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Speed breeding: An innovative approach in crop breeding

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Abstract
Speed breeding is an innovative and transformative approach in crop improvement aimed at drastically reducing the time required to develop improved cultivars. Conventional breeding methods are often constrained by long generation cycles and seasonal dependency, resulting in slow genetic gains. Speed breeding overcomes these limitations by manipulating environmental factors such as extended photoperiod, optimized temperature regimes and controlled light intensity under protected cultivation systems. This enables rapid generation advancement, allowing three to six generations per year in several crop species. The approach has been successfully applied in cereals, pulses and oilseeds and shows strong compatibility with modern breeding tools including marker-assisted selection, genomic selection, doubled haploids and genome editing technologies. Speed breeding also plays a crucial role in developing climate-resilient and stress-tolerant varieties, thereby supporting climate-smart agriculture and global food security. Despite challenges related to infrastructure costs, energy requirements and crop specificity, ongoing technological advancements are enhancing its efficiency and scalability. Overall, speed breeding represents a promising strategy for accelerating genetic gain and meeting the future demands of sustainable crop production.

Keywords: Speed breeding, rapid generation advancement, controlled environment agriculture, crop improvement, climate-resilient breeding, genomic-assisted selection

1. Introduction

Crop improvement has been central to ensuring global food security, particularly in the face of rising population pressure, climate variability and diminishing natural resources. Traditional plant breeding, though highly successful in improving yield and quality, is inherently slow due to long crop life cycles, seasonal dependence and limited generations per year. In most field-based breeding programmes, only one or two generations can be advanced annually, resulting in prolonged timelines of 8-12 years for the release of a new variety (Tester & Langridge, 2010) [13].

The urgency to accelerate genetic gain has intensified in recent decades owing to climate-induced stresses such as heat, drought, salinity and emerging pest-disease complexes. Conventional breeding approaches alone are insufficient to cope with the speed at which these challenges are evolving. As a result, innovative breeding strategies that reduce generation time while maintaining genetic integrity have gained prominence (Hickey *et al*., 2019) [6].

Speed breeding is one such revolutionary approach that enables rapid generation advancement by manipulating environmental parameters under controlled conditions. By extending photoperiods up to 20-22 hours per day and maintaining optimal temperature and light intensity, plants complete their life cycle much faster than under natural conditions. This approach was first demonstrated effectively in wheat and barley, where up to six generations per year were achieved without compromising seed viability or phenotypic expression (Watson *et al*., 2018) [16]. The significance of speed breeding extends beyond simple time reduction. It enhances the efficiency of selection, accelerates fixation of desirable alleles and complements modern molecular breeding tools such as marker-assisted selection, genomic selection and genome editing. Consequently, speed breeding has emerged as a key component of next-generation crop improvement programmes aimed at developing high-yielding, stress-tolerant and climate-resilient cultivars (Ghosh *et al*., 2018; Farooq *et al*., 2021) [5, 4].

2. Concept and Principles of Speed Breeding

Speed breeding is a crop improvement strategy designed to minimize generation time by accelerating plant growth and reproductive development through precise manipulation of environmental factors under controlled conditions. Unlike conventional breeding, which relies heavily on natural seasonal cycles, speed breeding creates an artificial but optimized growth environment that allows crops to complete their life cycle in a significantly shorter duration.

The fundamental concept of speed breeding lies in rapid generation advancement (RGA). By shortening the time from seed to seed, breeders can advance multiple generations per year, thereby increasing genetic gain per unit time. This approach does not involve genetic modification; rather, it exploits the inherent plasticity of plant developmental processes in response to environmental cues (Watson *et al*., 2018) [16].

2.1 Core Principles of Speed Breeding

2.1.1 Extended Photoperiod

Photoperiod manipulation is the most critical principle of speed breeding. Plants are exposed to prolonged light periods of 20-22 hours per day, which enhances photosynthetic activity and accelerates vegetative growth. Extended photoperiods also promote early floral induction, especially in long-day and day-neutral crops such as wheat and barley (Ghosh *et al*., 2018) [5]. Continuous or near-continuous light increases assimilate production, enabling plants to reach reproductive maturity faster.

