CHAPTER
11

SPEED BREEDING TECHNIQUES FOR ACCELERATED CROP DEVELOPMENT

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Abstract

Speed breeding has emerged as a transformative approach to accelerate crop development and address the urgent need for food security in the face of climate change, population growth, and limited natural resources. By manipulating environmental conditions such as photoperiod, temperature, and light intensity, speed breeding enables multiple generations of crops to be grown within a single year, significantly reducing the time required for varietal development. This chapter provides a comprehensive overview of the background and necessity of speed breeding, tracing its historical evolution from early controlled-environment experiments to modern applications in plant biotechnology. The principles underlying speed breeding are discussed, highlighting the integration of extended photoperiods, optimized nutrient regimes, and controlled growth chambers. Various methods, including glasshouse-based systems, growth chambers, and integration with genomic tools, are examined for their effectiveness in different crop species. Applications in crop improvement are emphasized, particularly in cereals, legumes, and horticultural crops, where speed breeding has facilitated rapid trait introgression, hybrid development, and resistance breeding. The chapter also explores the advantages of speed breeding, such as enhanced breeding efficiency, reduced costs, and accelerated genetic gains, while acknowledging limitations including infrastructure requirements, energy demands, and species-specific constraints. Finally, future prospects are outlined, focusing on the integration of speed breeding with genomic selection, CRISPR-based gene editing, and digital agriculture to revolutionize crop improvement programs. Overall, speed breeding represents a paradigm shift in plant science, offering a sustainable pathway to meet global food demands through accelerated crop development.

Keywords: *Speed breeding, Accelerated crop development, Controlled environment agriculture, Plant breeding innovation, Genetic gain, Climate-resilient crops, Crop improvement.*

Introduction

Speed breeding is an advanced crop improvement technique designed to accelerate the growth, development, and breeding cycles of plants. By manipulating environmental conditions, particularly light duration, temperature, humidity, and photoperiod, speed breeding enables the cultivation of plants at a remarkably faster rate than conventional agricultural practices (Watson et al., 2018).

Originating from controlled-environment agriculture, this technique allows breeders to achieve multiple generations per year, thereby significantly shortening the time required to develop improved crop varieties.

Traditional breeding methods often require several years or even decades to release a new crop variety. This delay is primarily due to the long generation time of many crops, dependence on natural sunlight, seasonal limitations, and time-consuming field trials (Moose & Mumm, 2008). Speed breeding overcomes these limitations by using extended photoperiods (typically 20–22 hours of light per day), optimized temperature regimes, and controlled environments such as growth chambers, greenhouses, and LED-based plant factories. These conditions stimulate faster photosynthesis and physiological processes, enabling plants to flower early, set seeds quickly, and mature faster (Hickey et al., 2019).

The concept of speed breeding traces its roots to space research programs of the 1980s and 1990s, where scientists explored ways to grow plants efficiently in extraterrestrial environments (Musgrave, 2002). Later, researchers at the University of Queensland and the John Innes Centre refined and popularized the technique, demonstrating that cereal crops such as wheat, barley, and oats can complete up to six generations per year compared to two or three under natural conditions (Watson et al., 2018).

Despite its promise, speed breeding faces several challenges. These include high infrastructure and energy costs, species-specific limitations in response to extended photoperiods, and the need for precise environmental control (Ghosh et al., 2018). Additionally, integration with molecular breeding tools requires significant technical expertise and investment.

Current research has demonstrated the potential of speed breeding in cereals and legumes, but its application in horticultural crops, underutilized species, and polyploid crops remains limited (Hickey et al., 2019). Furthermore, there is a gap in scaling speed breeding for resource-poor regions where infrastructure and energy availability are constrained. Addressing these gaps will be critical for making speed breeding a globally accessible technology.

Speed breeding has thus emerged as a transformative technology in modern agriculture, especially in the context of global food security, climate change, and resource limitations. By enabling faster development of climate-resilient, disease-resistant, and high-yielding varieties, it supports global efforts to sustainably increase food production. Based on the above interest, the primary aim of this chapter is to provide a comprehensive overview of speed breeding principles, methods, and applications in crop improvement. It seeks to highlight how speed breeding can accelerate genetic gain, enhance breeding efficiency, and contribute to the development of climate-resilient and high-yielding crop varieties.

