transformative opportunities in other areas of plant research and development. While SB has proven invaluable for accelerating the development of new crop varieties, its influence reaches into diverse and innovative domains within agriculture and biotechnology. These techniques enable researchers to explore new possibilities and achieve greater efficiencies in multiple contexts (Figure 3).

5.1 Genetic Mapping Populations

Speed Breeding (SB) has revolutionized the development of mapping populations by drastically reducing the time required to generate diverse segregating populations for genetic mapping. Traditionally, this process was labor-intensive and time-consuming, but SB’s rapid generation turnover has made it more efficient and accessible. This has expedited the field of quantitative trait locus (QTL) analysis and marker-assisted selection (MAS). For example, a biotron SB system was used to develop a mapping population to enhance salinity stress tolerance in rice. By integrating the hst1 gene from Kaijin into the high-yielding Yukinko-mai rice using SNP marker-assisted selection, researchers developed a BC3F2 homozygous line with salinity tolerance within 17 months. Additionally, SB has played a crucial role in a multi-trait approach to improve wheat yields in Australian regions facing water limitation and heat stress. This approach integrates QTL analysis, high-throughput phenotyping, and a nested association mapping strategy to identify key traits like stay-green and root characteristics, highlighting the role of SB in fast-tracking genetic mapping and advancing crop improvement.

5.2 Genetic Modification (GM) Crop Development

SB has emerged as an invaluable tool for genetic modification (GM) crop development, a crucial aspect of modern agriculture that addresses critical challenges such as pest resistance, disease resilience, and environmental adaptability. The technique's ability to accelerate the entire GM crop development process, from gene insertion to field trials, makes it a game-changer for the biotechnology sector. Controlled environments and shortened generation times allow researchers to conduct gene editing, phenotyping, and backcrossing in a fraction of the time it would take with traditional methods. One promising approach is ExpressEdit, which combines gene editing with SB to insert preassembled CRISPR-Cas9 ribonucleoproteins into plant shoot apical meristems. This technique, along with other CRISPR/Cas9-based approaches, has led to significant advancements in improving yield-related traits like grain size, grain quantity, and grain weight in crops such as rice and wheat.

5.3 Trait Stacking for Resilient Crop Varieties

SB facilitates the practice of trait stacking, where multiple desirable traits are introduced into a single crop variety [38]. This approach has become increasingly important in modern agriculture, where crop varieties must be robust against a range of challenges, including changing climate conditions and evolving pest pressures. With SB, breeders can quickly generate and evaluate multi-trait combinations, allowing for rapid development of resilient crop varieties. This efficiency not only saves time and resources but also leads to more adaptable crops. Studies in rice, for example, have focused on stacking genes associated with cellular detoxification, osmolyte accumulation, antioxidant mechanisms, and signaling pathways to enhance tolerance against abiotic stresses like drought and salinity in chickpea [55]. Likewise, in European two-rowed barley, SB has been used to rapidly introduce multiple disease-resistance genes, demonstrating the potential for swift trait stacking through modified backcrossing and early-generation selection [40].

5.4 Enhancing Research across Disciplines

The unique capabilities of SB extend beyond traditional crop improvement and genetic research, offering applications in fields like ecology, physiology, and agronomy [41]. These techniques enable researchers to speed up experiments and gather data more efficiently, which can be invaluable for exploring plant responses to environmental stressors, optimizing cultivation practices, and better understanding plant physiology. SB's rapid generation cycles also facilitate quicker hypothesis testing and more frequent collection of critical data, allowing researchers to make informed decisions and address global agricultural challenges [42]. The integration of SB with systems biology provides a comprehensive framework for plant development studies, offering detailed insights into genetic regulatory networks and predictive models that inform plant breeding strategies [43].

SB also supports advancements in high-throughput phenotyping, allowing researchers to rapidly screen diverse plant populations to identify superior genotypes [44]. This capability enhances the efficiency of breeding programs and accelerates the release of improved crop varieties.As SB continues to evolve, it holds promise for a wide range of emerging applications. The combination of SB with gene editing technologies, genotyping, and genomic selection represents a powerful synergy that can drive further innovation in plant breeding and crop enhancement [45]. This collaborative approach not only leverages the strengths of each technique but also lays the foundation for modern agricultural practices that meet the challenges of a changing world.