1. **Optimized Temperature Regimes**
   Temperature plays a crucial role in regulating plant metabolic activity and developmental rate. Speed breeding protocols typically maintain day temperatures of 22-25 °C and night temperatures of 17-20 °C, which are optimal for most temperate crops. Such conditions accelerate enzymatic reactions, cell division and floral development without inducing heat stress (Farooq *et al*., 2021) [4].
2. **High Light Intensity and Quality**
   Adequate light intensity is essential to support extended photoperiods. Artificial lighting systems, particularly LED lamps, are commonly used to deliver high photosynthetically active radiation (PAR). LEDs also allow manipulation of light spectra, particularly red and blue wavelengths, which influence stem elongation, leaf expansion and flowering responses (Cazzola *et al*., 2020) [1].
3. **Controlled Growth Environment**
   Speed breeding relies on growth chambers or glasshouses where humidity, CO_2 concentration, irrigation and nutrient supply can be precisely regulated. Controlled environments reduce biotic and abiotic stresses, ensuring uniform growth and minimizing environmental noise during selection (Hickey *et al*., 2017) [7]
4. **Early Seed Harvest and Rapid Drying**
   Another important principle is harvesting seeds before full physiological maturity, followed by rapid drying. Studies have shown that seeds harvested at the soft-dough stage retain high viability and germination capacity, allowing immediate advancement to the next generation (Watson *et al*., 2018) [16].

2.2 Physiological Basis of Speed Breeding

At the physiological level, speed breeding accelerates plant development by enhancing carbon assimilation, hormonal signalling and flowering gene expression. Prolonged light exposure influences the circadian clock and upregulates flowering-related genes such as *CONSTANS* and *FLOWERING LOCUS T*, leading to early transition from vegetative to reproductive stages (Farooq *et al*., 2021) [4]. Importantly, these changes are phenotypic and reversible, ensuring that genetic stability is maintained across generations.

The concept of speed breeding is grounded in well-established plant physiological principles and represents a practical, non-transgenic approach to accelerating crop improvement. Its effectiveness across multiple crop species highlights its potential as a core component of modern breeding programmes.

3. Methodology and Protocols of Speed Breeding

The methodology of speed breeding is centred on precise environmental control to accelerate plant growth, flowering and seed set. Protocols are adaptable to crop species, breeding stage and available infrastructure, but they share common operational elements that ensure rapid and reproducible generation advancement (Watson *et al*., 2018; Ghosh *et al*., 2018) [16, 5].

3.1 Infrastructure and Growth Facilities

Speed breeding can be implemented in growth chambers, glasshouses or controlled-environment rooms. Growth chambers offer the highest level of control over temperature, light and humidity, whereas glasshouses provide a cost-effective alternative when supplemented with artificial lighting (Hickey *et al*., 2017) [7]. Light is supplied using LEDs or metal halide lamps, positioned to ensure uniform illumination. LEDs are increasingly preferred due to their energy efficiency, spectral flexibility and reduced heat emission (Cazzola *et al*., 2020) [1].

3.2 Environmental Conditions for Speed Breeding

The success of speed breeding depends on maintaining optimal and consistent environmental parameters. Standardized conditions used across many studies are summarized in Table 1.

Table 1: Standard environmental conditions used in speed breeding protocols

Parameter	Recommended range	Purpose	Reference
Photoperiod	20-22 h light/2-4 h dark	Accelerates vegetative growth and flowering	Watson *et al*., 2018 [16]
Day temperature	22-25 °C	Enhances metabolic activity	Farooq *et al*., 2021 [4]
Night temperature	17-20 °C	Prevents thermal stress	Ghosh *et al*., 2018 [5]
Light intensity	400-600 µmol m^{-2} s^{-1}	Sustains high photosynthesis	Cazzola *et al*., 2020 [1]
Relative humidity	60-70%	Reduces moisture stress	Hickey *et al*., 2017 [7]

3.3 Stepwise Speed Breeding Protocol

A generalized speed breeding protocol followed across crops includes the following steps:

1. **Seed preparation and sowing**: Seeds are sown in pots or trays filled with standardized growth media. Uniform sowing depth and spacing are maintained to ensure synchronized growth.
2. **Vegetative growth under extended photoperiod**: Seedlings are exposed to 20-22 hours of light daily. Extended photoperiod enhances photosynthate accumulation, leading to rapid canopy development.
3. **Flower induction and pollination**: Early flowering is

induced due to prolonged light exposure. Controlled selfing or crossing is performed depending on breeding objectives.

