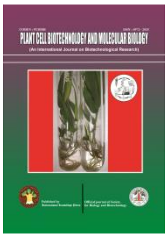

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Speed Breeding: A Transformative Approach to Accelerate Crop Improvement

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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ABSTRACT

Speed breeding has emerged as a transformative approach to expedite crop improvement by optimizing environmental conditions to achieve rapid generation turnover. This technique manipulates factors such as photoperiod, temperature, light intensity, and nutrition to hasten plant growth and reproduction cycles. Through the production of 4-6 generations per year, compared to 1-2 generations in traditional breeding, speed breeding unlocks the potential for rapid development of crop varieties with enhanced yield potential, biotic and abiotic stress resilience, improved nutritional quality, and climate adaptation. The key principles involve tailoring photoperiods, controlling temperatures, employing specialized lighting, creating controlled environments, and formulating targeted nutrition. Speed breeding has diverse applications across cereals, legumes, vegetables, and other crops, enabling accelerated introgression of desirable traits, efficient hybrid

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breeding, and integration with contemporary genomics technologies. The primary advantages of speed breeding include rapid genetic gain, year-round breeding, precision phenotyping and selection, flexibility across diverse species, and seamless integration with molecular tools. However, challenges such as infrastructure costs, protocol optimization needs, genetic diversity implications, phenotyping data management, and accessibility constraints, particularly in developing countries, require attention. Future prospects encompass the integration of advanced genomics techniques, next-generation phenotyping, sustainable approaches, global consortiums for collaboration, capacity building initiatives, and responsible governance frameworks. Realizing the immense potential of speed breeding through collaborative efforts, cutting-edge innovations, and participatory approaches can contribute significantly to global food and nutritional security in the face of climate change.

Keywords: Speed breeding; crop improvement; photoperiod manipulation; rapid genetic gain; genomic integration.

1. INTRODUCTION

The combination of increasing global population and evolving dietary patterns has resulted in a significant surge in the demand for food, requiring the need for sustainable enhancements in agricultural output [1]. Nevertheless, conventional methods of plant breeding encounter constraints in expediting crop enhancement to fulfil worldwide yield objectives [2]. Speed breeding has become a potential method in this situation, as it optimizes environmental variables to produce quick generation turnover in order to expedite the breeding process [3]. Speed breeding employs several techniques such as adjusting photoperiod, light intensity, temperature, humidity, and nutrients to hasten the growth and life cycles of plants [4,5]. This allows for the production of 4-6 generations per year, as opposed to only 1-2 generations through traditional breeding methods [6,3].

The concept of speed breeding was developed from first investigations into the manipulation of photoperiods to accelerate the process of flowering and enhance agricultural productivity in plants such as wheat, rice, and soybean [7]. Subsequent research has shown that customizing the length of daylight and optimizing growth conditions can effectively decrease the time it takes for cereals, legumes, and vegetables to reach maturity [5,8]. Speed breeding has successfully unlocked the potential for rapid development of crop varieties that possess improved resistance to pests and diseases, tolerance to environmental stresses, and enhanced nutritional quality. This breakthrough has been achieved in crops such as wheat, barley, canola, chickpea, and *Brassica oleracea* [9,10,3]. Integration with genomics technologies and high-throughput phenotyping provides precise selection for essential features [11,12]. Nevertheless, it is imperative to undertake proactive measures to enhance protocols across various genetic resources [13] and facilitate broader implementation on a worldwide scale [14].

This paper fully evaluates speed breeding methodologies, applications, benefits, and limitations. Photoperiod manipulation employing longer day length or continuous lighting is a main strategy in speed breeding [4]. Controlled temperature, humidity and specialized lighting modulate plant growth and development [5]. Targeted nutrients and substrates enable appropriate nutrition in speed breeding systems [3]. Speed breeding promotes quicker production of cultivars with greater yield potential, disease resistance, abiotic stress tolerance, and improved nutritional quality [10,15]. The primary advantages are rapid genetic gain, year-round breeding, and integration with contemporary genomics technologies [5,3,16-18]. However, infrastructure costs, protocol optimization across various germplasm, and implications on genetic diversity remain important challenges [10,14]. This review elucidates concepts, uses, benefits, limitations and future possibilities of speed breeding. Insights gathered can inform attempts to responsibly speed crop innovation to fulfil rising food demands.