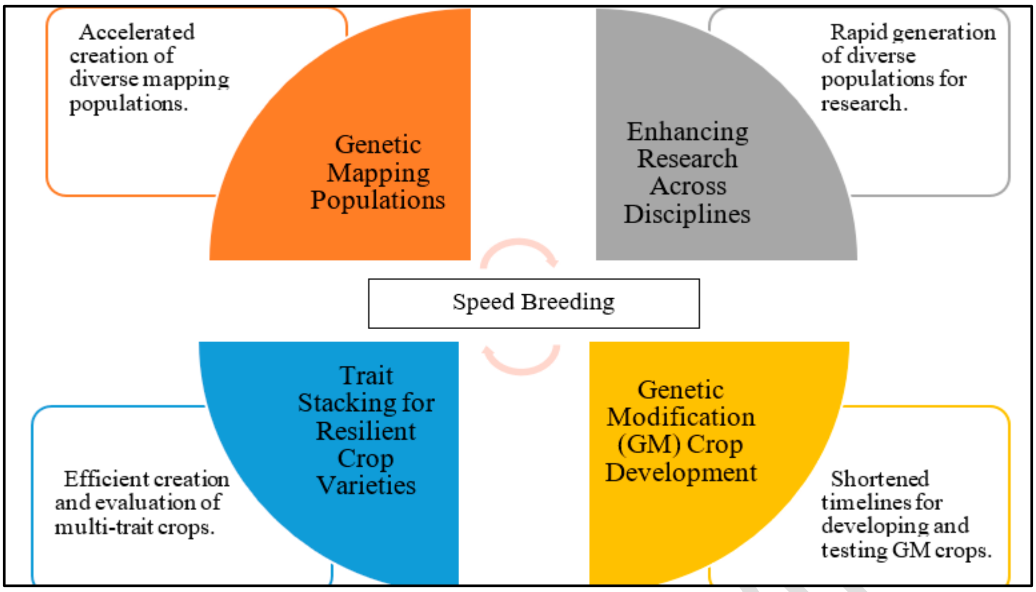


Figure 3: Applications of Speed Breeding (SB) extend beyond crop improvement

6. INTEGRATING SPEED BREEDING WITH MODERN BREEDING TECHNIQUES

Speed breeding (SB) has proven to be a transformative approach in plant breeding, reducing generation time and accelerating the development of new crop varieties [46]. When combined with other modern breeding techniques such as gene editing, genomic selection, and marker-assisted selection, SB further enhances the efficiency of trait selection and significantly reduces the time to release new varieties (Figure 4) [47].

Traditional plant breeding methods played a pivotal role in the Green Revolution, leading to significant increases in crop production and food security [48]. These conventional methods were responsible for making India self-sufficient in food production during the 1970s. However, traditional breeding has limitations, primarily due to its reliance on phenotypic selection, which can be misleading due to environmental effects. Traits with low heritability require multilocation trials for precise selection, which increases cost and time [49].To address these limitations, modern molecular breeding methods like marker-assisted selection (MAS) offer a solution. MAS uses DNA markers to select for desired traits, improving yield and disease resistance in crops like rice, maize, soybean, and wheat [50]. This technique has been successfully used to improve yield-related traits and develop disease-resistant varieties. However, MAS has its limitations, particularly with complex polygenic traits and quantitative trait loci (QTL) with small effects, as these are significantly influenced by environmental factors.Growth and yield of maize is significantly affected by sowing dates [59].

Speed breeding, when integrated with MAS and other advanced techniques like genomic selection, marker-assisted recurrent selection, and association mapping, can overcome these limitations [51]. Genomic selection, for instance, involves phenotyping and genotyping training populations to estimate genomic estimated breeding values (GEBV), allowing for more accurate selection in breeding populations. This method, combined with next-generation sequencing technologies and advanced phenotyping, has made it possible to identify the genetic basis of key agricultural traits. For example, genomic selection has been used in rice to improve blast resistance and evaluate grain-filling ability, while genotyping-by-sequencing techniques have been employed to construct genomic selection models for different traits in wheat.By integrating speed breeding with these modern techniques, plant breeders can significantly reduce the breeding cycle and enhance selection efficiency like heterosis in cerals and vegetables [56-58]. This integrated approach not only accelerates the release of new crop varieties but also addresses the challenges of complex traits and environmental influences, paving the way for a new era in plant breeding and agricultural innovation.