4. **Rapid seed development**: Developing seeds mature faster under optimized temperature and nutrition regimes.
5. **Early seed harvest and drying**: Seeds are harvested at the physiological or soft-dough stage and dried rapidly (30-35 °C) to preserve viability.
6. **Immediate next-generation sowing**: Dried seeds are directly used for the next cycle, allowing multiple generations per year.

3.4 Flowchart of Speed Breeding Methodology

Seed Selection and Sowing
↓
Controlled Environment Growth
↓
Extended Photoperiod (20-22 h)
↓
Rapid Vegetative Development
↓
Early Flowering and Pollination
↓
Accelerated Seed Development
↓
Early Seed Harvest and Drying
↓
Next Generation Advancement

3.5 Crop-Specific Protocol Adjustments

While the basic methodology remains consistent, crop-specific modifications are often required. For example, legumes may require adjusted nutrient regimes, whereas cereals respond strongly to photoperiod extension. Rice and other short-day crops may require modified light schedules to avoid delayed flowering (Yadav *et al*., 2021) [17].

3.6 Reproducibility and Selection Efficiency

One of the strengths of speed breeding methodology is its high reproducibility. Uniform environmental conditions reduce phenotypic variability caused by external factors, allowing breeders to make more accurate selections at early generations. This is particularly advantageous when integrating speed breeding with molecular selection tools (Voss-Fels *et al*., 2019) [15].

4. Crop-wise Applications of Speed Breeding (Elaborated)

Speed breeding has been successfully applied across a wide range of crop species, particularly cereals, pulses and oilseeds. Its effectiveness varies among crops depending on their photoperiod sensitivity, growth habit and reproductive biology. Nevertheless, numerous studies have demonstrated that speed breeding can significantly reduce generation time and accelerate genetic improvement across diverse cropping systems (Hickey *et al*., 2017; Watson *et al*., 2018) [7, 16].

4.1 Cereals

4.1.1 Wheat

Wheat was among the first crops in which speed breeding protocols were standardized. Under extended photoperiods of 22 hours, wheat plants can flower within 35-40 days, allowing up to six generations per year. Speed breeding has been extensively used to accelerate the development of disease-resistant and stress-tolerant wheat lines without compromising grain quality or seed viability (Watson *et al*., 2018) [16].

4.1.2 Barley

Barley responds strongly to photoperiod extension. Studies report four to six generations per year using speed breeding, enabling rapid fixation of desirable traits such as malting quality and disease resistance (Hickey *et al*., 2017) [7].

4.1.3 Rice

Rice, being a short-day crop, requires modified speed breeding protocols. Nevertheless, successful acceleration of generation cycles (three to four generations per year) has been achieved through careful manipulation of photoperiod and temperature, facilitating faster development of early-maturing and stress-tolerant rice genotypes (Yadav *et al*., 2021) [17].

4.2 Pulses

4.2.1 Chickpea

Speed breeding has shown considerable promise in chickpea, a crop traditionally limited to one generation per year under field conditions. Using controlled environments, researchers have achieved up to four generations annually, enabling rapid advancement of segregating populations and early identification of superior lines (Samineni *et al*., 2020) [12].

4.2.2 Pea

In pea, speed breeding has reduced generation time from approximately 120 days to nearly 70 days. This has proven particularly useful in breeding programmes targeting yield improvement and resistance to biotic stresses (Mobini *et al*., 2020) [9].

4.3 Oilseeds

4.3.1 Canola (Rapeseed)

Canola responds well to extended photoperiod and optimized temperature regimes. Speed breeding has enabled four to five generations per year, significantly accelerating trait pyramiding for oil content and disease resistance (Ghosh *et al*., 2018) [5].

4.3.2 Soybean

Although soybean is photoperiod sensitive, controlled environment techniques have successfully shortened its life cycle, allowing rapid generation advancement and faster development of improved cultivars (Nagatoshi & Fujita, 2019) [10].