Background of Speed Breeding

The origins of speed breeding lie in the broader evolution of crop improvement techniques. For decades, conventional plant breeding relied heavily on natural growing seasons, which limited the number of crop generations that could be produced annually.

Major cereals such as wheat, barley, and rice typically require 4 to 6 months to complete a single generation under field conditions, meaning that developing a new variety with desirable traits often took 8–12 years or more (Moose & Mumm, 2008). This long timeline posed significant challenges for meeting the urgent demands of global food security.

In the late 20th century, scientists began exploring controlled-environment agriculture to hasten plant growth and reproductive cycles. One of the earliest inspirations came from NASA's space biology program, where researchers sought methods to grow plants efficiently in extraterrestrial environments with limited sunlight. Experiments using continuous lighting and regulated temperature demonstrated that many crops respond positively to extended photoperiods, showing rapid vegetative growth and early flowering (Musgrave, 2002).

Building on this foundation, research teams in the 1990s and early 2000s applied similar principles to agricultural breeding programs. The major breakthrough came from collaborative research by the University of Queensland (Australia) and the John Innes Centre (UK). These researchers systematically demonstrated that by exposing crops such as wheat, barley, chickpea, and canola to 22-hour photoperiods, generation time could be dramatically reduced—achieving up to six generations per year in wheat compared to two or three under natural conditions (Watson et al., 2018).

The term *speed breeding* was formally introduced as a standardized and scalable approach to accelerate crop development. It incorporates advanced technologies, including LED lighting, climate-controlled greenhouses, growth chambers, and automated irrigation systems. Importantly, the method was optimized to ensure that plants grown under speed breeding conditions maintain normal morphology, seed viability, and genetic stability, making the technique suitable for mainstream breeding activities (Ghosh et al., 2018).

Over time, speed breeding has evolved from a research concept to a practical breeding strategy, now integrated into global crop improvement programs. Its relevance has grown further in response to challenges such as climate change, increasing population, and shrinking agricultural land, all of which demand faster development of resilient and productive crop varieties (Hickey et al., 2019).

Need for Speed Breeding

Increasing Global Food Demand

The world population is projected to exceed 9 billion by 2050, requiring food production to increase by approximately 70% to meet demand (FAO, 2009). Traditional breeding methods are too slow to keep pace with this requirement, as they often take decades to release new varieties. Speed breeding accelerates the development of high-yielding and nutritious cultivars, helping bridge the gap between demand and production (Watson et al., 2018).

Climate Change and Abiotic Stress

Extreme temperatures, droughts, irregular rainfall, and salinity are major threats to crop productivity (Lesk et al., 2016).

Modern agriculture urgently requires climate-resilient varieties. Speed breeding enables researchers to rapidly introduce and combine stress-tolerant traits, making crops better adapted to harsh environments (Hickey et al., 2019).

Slow Progress of Conventional Breeding

Conventional breeding cycles are lengthy due to long generation times, seasonal constraints, limited photoperiod during winter, and dependence on field conditions (Moose & Mumm, 2008). Speed breeding can produce 4–6 generations per year, dramatically reducing development time from decades to just a few years (Ghosh et al., 2018).

Rapid Integration with Modern Biotechnology

Techniques such as genomics, marker-assisted selection, CRISPR gene editing, and doubled haploid technology require rapid generation advancement. Speed breeding complements these technologies by quickly producing homozygous lines, validating edited genes, and accelerating trait introgression (Hickey et al., 2019).

Need for Faster Variety Release

Farmers require timely solutions to pest and disease outbreaks, such as new rust races in wheat, viral diseases in legumes, and emerging insect pests due to climate shifts (Singh et al., 2016). Speed breeding allows breeders to respond rapidly and produce improved varieties before damage becomes widespread (Watson et al., 2018).

Efficient Use of Controlled-Environment Agriculture

Advances in power-efficient LEDs, automated systems, and climate-controlled growth chambers have made year-round cultivation cheaper and more feasible. Speed breeding utilizes these technologies to maximize growth efficiency while minimizing the need for large field space (Ghosh et al., 2018).