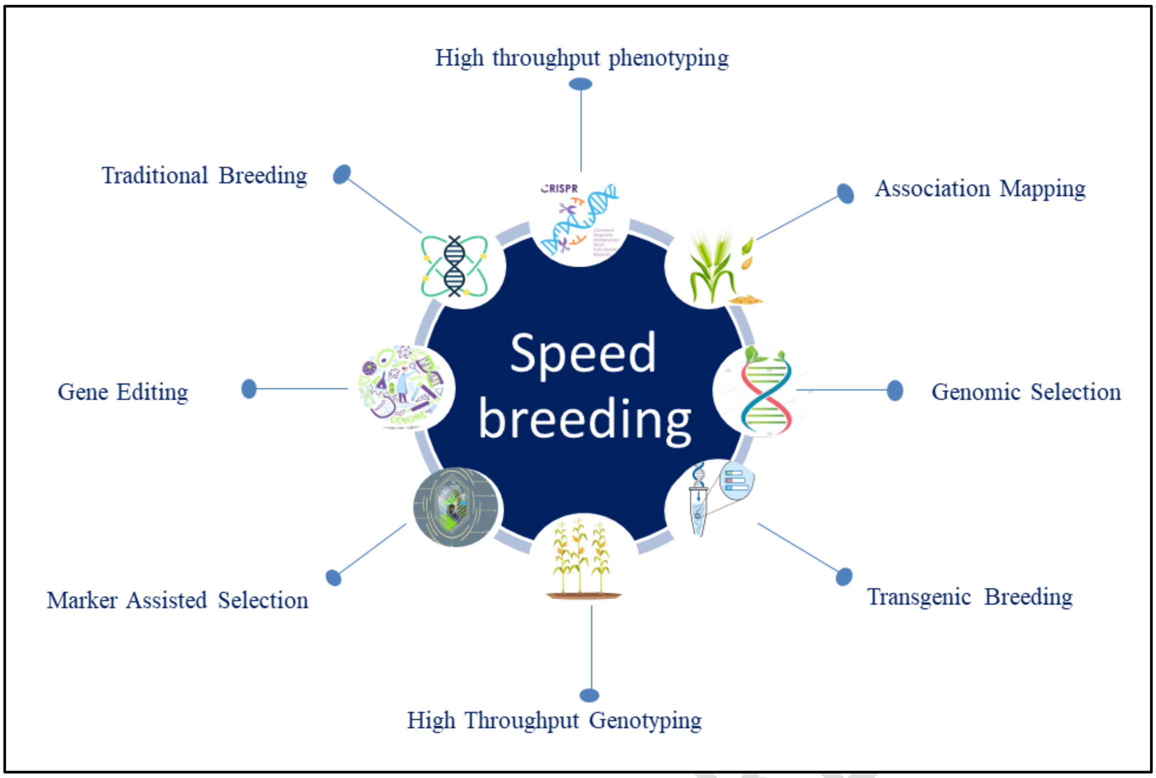


Figure 4: Integrating speed breeding with other modern breeding techniques [54]

7. MERITS OF SPEED BREEDING

Speed breeding methods are continuously evolving and being refined to expedite crop improvement programs [53]. These techniques offer the potential to shorten the breeding cycle, rapidly introduce new genetic variation, and enhance the efficiency of plant breeding efforts. Speed breeding in groundnut offers several merits that can significantly benefit crop improvement programs. Some of the key advantages include [54]:

- ***Faster Generation Turnover:*** Speed breeding techniques allow for accelerated generation turnover in groundnut, reducing the time required to develop new varieties [54]. By manipulating environmental conditions and growth factors, such as light, temperature, and photoperiod, the time taken to reach successive generations can be shortened, enabling breeders to make genetic progress at a faster pace.
- ***Rapid Trait Selection:*** With speed breeding, breeders can expedite the process of trait selection in groundnut. By implementing early generation selection techniques and marker-assisted selection (MAS), desirable traits can be identified and selected in the early stages of plant development. This speeds up the breeding process and enables breeders to focus on individuals with the desired traits.
- ***Increased Genetic Variation:*** Speed breeding methods can facilitate the introduction and incorporation of new genetic variation into groundnut breeding programs [55]. By rapidly cycling through generations, breeders have more opportunities to create and select diverse populations, leading to increased genetic variation. This can enhance the potential for finding novel traits and improving crop performance.
- ***Optimal Environmental Control:*** Speed breeding techniques allow precise control over environmental conditions, providing optimal growth conditions for groundnut plants. By creating controlled environments, breeders can manipulate factors like temperature, humidity, and light intensity to maximize plant growth and development. This control enables year-round breeding activities and reduces the reliance on seasonal variations.
- ***Time and Cost Efficiency:*** Speed breeding methods can improve the efficiency of groundnut breeding programs, saving both time and costs. By reducing the generation turnover time, breeders can achieve their breeding objectives more quickly. This efficiency can translate into cost savings in terms of resources, labor, and infrastructure required for conventional breeding methods.
- ***Accelerated Crop Improvement:*** Overall, speed breeding in groundnut can expedite the crop improvement process. By combining the benefits of faster generation turnover, rapid trait

selection, increased genetic variation, and controlled environmental conditions, breeders can accelerate the development of improved groundnut varieties. This can help address challenges such as disease resistance, yield improvement, and adaptation to changing environmental conditions.