4.4 Comparative Performance across Crops

Table 2: Crop-wise performance of speed breeding

Crop	Generations per year	Reduction in generation time	Key breeding outcomes	Reference
Wheat	5-6	60-70%	Disease and stress resistance	Watson *et al*., 2018 [16]
Barley	4-6	55-65%	Rapid genetic gain	Hickey *et al*., 2017 [7]
Rice	3-4	40-50%	Early flowering varieties	Yadav *et al*., 2021 [17]
Chickpea	4	50-60%	Fast population advancement	Samineni *et al*., 2020 [12]
Pea	4-5	45-55%	Yield and disease resistance	Mobini *et al*., 2020 [9]
Canola	4-5	50-60%	Trait pyramiding	Ghosh *et al*., 2018 [5]

4.5 Significance for Breeding Programmes

The successful application of speed breeding across multiple crops demonstrates its versatility and scalability. By enabling rapid cycling of generations, breeders can shorten the time required to release improved cultivars and respond quickly to emerging production challenges. Moreover, speed breeding facilitates early generation selection, thus improving overall breeding efficiency and resource utilization (Hickey *et al*., 2019) [6].

5. Integration of Speed Breeding with Modern Breeding Tools (Elaborated)

Speed breeding alone accelerates generation turnover; however, its true potential is realized when it is integrated with modern molecular, genomic and biotechnological tools. This integration enables breeders to not only advance generations rapidly but also identify, select and fix desirable traits with greater precision, thereby substantially increasing genetic gain per unit time (Hickey *et al*., 2019; Varshney *et al*., 2021) [6, 14].

5.1 Integration with Marker-Assisted Selection (MAS)

Marker-assisted selection allows early identification of plants carrying desirable alleles using DNA markers linked to target traits. When combined with speed breeding, MAS enables selection at seedling or early vegetative stages, eliminating the need to wait for full phenotypic expression (Voss-Fels *et al*., 2019) [15]. For example, resistance genes for rusts in wheat or Fusarium wilt in chickpea can be rapidly fixed across successive generations using speed breeding combined with marker screening. This integration significantly shortens the breeding cycle while maintaining selection accuracy (Samineni *et al*., 2020) [12].

5.2 Integration with Genomic Selection

Genomic selection (GS) uses genome-wide marker information to predict breeding values of individuals. Speed breeding complements GS by enabling rapid cycling between selection and recombination phases. This accelerates the realization of predicted genetic gains in actual breeding populations (Crossa *et al*., 2017) [3].

Studies indicate that combining speed breeding with genomic selection can double or even triple the rate of genetic gain compared to conventional breeding methods, particularly in complex traits such as yield and drought tolerance (Voss-Fels *et al*., 2019) [15].

5.3 Integration with Genome Editing Technologies

Recent advancements in genome editing, particularly CRISPR/Cas9 technology, have opened new avenues for precise modification of target genes. Speed breeding facilitates rapid advancement and fixation of edited lines by quickly progressing them through successive generations (Varshney *et al*., 2021) [14]. This approach is especially valuable for validating gene function and developing elite lines with improved stress tolerance, disease resistance or nutritional quality within a short timeframe.

5.4 Integration with Doubled Haploid (DH) Technology

Doubled haploid technology produces completely homozygous lines in a single generation. When combined with speed breeding, DH lines can be rapidly evaluated and advanced, further reducing the time required to develop pure lines (Hickey *et al*., 2017) [7].

5.5 High-Throughput Phenotyping and Digital Tools

Controlled environments used in speed breeding are ideal for deploying high-throughput phenotyping platforms, including imaging systems, spectral sensors and automated data collection tools. These technologies enable precise, repeatable phenotyping, improving selection efficiency and data quality (Reynolds *et al*., 2017) [11].

5.6 Comparative Advantage of Integrated Approaches

Table 3: Benefits of integrating speed breeding with modern breeding tools

Tool Integrated	Benefit	Outcome
Marker-assisted selection	Early and precise selection	Faster fixation of traits
Genomic selection	Prediction-based selection	Higher genetic gain
Genome editing	Targeted gene modification	Rapid trait development
Doubled haploids	Instant homozygosity	Reduced breeding cycles
High-throughput phenotyping	Accurate trait measurement	Improved selection efficiency

5.7 Implications for Future Breeding Programmes

The integration of speed breeding with modern breeding tools transforms traditional breeding pipelines into high-efficiency, data-driven systems. This integrated approach is particularly critical for addressing complex challenges such as climate resilience, nutritional security and sustainable productivity under resource-limited conditions (Hickey *et al*., 2019) [6].