Enhancing Genetic Gain

Genetic gain is defined as: Genetic gain=Selection differential × Heritability time. By reducing the time component, speed breeding directly increases annual genetic gain, thereby improving crop improvement rates (Hickey et al., 2019).

Supporting Food Security Programs

Governments and international organizations such as CGIAR, ICAR, and FAO emphasize rapid crop improvement to address malnutrition, food shortages, declining productivity, and agricultural sustainability (FAO, 2017). Speed breeding contributes directly to these global goals by accelerating the release of resilient and productive varieties.

Reducing Costs in Breeding Programs

Although speed breeding requires initial investment in infrastructure, it reduces overall breeding costs by shortening breeding cycles, minimizing field trials, and providing more predictable experimental conditions. This allows institutions to produce results faster with fewer long-term resources (Watson et al., 2018).

Historical Development of Speed Breeding

Early attempts to accelerate plant development date back several decades, when scientists experimented with extended daylight exposure, greenhouse environments, and controlled growth chambers. These methods, however, were costly and lacked consistency (Moose & Mumm, 2008). A breakthrough came from NASA's space biology research in the 1980s, where scientists sought to grow plants efficiently in extraterrestrial environments. Continuous lighting systems capable of providing up to 22 hours of light per day were developed, and wheat, along with other crops, responded remarkably well, completing their growth cycles in only a few weeks (Musgrave, 2002; Wheeler, 2020).

Building on these foundations, researchers at the University of Queensland (Australia) and the John Innes Centre (UK) adapted these principles for agricultural purposes. They formalized the concept of *speed breeding*, demonstrating that crops such as wheat, barley, chickpea, and canola could complete up to six generations per year under extended photoperiods compared to two or three generations under natural conditions (Watson et al., 2018; Hickey et al., 2019). Importantly, plants grown under speed breeding conditions maintained normal morphology, seed viability, and genetic stability, making the technique suitable for mainstream breeding programs (Ghosh et al., 2018).

The technology was later extended to horticultural crops, including broccoli and tomato, and to rice through initiatives by the University of Sydney, UC Davis, and the International Rice Research Institute (IRRI) (John Innes Centre, 2018; IRRI, 2021). Global institutions such as CIMMYT also adopted speed breeding to accelerate wheat improvement programs (CIMMYT, 2019).

Table 1. Timeline of key achievements in speed breeding

Year	Achievement	Institution/Researchers	Reference
1980s	Use of artificial lights to multiply wheat; space biology experiments	USDA Mississippi; NASA & Utah State University	Musgrave (2002); Wheeler (2020)
1990s	Discovery of LED lights and their impact on plant growth	University of Wisconsin, USA	NASA (2018)
2003	Term "Speed Breeding" coined	University of Queensland, Australia	Watson et al. (2018)
2016	Speed breeding successfully applied in wheat	University of Queensland, Australia	Hickey et al. (2019)
2017	Development of new wheat varieties	John Innes Centre, UK	John Innes Centre (2018)
2018	New broccoli variety developed using speed breeding	University of Sydney, Australia	Chaudhary & Sandhu (2024)

2019	CIMMYT developed new wheat variety via speed breeding	CIMMYT, Mexico	CIMMYT (2019)
2020	Tomato variety developed in just 2 years	University of California, Davis	Vu et al. (2020)
2021	Rice variety developed using speed breeding	International Rice Research Institute (IRRI), Philippines	IRRI (2021)

Principles of Speed Breeding

Speed breeding is a climate-controlled, photoperiod-optimized technique designed to accelerate plant life cycles and generation turnover. It operates on the principle that environmental manipulation, particularly light duration, temperature, and humidity, can dramatically influence plant physiology, enabling faster flowering, seed set, and maturity without compromising genetic integrity (Watson et al., 2018).

Extended Photoperiods

The cornerstone of speed breeding is the use of extended photoperiods, typically 22 hours of light and 2 hours of darkness. This regime enhances photosynthetic activity, promotes early floral induction, and shortens the vegetative phase. Studies have shown that crops like wheat, barley, and chickpea respond positively to prolonged light exposure, completing up to six generations per year under controlled conditions (Ghosh et al., 2018).

