

Speed Breeding: Accelerating the Future of Crop Improvement

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Abstract

Traditional crop breeding takes a lot of time, space, and resources because selecting and crossing plants often involves long seed-to-seed cycles. Speed breeding (SB) offers a faster way to improve crops by extending daylight, controlling temperature, and harvesting seeds earlier. These methods shorten the time needed to grow new plant generations and have been especially effective in long-day plants, with efforts now expanding to short-day plants. SB is flexible and can support various research activities, such as developing plant populations, genomic selection, phenotyping, and gene editing. This review highlights the methods and applications of SB in speeding up plant improvement. While SB has been successful in improving traits and creating new crop varieties, some challenges, like limited use in certain crops, still need to be addressed. Optimizing SB techniques for major food crops and integrating them into breeding programs could overcome these issues and help make plant breeding more efficient in the future.

Keywords: Speed breeding, Crop improvement, Shortened growth cycles, Plant breeding innovation, Genomic selection

1. Introduction

In the face of rising global food demands, climate uncertainty, and biotic and abiotic stressors, traditional crop breeding approaches are no longer sufficient to meet the urgency for faster varietal development. Conventional breeding

often requires 7 to 12 years to develop and release a new variety due to its reliance on full-season growth cycles and time-consuming selection processes (Watson et al., 2018). As a result, crop improvement has become a bottleneck in achieving sustainable agriculture and food security.

To overcome these limitations, Speed Breeding (SB) has emerged as a powerful strategy that accelerates plant growth and reduces generation time by modifying environmental factors such as photoperiod, temperature, and humidity (Hickey et al., 2019). The core concept of SB is to induce early flowering and seed set by extending the photoperiod to 20–22 hours per day using artificial lighting, coupled with controlled temperature and humidity conditions. This allows breeders to grow up to six generations per year, compared to only one or two under normal field conditions (Watson et al., 2018).

Originally developed for long-day crops such as wheat, barley, and canola, speed breeding protocols have now been adapted for short-day and day-neutral crops including chickpea, cowpea, tomato, and even tree species in controlled environments (Zheng et al., 2013). Speed breeding not only reduces the time required to develop new varieties but also enables rapid phenotyping, high-throughput screening, and efficient integration with genomic tools such as marker-assisted selection (MAS), genomic selection (GS), and genome editing (Ghosh et al., 2021).

This paper provides a comprehensive review of the principles, techniques, applications, benefits, and limitations of speed breeding. It also highlights how this approach can reshape modern crop improvement programs by accelerating generation cycles and facilitating the rapid development of stress-resilient, high-yielding varieties.

2. Principles and Techniques of Speed Breeding

Speed breeding (SB) is based on the concept of accelerating a plant's life cycle by manipulating environmental conditions that govern growth and development. The primary factors involved include photoperiod extension, temperature control, and rapid harvesting techniques, all of which aim to reduce

the time from seed to seed and allow multiple generations within a year.

Photoperiod Extension

A key driver of SB is the extension of light exposure to up to 20–22 hours per day using artificial lighting (e.g., LED or high-pressure sodium lamps). This simulates long-day conditions, promotes rapid vegetative growth, and induces early flowering, particularly in long-day crops like wheat and barley (Watson et al., 2018).

Temperature Optimization

Day/night temperature regulation is essential for ensuring consistent development. Typically, day temperatures are maintained between 22–24°C and night temperatures between 17–19°C. This controlled setting minimizes stress and enhances photosynthetic efficiency, speeding up biomass accumulation (Hickey et al., 2019).

Early Seed Harvest and Recycling

In SB, seeds are often harvested at physiological maturity, which can occur 14–18 days post-anthesis in crops like wheat. After drying and dormancy breaking (if needed), these seeds can be immediately replanted, thereby drastically reducing generational time (Zheng et al., 2013).

Use of Controlled Environment Facilities

SB protocols can be implemented in greenhouses, growth chambers, or vertical farming units, depending on the scale and crop. Controlled environments allow breeders to circumvent seasonal limitations, ensure consistent growth conditions, and reduce pest and disease pressures (Ghosh et al., 2021).

Integration with Breeding Tools

Speed breeding is particularly effective when integrated with marker-assisted selection (MAS), genomic selection (GS), and gene editing technologies. These combinations enable faster identification and fixation of desirable alleles across generations (Watson et al., 2018; Alahmad et al., 2020).