6. Advantages of Speed Breeding (Elaborated)

Speed breeding offers multiple advantages over conventional crop breeding approaches by significantly enhancing efficiency, precision and responsiveness of breeding programmes. These advantages have positioned speed breeding as a core component of modern and future-oriented crop improvement strategies (Watson *et al*., 2018; Farooq *et al*., 2021) [16, 4].

6.1 Reduction in Breeding Cycle Duration

The most significant advantage of speed breeding is the drastic reduction in generation time. Conventional field-based breeding typically allows only one or two generations per year, whereas speed breeding enables three to six generations annually depending on the crop species. This results in a 50-70% reduction in the time required to develop stable breeding lines and release new cultivars (Watson *et al*., 2018) [16].

6.2 Increased Genetic Gain per Unit Time

By allowing rapid cycling of generations, speed breeding increases the number of selection cycles that can be completed within a given time frame. This accelerates genetic gain, particularly when combined with selection strategies such as genomic selection and marker-assisted selection (Voss-Fels *et al*., 2019) [15].

6.3 Year-Round Breeding Independent of Seasons

Speed breeding eliminates dependence on seasonal field conditions. Breeding activities can be conducted throughout the year in controlled environments, ensuring continuity of research and efficient utilization of resources. This is especially beneficial in regions with harsh climates or limited growing seasons (Hickey *et al*., 2017) [7].

6.4 Enhanced Selection Efficiency
Controlled environmental conditions reduce phenotypic variation caused by external factors such as rainfall, temperature fluctuations and pest pressure. This uniformity enhances selection accuracy, particularly for traits with moderate to high heritability (Farooq *et al*., 2021) [4].

6.5 Compatibility with Modern Breeding Technologies
Speed breeding integrates seamlessly with modern breeding tools including marker-assisted selection, genomic selection, genome editing and doubled haploid technology. This compatibility enables rapid fixation of target traits and validation of gene function (Varshney *et al*., 2021) [14].

6.6 Rapid Response to Emerging Challenges
Speed breeding enables breeders to respond quickly to emerging threats such as new disease races, pest outbreaks and climate-induced stresses. The ability to rapidly develop and test improved genotypes enhances resilience of agricultural systems (Reynolds *et al*., 2017) [11].

6.7 Efficient Use of Space and Resources
Due to shortened growth duration and compact plant architecture under controlled environments, speed breeding allows efficient use of space. Multiple generations can be advanced within the same facility, improving cost-effectiveness over time (Cazzola *et al*., 2020) [1].

Table 4: Summary of advantages of speed breeding

Advantage	Impact on breeding	Reference
Reduced generation time	Faster varietal development	Watson *et al*., 2018 [16]
Higher genetic gain	Improved selection response	Voss-Fels *et al*., 2019 [15]
Year-round breeding	Continuous breeding cycles	Hickey *et al*., 2017 [7]
Improved selection accuracy	Reduced environmental noise	Farooq *et al*., 2021 [4]
Rapid stress response	Climate resilience	Reynolds *et al*., 2017 [11]

7. Limitations and Challenges of Speed Breeding
Despite its significant advantages, speed breeding is not without limitations. Understanding these constraints is essential for realistic adoption, optimization and scaling of speed breeding protocols in diverse breeding programmes. Several technical, economic and biological challenges influence its effectiveness and widespread implementation (Watson *et al*., 2018; Farooq *et al*., 2021) [16, 4].

7.1 High Initial Infrastructure and Operational Costs
One of the primary limitations of speed breeding is the high initial investment required for infrastructure such as growth chambers, controlled-environment rooms and artificial lighting systems. The installation and maintenance of high-intensity lighting, temperature control units and automated systems can be cost-prohibitive, particularly for public-sector breeding programmes in developing countries (Cazzola *et al*., 2020) [1].

7.2 Energy Consumption and Sustainability Concerns
Extended photoperiods of 20-22 hours per day significantly increase electricity consumption. This raises concerns regarding operational costs and environmental sustainability, especially in regions where energy resources are limited or expensive. Although LED technology has improved energy efficiency, energy demand remains a critical constraint (Watson *et al*., 2018) [16].