Temperature Regulation

Optimal temperature regimes, commonly 22°C during the day and 17°C at night, are maintained to support metabolic efficiency and reduce abiotic stress. These conditions mimic ideal spring environments year-round, allowing uniform growth and minimizing seasonal variability (Chaudhary & Sandhu, 2024).

LED Lighting Systems

Speed breeding relies on LED lighting to deliver precise wavelengths tailored to plant photosynthetic needs. Red and blue spectra are particularly important for vegetative growth and flowering. LEDs offer energy efficiency, spectral control, and programmable intensity, making them ideal for growth chambers and vertical farming setups (NASA, 2018).

Controlled Humidity, CO_2 , and Nutrients

Humidity levels are maintained between 60–70%, and CO_2 enrichment (up to 600 ppm) is used to boost photosynthetic rates. Nutrient delivery is optimized through hydroponic or soil-based systems, ensuring consistent uptake and minimizing deficiencies (Ghosh et al., 2018).

Physiological Maturity and Rapid Replanting

Unlike conventional breeding, which waits for full seed maturity, speed breeding harvests seeds at physiological maturity, when embryos are fully developed but moisture content is still high. This allows immediate replanting after drying, reducing intergenerational lag (Watson et al., 2018).

Integration with Molecular Breeding

Speed breeding synergizes with modern biotechnologies such as marker-assisted selection (MAS), genomic selection, CRISPR/Cas9 gene editing, and doubled haploid (DH) production. Rapid generation advancement enables faster validation of edited genes, fixation of traits, and development of homozygous lines (Hickey et al., 2019).

Impact on Breeding Efficiency

By compressing the breeding cycle, speed breeding increases annual genetic gain, defined as: Genetic gain=Selection differential×Heritability/Time. Reducing the time denominator directly enhances breeding efficiency, enabling faster release of climate-resilient, disease-resistant, and high-yielding varieties (Moose & Mumm, 2008). The differentiate of conventional and speed breeding were summarized in Table 11.2 and Figure 11.1.

Table 11.2. Differentiation of conventional and speed breeding

Feature	Conventional Breeding	Speed Breeding
Light regime	Natural (12h light/12h dark)	LED-controlled (22h light/2h dark)
Temperature	Seasonal variation	Controlled (22°C/17°C)
Generations/year	1–2	Up to 6
Line development time	8–12 years	2–4 years
Seed harvest	Full maturity	Physiological maturity
Infrastructure	Field/glasshouse	Growth chambers, LED setups
Integration with biotech	Slow validation	Rapid MAS, CRISPR, DH line

Sources: Watson et al. (2018); Ghosh et al. (2018); Chaudhary & Sandhu (2024); NASA (2018); Hickey et al. (2019); Moose & Mumm (2008)

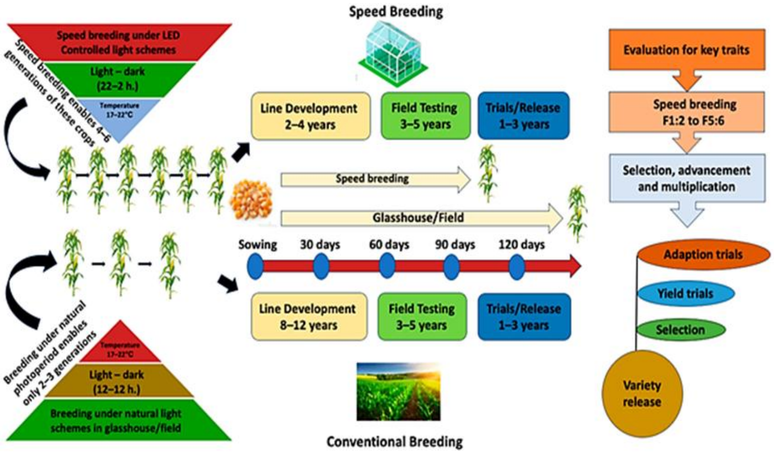

Figure 11.1. Conceptual diagram of speed breeding principles and method. Source: Adapted by Chaudhary & Sandhu (2024).

Methods of Speed Breeding

Speed breeding encompasses a suite of controlled-environment strategies that accelerate plant development, allowing multiple generations per year. These methods are increasingly adopted by national breeding programs, CGIAR centers, and universities to meet urgent food security goals (FAO, 2021; IRRI, 2021). Below is a detailed breakdown of the core techniques, supported by recent literature.