2. SPEED BREEDING METHODOLOGY

Speed breeding tries to accelerate crop improvement by optimizing environmental factors to achieve rapid generation turnover [3]. The main principles entail changing parameters including photoperiod, temperature, light intensity and nutrition to expedite plant growth and reproduction (Fig. 1) [5].

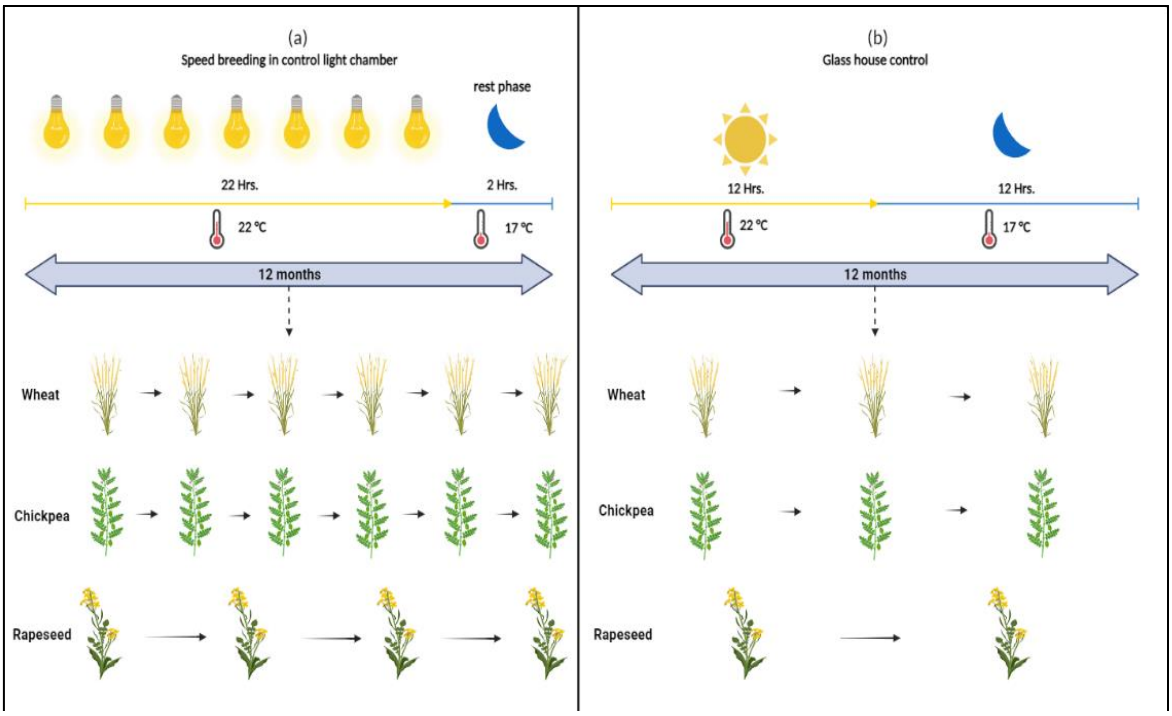

Fig. 1. Comparison of speed breeding conditions in a controlled light chamber

(a) and regular greenhouse conditions (b). (a) In the speed breeding chamber, plants are grown under continuous light (22 hours) at 22°C, with a 2-hour rest phase of darkness at 17°C. This optimized environment allows completing 6 generations of wheat, chickpea, and rapeseed within 12 months. (b) In the regular greenhouse control, plants are subjected to natural day/night cycles (12 hours light/12 hours dark) with day temperatures of 22°C and night temperatures of 17°C. Under these conditions, only 1 generation can be obtained for the three crops in 12 months. The illustrations depict the accelerated generation cycling achieved through speed breeding by manipulating light periods, temperatures, and providing controlled environmental factors compared to regular greenhouse conditions.