7.3 Crop and Genotype Specificity
Not all crops or genotypes respond uniformly to speed breeding conditions. Photoperiod-sensitive and perennial crops may exhibit delayed flowering or abnormal growth under extended light regimes. Short-day crops such as rice and soybean require careful protocol modification to avoid flowering delays (Yadav *et al*., 2021; Nagatoshi & Fujita, 2019) [17, 10].

7.4 Physiological Stress and Trait Expression
Prolonged exposure to artificial light and accelerated growth may impose physiological stress on plants. Certain traits, particularly those related to root development, biomass accumulation and stress tolerance, may not be fully expressed under controlled conditions. This can limit the reliability of phenotypic selection for complex traits (Farooq *et al*., 2021) [4].

7.5 Limited Field Validation
Genotypes developed or selected under speed breeding conditions require extensive field validation to ensure stable performance under natural environments. Differences between controlled and field conditions may result in genotype × environment interactions that affect yield and stress response (Reynolds *et al*., 2017) [11].

7.6 Requirement for Skilled Manpower
Successful implementation of speed breeding requires trained personnel with expertise in plant physiology, controlled-environment management and breeding protocols. Lack of technical expertise can limit adoption and consistency of results (ICAR, 2022) [8].

Table 5: Major limitations and challenges of speed breeding

Limitation	Implication	Reference
High infrastructure cost	Limited adoption in resource-poor settings	Cazzola *et al*., 2020 [1]
High energy requirement	Increased operational cost	Watson *et al*., 2018 [16]
Crop specificity	Protocol modification needed	Yadav *et al*., 2021 [17]
Physiological stress	Altered trait expression	Farooq *et al*., 2021 [4]
Field validation need	G×E interaction concerns	Reynolds *et al*., 2017 [11]
Skilled manpower	Training and capacity building required	ICAR, 2022 [8]

7.7 Strategies to Overcome Limitations
Recent research focuses on developing energy-efficient LED systems, optimizing light spectra and integrating speed breeding with field-based selection to overcome these limitations. Public-private partnerships and institutional support are also crucial for scaling speed breeding infrastructure (CGIAR, 2021) [2].

8. Role of Speed Breeding in Climate Change Adaptation
Climate change poses one of the greatest challenges to global agriculture by increasing the frequency and intensity of abiotic stresses such as heat, drought, salinity and erratic rainfall. These stresses significantly reduce crop productivity and threaten food security, particularly in vulnerable regions. In this context, speed breeding has emerged as a crucial tool for rapidly developing climate-resilient crop varieties capable of adapting to changing environmental conditions (Reynolds *et al*., 2017; Hickey *et al*., 2019) [11, 6].

8.1 Accelerated Development of Stress-Tolerant Varieties
Speed breeding enables rapid cycling of generations, allowing breeders to quickly introgress and fix genes associated with tolerance to heat, drought and salinity. Traits that would traditionally require several years to stabilize can be developed within a much shorter timeframe using controlled environment conditions (Watson *et al*., 2018) [16].

8.2 Rapid Screening under Simulated Stress Conditions
Controlled environments used in speed breeding can simulate climate stress scenarios such as high temperature or limited water availability. This allows early-stage screening of genotypes under stress conditions, improving the efficiency of selection for climate resilience (Farooq *et al*., 2021) [4].

8.3 Faster Response to Emerging Biotic Stresses
Climate change also alters pest and disease dynamics, leading to the emergence of new pathogen races and pest populations. Speed breeding facilitates rapid development of resistant varieties by enabling faster gene pyramiding and validation of resistance sources (Hickey *et al*., 2017) [7].

8.4 Support for Climate-Smart Agriculture
By reducing breeding time and enabling rapid varietal turnover, speed breeding supports climate-smart agriculture initiatives. Improved varieties can be released more frequently, ensuring that farmers have access to cultivars better adapted to current climatic conditions (Tester & Langridge, 2010) [13].

8.5 Integration with Predictive Breeding Models
Speed breeding complements climate modeling and genomic prediction tools by allowing quick validation of predicted genotype performance. This integration enhances the reliability of breeding decisions under uncertain future climates (Voss-Fels *et al*., 2019) [15].