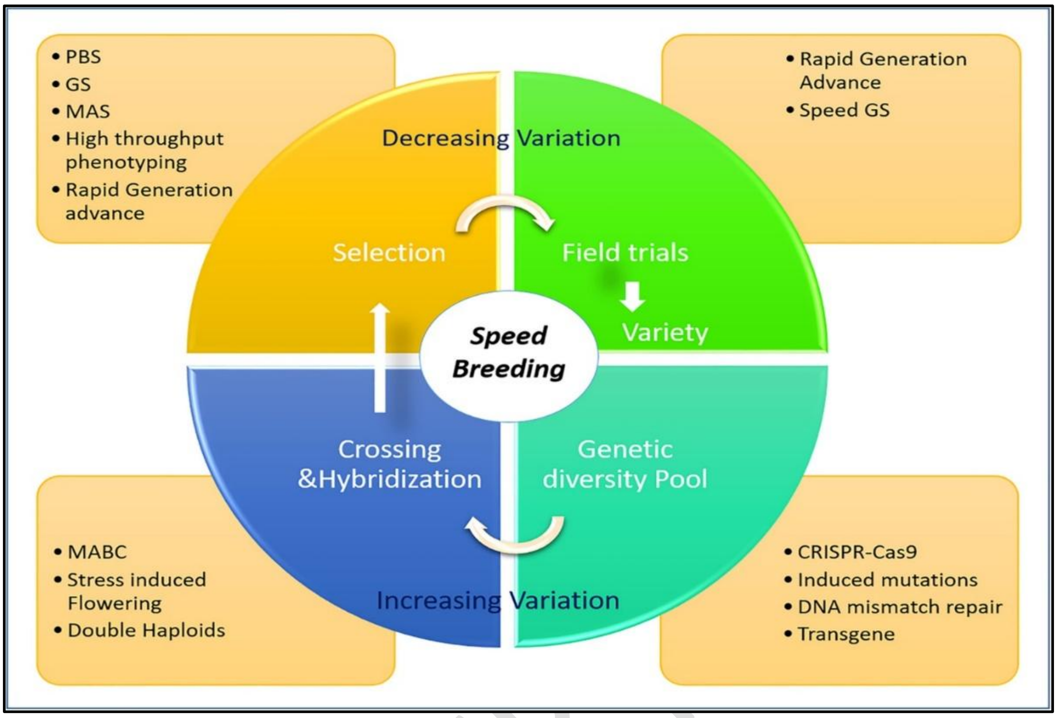


Figure 5. Combining speed breeding with traditional and genomics-assisted breeding for crop improvement

8. FUTURE PERSPECTIVES

Speed breeding (SB) has already demonstrated its potential to revolutionize crop development by dramatically reducing generation times. In the future, advancements in technology are expected to further enhance SB's efficiency and versatility. The integration of gene editing techniques, such as CRISPR/Cas9, with SB could allow for precise modifications of crop genomes within accelerated breeding cycles. This would enable breeders to quickly introduce desirable traits, such as disease resistance or enhanced nutritional content, while removing undesirable ones, significantly shortening the time from concept to commercial release. The incorporation of high-throughput phenotyping and genotyping techniques will also contribute to the success of SB, allowing for rapid identification and selection of desirable traits from large plant populations [63].

Another future aspect of SB is its role in sustainable agriculture. As the global population continues to grow, and climate change poses new threats to food security, the ability to rapidly develop resilient and high-yielding crops will become increasingly important. SB can facilitate the development of crop varieties with improved tolerance to abiotic stresses such as drought, heat, and salinity, as well as biotic stresses like pests and diseases. Moreover, by reducing generation times, SB contributes to more efficient use of resources, such as land and water, making it a key component in sustainable agriculture practices [62]. As farmers and researchers seek solutions to produce more food with fewer resources, SB's rapid breeding cycles can provide a competitive advantage in the quest for a more sustainable food system.

9. CONCLUSION

Speed breeding (SB) has established itself as a game-changer in the field of plant breeding, offering a highly effective method to significantly accelerate the seed-to-seed cycle. The ability to achieve multiple generations within a single year has opened up new possibilities for advancing crop development and addressing the global challenges of food security, climate change, and a growing population. By leveraging controlled-environment technologies, SB provides a platform for rapid genetic improvement, allowing breeders to respond quickly to evolving demands and environmental pressures.The integration of speed breeding with other modern breeding techniques, such as gene editing, genomic selection, and marker-assisted selection, has proven instrumental in enhancing breeding efficiency. This synergy not only expedites the development of new crop varieties but also improves the selection process by offering more accurate and rapid assessment of desirable traits. The flexibility to combine SB with these cutting-edge technologies amplifies its impact, contributing to faster delivery of improved crop varieties and supporting a more sustainable agricultural future.Speed breeding represents a significant advancement in plant breeding, providing a powerful tool for rapid agricultural progress. Its ability to reduce the time required for cultivar development has far-reaching implications, enabling more efficient use of resources and contributing to sustainable food production. As the demand for food continues to rise, SB's role in accelerating genetic improvement and supporting resilient agricultural systems will be critical in shaping the future of agriculture.

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