Photoperiod Manipulation

Photoperiod extension is the foundational method in speed breeding. By exposing plants to 20–22 hours of light daily, breeders stimulate continuous photosynthesis, early floral induction, and rapid vegetative growth. LED lighting systems are preferred for their spectral precision, energy efficiency, and programmable intensity (NASA, 2018; Vu et al., 2020). Red and blue wavelengths promote leaf expansion and flowering, while far-red light influences stem elongation and photomorphogenesis (Singh et al., 2023). Light intensity is typically maintained at 400–500 μmol $m^{-2} s^{-1}$ to avoid photo-inhibition (Ghosh et al., 2018). This method is especially effective for long-day crops such as wheat, barley, oats, and canola (Watson et al., 2018).

Temperature Regulation

Temperature control complements photoperiod manipulation by optimizing metabolic rates and synchronizing flowering. Day temperatures of 22–25°C and night temperatures of 17–19°C promote cell division, nutrient uptake, and reproductive development (Chaudhary & Sandhu, 2024). Temperature cycling supports respiration balance and uniform flowering across genotypes (Hickey et al., 2019). Growth chambers and greenhouses equipped with HVAC systems enable precise thermal control, reducing variability and stress-related delays (Wheeler, 2020).

Early Seed Harvest and Rapid Cycling

To further reduce generation time, seeds are harvested 10–14 days post-anthesis, before full physiological maturity, and dried under controlled conditions. This technique shortens the seed-to-seed cycle and enables immediate replanting (Ghosh et al., 2018). In some cases, embryo rescue or low-temperature drying is used to ensure viability (Zhang et al., 2022). Combined with photoperiod and temperature control, this method allows up to 6–8 generations per year in crops like wheat and chickpea (Watson et al., 2018).

Speed Breeding in Greenhouses and Growth Chambers

Speed breeding can be implemented in growth chambers for precision or in greenhouses for scalability. Growth chambers offer tight control over light, temperature, humidity, and CO_2 , making them ideal for early-generation selection and research (Ghosh et al., 2018). Greenhouses allow larger populations and combine natural sunlight with supplemental LEDs. Institutions like CIMMYT and IRRI use greenhouse-based speed breeding to accelerate varietal development in wheat and rice (CIMMYT, 2019; IRRI, 2021). Integration with automated irrigation, shading, and phenotyping platforms enhances throughput and reproducibility (Hickey et al., 2019).

Hydroponic and Soil-less Cultivation Methods

Hydroponics and aeroponics improve nutrient delivery and root development, reducing soil-borne disease risks. Systems like nutrient film technique (NFT), deep-water culture, and cocopeat substrates allow precise control of pH, EC, and nutrient concentrations (Singh et al., 2023). These methods are especially useful in dense planting setups within growth chambers. Automated nutrient dosing and real-time monitoring tools further enhance uniformity and growth rates (Chaudhary & Sandhu, 2024).

Single Seed Descent (SSD) Under Speed Breeding Conditions

SSD is a rapid method for developing homozygous lines in segregating populations. Only one seed per plant is advanced to the next generation, preserving genetic diversity while minimizing space and time requirements (Moose & Mumm, 2008). Under speed breeding conditions, SSD can advance populations from F_2 to F_6 in 1–2 years, enabling early fixation of traits for downstream selection (Watson et al., 2018). This method is widely used in cereals and legumes and is compatible with doubled haploid and genomic selection pipelines (Hickey et al., 2019).

Speed Breeding Applications in Crop Improvement

Speed breeding has emerged as a transformative tool in modern plant science, enabling researchers and breeders to develop improved crop varieties at a pace previously unattainable through conventional methods. By producing multiple generations within a single year, speed breeding accelerates population development, trait introgression, genetic fixation, and evaluation of breeding lines.

This rapid cycling capability integrates seamlessly with molecular breeding, genomic tools, and advanced phenotyping technologies, making it one of the most powerful strategies for crop improvement in the 21st century (Watson et al., 2018; Hickey et al., 2019).