Table 6: Contribution of speed breeding to climate change adaptation

Climate challenge	Role of speed breeding	Outcome
Heat stress	Rapid development of heat-tolerant lines	Yield stability
Drought stress	Fast fixation of drought-tolerance traits	Improved water-use efficiency
Emerging diseases	Quick resistance gene pyramiding	Reduced crop losses
Climate variability	Faster varietal replacement	Enhanced resilience

8.6 Global and Regional Relevance
International research organizations and national breeding programmes have recognized speed breeding as a strategic tool to address climate change challenges. Institutions such as CGIAR and ICAR have initiated programmes to integrate speed breeding into climate-resilient crop development pipelines (CGIAR, 2021; ICAR, 2022) [2, 8].

9. Future Prospects of Speed Breeding (Elaborated)
Speed breeding is rapidly evolving from a niche research technique into a mainstream component of modern crop improvement programmes. Continuous technological advancements and growing global demand for climate-resilient, high-yielding crops are expected to further expand its application and effectiveness in the coming years (Hickey *et al*., 2019; Varshney *et al*., 2021) [6, 14].

9.1 Technological Advancements in Controlled Environments
Future speed breeding systems are expected to incorporate automation, sensor-based monitoring and artificial intelligence (AI) to optimize environmental parameters in real time. Automated lighting, temperature and irrigation control will enhance precision, reduce human error and improve reproducibility of breeding outcomes (CGIAR, 2021) [2].

9.2 Energy-Efficient and Sustainable Speed Breeding Systems
To address concerns related to energy consumption, research is increasingly focused on developing energy-efficient LED lighting systems and optimized light spectra that maximize photosynthesis while minimizing power usage. Integration of renewable energy sources is also expected to improve the sustainability of speed breeding facilities (Cazzola *et al*., 2020) [1].

9.3 Expansion to Minor, Orphan and Underutilized Crops
While speed breeding has been extensively applied in major cereals and pulses, its future expansion to minor and orphan crops holds significant promise. Accelerating breeding in these crops can enhance nutritional diversity, regional food security and livelihood resilience in marginal environments (Varshney *et al*., 2021) [14].

9.4 Integration with Advanced Genomic Technologies
The convergence of speed breeding with advanced genomic tools such as genome-wide association studies, genomic prediction and next-generation sequencing will further accelerate genetic gains. Rapid cycling of generations will allow faster validation of genomic predictions and gene-trait associations (Voss-Fels *et al*., 2019) [15].

9.5 Role in Global Food and Nutritional Security
Speed breeding is expected to play a pivotal role in achieving global food and nutritional security by enabling faster development of biofortified and climate-resilient crop varieties. Its adoption across national and international breeding programmes will support timely varietal replacement and improved farmer access to superior cultivars (Hickey *et al*., 2019) [6].

Table 7: Emerging trends and future directions of speed breeding

Future direction	Expected impact	Reference
AI-based growth control	Improved efficiency and precision	CGIAR, 2021 [2]
Energy-efficient LEDs	Reduced operational costs	Cazzola *et al*., 2020 [1]
Expansion to orphan crops	Enhanced food diversity	Varshney *et al*., 2021 [14]
Genomic integration	Faster genetic gain	Voss-Fels *et al*., 2019 [15]
Climate-focused breeding	Improved resilience	Hickey *et al*., 2019 [6]

9.6 Policy and Institutional Support

The successful scaling of speed breeding will require supportive policies, institutional investments and capacity-building initiatives. Public research organizations, international agencies and private-sector partnerships will play a crucial role in mainstreaming speed breeding technologies, particularly in developing countries (ICAR, 2022) [8].

10. Conclusion

Speed breeding represents a transformative advancement in crop improvement by significantly reducing generation time and accelerating varietal development. Through precise manipulation of photoperiod, temperature and light intensity under controlled environments, multiple generations can be advanced within a single year. This approach enhances genetic gain per unit time and improves selection efficiency, particularly when integrated with modern breeding tools such as marker-assisted selection, genomic selection and genome editing. Speed breeding plays a crucial role in developing climate-resilient and stress-tolerant cultivars capable of addressing the challenges posed by climate change and global food insecurity. Despite certain limitations related to infrastructure cost, energy use and crop specificity, ongoing technological innovations are steadily overcoming these constraints. Expansion of speed breeding to minor and underutilized crops further strengthens its relevance for nutritional and regional food security. With adequate policy support and institutional investment, speed breeding is poised to become a cornerstone of sustainable and future-ready crop breeding programmes worldwide.

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