3. Applications of Speed Breeding in Crop Improvement

Speed breeding (SB) is not only a tool for faster generational turnover but also a platform for enhancing the efficiency of diverse crop improvement strategies. From developing stress-resilient varieties to supporting cutting-edge molecular breeding, SB is revolutionizing plant breeding programs worldwide.

Accelerated Development of Homozygous Lines

One of the primary uses of SB is in the rapid fixation of homozygous lines, which are foundational for hybrid breeding and trait stability. When combined with methods like single seed descent (SSD) or doubled haploidy, SB facilitates the development of pure lines in 1–2 years, compared to the conventional 5–6 years (Watson et al., 2018; Ghosh et al., 2021). This is particularly impactful for crops like wheat, barley, chickpea, and lentil where early-generation selection is critical.

Enhanced Selection for Biotic and Abiotic Stress Tolerance

SB enables screening for traits under controlled stress conditions, accelerating the identification of lines resistant to heat, drought, salinity, and diseases. For example, disease-resistant wheat lines have been rapidly developed by combining SB with marker-assisted backcrossing (MABC) (Alahmad et al., 2020). The use of SB in screening under managed stress environments helps breeders assess genotype performance more reliably and reduces the influence of seasonal variability.

Supporting Genomic Selection and Marker-Assisted Breeding

Speed breeding can significantly reduce the time between genotype assessment and selection decisions, making it a perfect companion for genomic selection (GS) and marker-assisted selection (MAS). In GS, where prediction models require rapid cycles of genotyping and phenotyping, SB helps generate large datasets across multiple generations in a single year (Crossa et al., 2017). This has been successfully demonstrated in crops like wheat, sorghum, and rice.

Integration with Gene Editing Technologies

Gene editing tools such as CRISPR/Cas9 are most effective when their outcomes can be quickly assessed over successive generations. SB allows for the fast-forwarding of edited lines through the T₀, T₁, and T₂ generations, facilitating faster validation and fixation of target mutations (Watson et al., 2018; González-Navarro et al., 2021). This integration is revolutionizing functional genomics in staple crops.

Rapid Pre-breeding and Trait Introgression

Pre-breeding involves transferring beneficial traits from wild relatives or landraces into elite backgrounds. These introgressions typically require multiple backcross generations. Speed breeding compresses this timeline, allowing breeders to complete 3–4 backcross generations in a single year and quickly develop trait-rich, adapted pre-breeding lines (Voss-Fels et al., 2019).

Capacity Building in Breeding Programs

Beyond elite research institutions, SB has been incorporated into national and regional breeding programs, enhancing their responsiveness. The development of low-cost LED-based SB systems is making this technology accessible even in low-resource settings (Zheng et al., 2013). It supports training programs, student research, and rapid field trials, empowering the next generation of breeders.

4. Crops Adapted to Speed Breeding and Achievements

The application of speed breeding (SB) has expanded significantly since its initial success in long-day crops like wheat and barley. By optimizing photoperiod, temperature, and humidity conditions, researchers have adapted SB protocols to a wide range of crops including cereals, legumes, vegetables, and even fruit species. This adaptability highlights the versatility of SB in modern crop improvement programs.

Cereal Crops

Speed breeding has been highly effective in wheat (*Triticum aestivum*) and barley (*Hordeum vulgare*), where up to six generations per year have been achieved under controlled

conditions (Watson et al., 2018). In these crops, SB has been used not only for early-generation advancement but also for accelerating trait introgression and pyramiding resistance genes. In rice (*Oryza sativa*), which is sensitive to light and temperature, tailored SB protocols have enabled up to four generations annually, facilitating rapid breeding of stress-tolerant lines (Islam et al., 2021).

Leguminous Crops

Legumes such as chickpea (*Cicer arietinum*) and cowpea (*Vigna unguiculata*) have shown promising responses to SB when exposed to extended light durations and optimal temperatures. In chickpea, breeders have been able to shorten the generation cycle to 70–80 days with improved flower initiation and seed set under long photoperiods (Ghosh et al., 2021). These outcomes support the feasibility of SB in traditionally slow-growing pulse crops.