Development of Early-Maturing and High-Yielding Varieties

One of the most significant applications of speed breeding is the rapid development of early-maturing and high-yielding crop varieties. By enabling 4–6 generations per year, breeders can quickly combine desirable yield traits such as increased biomass, enhanced grain weight, optimized plant architecture, and improved harvest index. This accelerated turnover allows earlier selection of promising lines and shortens the overall breeding pipeline, reducing the time required for variety release from 10–12 years to just 3–5 years (Potts et al., 2023). Such efficiency is particularly valuable in cereals and legumes where yield stability is critical for food security.

Accelerated Introgression of Disease-Resistant Traits

Speed breeding is highly effective for transferring disease-resistance genes from donor lines into elite cultivars. By enabling multiple backcrosses within a single year, breeders can introgress resistance to major diseases such as wheat rusts, rice blast, chickpea wilt, and maize downy mildew in record time. Controlled environments allow early generation selection and rapid screening of resistant lines, minimizing the impact of new and emerging pathogens that pose serious threats to global food security (Ahtisham & Obaid, 2025; Singh et al., 2023). This makes speed breeding a cornerstone in resistance breeding programs worldwide.

Rapid Development of Abiotic Stress–Tolerant Varieties

With climate change leading to increased drought, salinity, extreme temperatures, and irregular rainfall, breeding for abiotic stress tolerance has become essential. Speed breeding accelerates the development of crop varieties that can withstand heat stress, water scarcity, salinity, and cold environments. Early generation testing under controlled stress conditions enables breeders to identify tolerant genotypes quickly, ensuring that resilient varieties reach farmers faster (Chaudhary & Sandhu, 2024). This is particularly critical for crops like wheat, barley, legumes, and oilseeds that face substantial yield losses due to climatic stressors.

Enhancing Genetic Gain in Breeding Programs

Genetic gain is a central objective of crop improvement and is influenced by heritability, selection intensity, and generation time. Speed breeding directly improves genetic gain by drastically reducing the time component of this equation. By producing more generations per year, breeders gain more opportunities to apply selection, evaluate genetic variation, and fix desirable alleles. When combined with genomic selection or marker-assisted breeding, speed breeding significantly enhances the efficiency and accuracy of selection (Moose & Mumm, 2008; Hickey et al., 2019).

Integration with Molecular Breeding and Genomic Tools

Speed breeding aligns seamlessly with modern genomic technologies. It supports marker-assisted selection (MAS), genomic selection (GS), CRISPR/Cas-mediated gene editing, mutation breeding, and doubled haploid technology. By quickly cycling populations, breeders can validate gene edits, introgress mapped QTLs, and rapidly improve segregating populations. For example, CRISPR-edited plants can be advanced through several generations in a single year to attain stable, homozygous edited lines suitable for trait evaluation (Vu et al., 2020; Zhang et al., 2022). This integration makes speed breeding indispensable in precision breeding pipelines.

Development of Pure Lines Using Single Seed Descent

Single Seed Descent (SSD) under speed breeding conditions is a highly efficient strategy for rapidly developing homozygous lines. In conventional breeding, achieving homozygosity may take several years, but under speed breeding conditions, breeders can reach the F6 or F7 generation within a year. This enables the quick creation of inbred lines for hybrid development, trait evaluation, and genetic studies (Watson et al., 2018). SSD combined with speed breeding thus accelerates the foundation of breeding programs.

Hybrid Development and Parental Line Improvement

Hybrid breeding programs benefit greatly from speed breeding. The method accelerates the development of new inbred parental lines, rapid purification and stabilization of parental seeds, faster evaluation of combining ability, and quick rotation of hybrid combinations. By reducing generation time, seed companies and research institutions can introduce new hybrid varieties with superior yield and stress tolerance in a much shorter period (Chaudhary & Sandhu, 2024). This is particularly important in maize, rice, and vegetable crops were hybrid vigor drives productivity.

Characterization and Utilization of Genetic Diversity

Speed breeding enables faster evaluation of germplasm collections and mapping populations. Researchers can quickly characterize traits such as growth habit, flowering behavior, stress responses, disease reactions, and morphological variations. This rapid assessment supports better utilization of genetic resources, identification of novel alleles, and creation of broad-based breeding populations (Potts et al., 2023). It also enhances pre-breeding efforts by accelerating the incorporation of wild relatives and landraces into elite backgrounds.