Horticultural Crops

SB has also been adapted for use in vegetable crops like tomato (*Solanum lycopersicum*) and brassicas. For tomato, combining extended photoperiods with early fruit harvesting and seed maturation has enabled up to four generations per year, supporting both conventional and genome-edited line development (González-Navarro et al., 2021). This acceleration is particularly beneficial for functional genomics, backcrossing, and hybrid development in vegetable breeding.

Notable Achievements

Some of the key achievements of speed breeding to date include:

Development of multi-disease resistant wheat lines through MAS and backcrossing within 12–18 months (Alahmad et al., 2020).

Establishment of low-cost LED-based speed breeding facilities in developing countries, enabling rapid varietal trials and national capacity building.

Integration with CRISPR/Cas9 gene-editing in tomato and wheat for trait validation within two generations (Ghosh et al., 2021).

These milestones demonstrate that SB not only accelerates traditional breeding timelines but also enhances the integration of modern genomic tools into crop improvement pipelines.

5. Advantages and Limitations of Speed Breeding

Speed breeding (SB) is a transformative approach that has rapidly gained traction in plant breeding programs across the globe. While it offers a suite of benefits, its implementation also comes with a few technical and practical challenges that must be considered.

Advantages of Speed Breeding

(i) Rapid Generation Turnover

The most significant advantage of SB is the ability to grow 4–6 generations per year, compared to 1–2 generations in traditional field-based programs (Watson et al., 2018). This drastically shortens the time required to fix desirable traits, introgress genes from wild relatives, and develop new varieties.

(ii) Accelerated Breeding for Stress Tolerance

By providing a controlled environment, SB allows breeders to impose artificial stress conditions (e.g., drought, salinity, disease) and rapidly screen genotypes for resilience. This is especially important for climate-smart breeding programs (Alahmad et al., 2020).

(iii) Integration with Modern Genomic Tools

SB is highly compatible with genomic selection (GS), marker-assisted selection (MAS), and gene editing technologies (e.g., CRISPR/Cas9). These integrations streamline both the discovery and deployment of beneficial alleles (Ghosh et al., 2021).

(iv) Resource Efficiency

SB systems—particularly low-cost LED and vertical farming setups—reduce dependency on field space and seasonal variation, and minimize pest and pathogen pressure. This makes it a sustainable and scalable option, even for developing countries (Islam et al., 2021).

Limitations of Speed Breeding

(i) Limited Crop Responsiveness

While SB has proven effective in long-day crops like wheat and barley, short-day and photoperiod-sensitive crops (e.g., rice, maize, groundnut) may not respond equally well without extensive protocol optimization (Watson et al., 2018).

(ii) Infrastructure and Energy Requirements

Setting up controlled environment systems involves high initial costs and continuous energy input for lighting, temperature regulation, and humidity control. This can be a barrier for small-scale breeding programs, particularly in low-income regions.

(iii) Potential for Altered Phenotypes

Plants grown under SB conditions may exhibit atypical phenotypes due to unnatural light regimes or stress-free environments. This can sometimes complicate field performance predictions or mask undesirable traits (Alahmad et al., 2020).

(iv) Human Resource and Technical Skill Gap

Running SB facilities requires trained personnel, from managing photoperiod schedules to handling rapid generation cycles and molecular tools. Many institutions still lack the technical expertise or interdisciplinary coordination needed for effective SB adoption.

6. Conclusion and Future Perspectives

Speed breeding (SB) is reshaping the landscape of modern crop improvement by enabling rapid generation advancement and seamless integration with genomic tools. Its capacity to shorten breeding cycles, facilitate trait introgression, and accelerate the release of climate-resilient, high-yielding crop varieties makes it an indispensable tool in the face of global food and climate challenges. Despite the challenges – ranging from infrastructure needs to crop-specific adaptability – ongoing research continues to refine SB protocols for a broader range of species. Future prospects lie in integrating

SB with AI-driven phenotyping, robotic automation, and precision gene editing, which can make the breeding pipeline even faster and more efficient. Additionally, the development of low-cost, decentralized SB setups will democratize its use across national and smallholder breeding programs. To fully harness its potential, interdisciplinary collaboration among breeders, molecular biologists, engineers, and policymakers is essential. When scaled effectively, speed breeding could become a cornerstone of climate-smart, resource-efficient, and globally responsive agriculture.

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