Functional Genomics and Trait Discovery

Speed breeding is a valuable tool in functional genomics, allowing rapid cycling of mutant populations and gene-edited lines. It enables faster establishment of T1, T2, and T3 generations, quick confirmation of gene function, high-throughput screening of phenotypes, and accelerated production of mapping populations for QTL identification (Zhang et al., 2022).

This dramatically shortens the discovery-to-application pipeline for key agronomic traits, making functional genomics more efficient.

Seed Production and Improvement Programs

Speed breeding aids in the early generation seed multiplication process. It enables rapid production of breeder seed, faster multiplication of foundation and certified seeds, and quick purification of seed lots. This ensures the timely availability of improved seeds to farmers, especially during emergencies or the rapid expansion of new varieties (IRRI, 2021). Such efficiency strengthens seed systems and supports agricultural resilience.

Studying Plant–Environment Interactions

Controlled speed breeding environments allow researchers to observe plant responses to specific photoperiods, temperature stress, nutrient management, CO_2 enrichment, and controlled humidity and light spectra. These insights aid researchers in developing crop varieties that are better adapted to future climate scenarios (Wheeler, 2020). This application bridges breeding with climate-smart agriculture, ensuring sustainability.

Success of Speed Breeding in Crop Improvement

Speed breeding has demonstrated remarkable success across diverse crop groups, ranging from cereals and legumes to oilseeds, vegetables, tuber crops, horticultural species, and forage plants. By manipulating photoperiod, temperature, and controlled-environment conditions, breeders can accelerate generation turnover, enabling 3–6 cycles per year compared to the conventional 1–2 cycles under field conditions (Watson et al., 2018; Ghosh et al., 2018).

For example, wheat and barley can complete up to six generations annually under optimized speed breeding protocols, compared to only one or two in traditional field settings. This acceleration supports rapid introgression of disease resistance, abiotic stress tolerance, and yield-enhancing traits. Legumes such as chickpea and pea benefit from faster fixation of resistance genes and nutritional improvements, while oilseeds like canola and sunflower show enhanced hybrid development and stress resilience. Vegetables, tuber crops, and horticultural species also respond positively, with tomato, potato, and strawberry exhibiting faster cycles for disease resistance and quality traits. The following table summarizes key crops, their approximate number of generations per year under speed breeding, and the major benefits achieved (Table 11.2).

Table 11.2. Success of speed breeding in crop improvement.

Crop Group	Crop	Generations per Year (Approx.)	Improvements	Reference
Cereals	Wheat	5–6	Rust resistance, drought tolerance,	Watson et al. (2018); Hickey et al. (2019)

			grain quality, early maturity	
	Barley	5–6	Malting quality, powdery mildew resistance, early flowering	Ghosh et al. (2018)
	Rice	3–4	Submergence tolerance, salinity tolerance, yield improvement	IRRI (2021)
	Maize	2–3	Faster inbred line development, hybrid creation, stress resistance	Chaudhary & Sandhu (2024)
	Sorghum	2–4	Heat tolerance, biomass improvement	Potts et al. (2023)
	Oats / Rye	2–4	Cold tolerance, disease resistance	Hickey et al. (2019)
Legumes	Chickpea	3	Fusarium wilt resistance, early maturity, nutrition improvement	Watson et al. (2018)
	Lentil	2–3	Climate resilience, grain quality improvement	Chaudhary & Sandhu (2024)
	Pea	4	Powdery mildew resistance, flowering time improvement	Ghosh et al. (2018)
	Soybean	2–3	Oil quality, nematode resistance	Potts et al. (2023)
Oilseeds	Canola / Rapeseed	5–6	Blackleg resistance, high oil content, hybrid parent lines	Watson et al. (2018)
	Sunflower	2–4	Heat tolerance, downy mildew resistance	Chaudhary & Sandhu (2024)
	Groundnut	2–3	High oil lines, rust and leaf spot resistance	Potts et al. (2023)
Vegetables	Tomato	3–4	Virus resistance, shelf life, early yield	Vu et al. (2020)
	Capsicum / Chili	2–3	Hybrid development, viral resistance	Chaudhary & Sandhu (2024)

	Cabbage / Cauliflower / Broccoli	2–3	Heat tolerance, head quality improvement	Chaudhary & Sandhu (2024)
	Lettuce / Spinach	3–5	Nutrient enhancement, faster selection	Potts et al. (2023)
Tuber & Root Crops	Potato (from TPS)	2–3	Late blight resistance, early maturity	Zhang et al. (2022)
	Sweet Potato	2–3	High vitamin content, rapid propagation	Chaudhary & Sandhu (2024)
	Cassava / Yam	1–2	Faster clonal selection, stress resilience	Hickey et al. (2019)
Horticulture crops	Strawberry	3–4	Disease resistance, rapid flowering	Watson et al. (2018)
	Apple / Grapes / Banana (early-stage research)	1–2	Juvenility reduction, faster marker-assisted selection	Chaudhary & Sandhu (2024)
Forage & Biofuel Crops	Alfalfa	3–4	Rapid cycling, biomass improvement	Potts et al. (2023)
	Switchgrass / Miscanthus	2–3	Biofuel trait enhancement, stress tolerance	Hickey et al. (2019)
	Napier Grass	2–3	Faster propagation, improved feed quality	Chaudhary & Sandhu (2024)

Limitations and Challenges of Speed Breeding

Although speed breeding has revolutionized crop improvement, several limitations restrict its universal application. One major limitation is that crop responses vary significantly; while cereals such as wheat and barley show excellent acceleration under extended photoperiods, crops with long juvenile phases, including many perennials and fruit trees, remain less responsive (Watson et al., 2018). The infrastructure required for speed breeding, growth chambers, LED lighting systems, and HVAC-controlled greenhouses demands high initial investment, which can be prohibitive for resource-limited breeding programs (Wanga et al., 2021). In addition, extended photoperiods of 20–22 hours per day increase energy consumption, raising sustainability concerns unless renewable energy sources are integrated (Sharma et al., 2022). Another limitation is the risk of reduced seed viability when immature seeds are harvested too early, as improper drying and storage protocols can compromise germination (Zhang et al., 2022). Finally, while speed breeding is highly effective in controlled environments, scaling it to large populations under field conditions remains challenging (Blinkov et al., 2025).

Beyond these limitations, speed breeding faces several challenges that hinder its widespread adoption. Genotype × environment interactions often complicate trait expression, as controlled conditions may not fully replicate field environments, leading to discrepancies in performance (Hickey et al., 2019). Integrating speed breeding with molecular tools such as CRISPR/Cas9, marker-assisted selection, and genomic prediction requires advanced bioinformatics and phenotyping platforms, which are not universally available (Vu et al., 2020). Technical expertise is another challenge, as managing growth chambers, hydroponics, and automated phenotyping systems demands skilled personnel, which may be lacking in developing regions (Sharma et al., 2022). Moreover, simulating complex abiotic stresses such as drought or salinity in controlled environments is difficult, limiting accurate selection for resilience traits (Wanga et al., 2021). Policy and regulatory barriers also slow adoption, particularly in countries where biotechnology and gene editing face restrictions (Blinkov et al., 2025).

Future Directions of Speed Breeding

Looking ahead, future directions for speed breeding focus on overcoming these limitations through innovation and collaboration. Integration with artificial intelligence, robotics, and automation can optimize environmental parameters such as light, temperature, and nutrient regimes, reducing human error and energy costs (Sharma et al., 2022). Renewable energy adoption, including solar-powered LED systems, will make speed breeding more sustainable and accessible (Wheeler, 2020). Expanding protocols to perennial and horticultural crops is a critical frontier, as reducing juvenile phases in fruit trees and vines could transform breeding timelines (Chaudhary & Sandhu, 2024). Climate-smart breeding approaches that combine speed breeding with stress simulation chambers will enable more accurate selection for drought, salinity, and heat tolerance (Hickey et al., 2019). Global collaboration among CGIAR centers, universities, and private companies will democratize access to infrastructure, protocols, and training, ensuring equitable adoption worldwide (Wanga et al., 2021). Finally, coupling speed breeding with genomic prediction pipelines will accelerate trait fixation and improve accuracy in selecting complex traits, thereby enhancing genetic gain and ensuring food security in the face of climate change (Potts et al., 2023).

Disclosure Statement

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