- **Photoperiod Management:** Photoperiod modification is a fundamental approach in fast breeding. Providing increased day length or continuous lighting reduces the dark period, enabling synchronized flowering and rapid cycling between generations [4]. In wheat, photoperiods above 16 hours can accelerate breeding cycles [8]. Specific responses vary between long-day, short-day and day-neutral plants [19,20]. Tailoring photoperiods depending on photosensitivity provides optimization for varied crops [21,3].

- **Temperature Control:** Elevated temperatures promote developing rates by activating metabolic processes. Optimized day/night temperatures of 28/23°C in rice and 25/20°C in wheat can hasten growth [22,3]. However, overly high temperatures can impede growth. Thresholds change between species due to adaption. Modulating temperature regimes based on environment of origin and thermal restrictions permits optimization [23].

- **Specialized Lighting:** High intensity discharge lamps, fluorescent tubes or LED arrays offer light intensities up to 1000 µmol/m2/s in speed breeding [3]. Specific wavelengths can be modified to alter morphogenesis and blooming based on photoreceptor responses [24,25]. Vertical lighting designs maximize light interception for dense plant stands [26].

- **Controlled Environments:** Growth chambers, rooms and greenhouses integrated with adaptive control systems allow precision regulation of temperature, humidity, illumination, and other environmental conditions [3]. Hydroponics and aeroponics optimize nutrition delivery. Isolation from biotic and abiotic stressors ensures optimal growth [27].

- **Specialized Nutrition:** Formulating specific nutrient solutions, misting regimes, growing media or substrates ensures optimal nutrition for speeding growth [28]. Effective fertilizer control prevents deficits. Automated or hydroponic systems allow responding to plant response [29].

- **Integrating Innovations:** Automation for seed handling, imaging-based phenotyping and data analytics tools can boost speed breeding [30,31]. Combining speed breeding with genomics, gene editing and genomic selection provides accurate introgression of essential traits [32,33].

By utilizing photoperiod modification, controlled surroundings, optimal nutrition and agricultural technologies, speed breeding permits quick cycling between generations. Further understanding genotype-by-environment interactions, phenotypic plasticity and epigenetic influences will assist enhance protocols for varied crops [34,35]. Overall, enhancing climatic conditions coupled with breakthroughs in genetics and robotics provides a framework for sustainably accelerating breeding cycles.

3. APPLICATIONS OF SPEED BREEDING

The increased generation turnover afforded by speed breeding promotes rapid development of superior agricultural varieties. Diverse applications exploit the capabilities of speed breeding for boosting yield, abiotic stress resilience, disease resistance, nutritional quality and climatic adaptation.

- **Enhancing Yield Potential:** Speed breeding promotes quicker identification and selection for features associated with enhanced productivity including upright leaves, dwarfing genes and efficient metabolism [36,3]. Rapid generation cycling speeds crossing and evaluation to develop high yielding hybrids [6]. Early vigor and reproductive success can also be increased with speed breeding [37,38].

- **Improving Biotic Stress Resistance:** Speed breeding allows rapid introgression and pyramiding of resistance genes by permitting quick crosses between target lines [39,3]. Early generation selection under simulated infection accurately identifies resistant progeny [40]. This permits fast response to emerging diseases. Resistance to several viral, bacterial, fungal and nematode infections has been increased using speed breeding [10].

- **Enhancing Abiotic Stress Tolerance:** Exposing plants to simulated drought, salinity, heat, cold or flooding conditions during rapid cycling enables identification of resilient genotypes [3]. Characterizing physiological adaptations as stomatal responses, photosynthetic stability and root architecture allows selecting optimal phenotypes [11]. Speed breeding thereby accelerates developing climate-resilient variants.

- **Biofortification:** Rapid generation turnover coupled with precision phenotyping offers successful selection for higher nutritional content [41,42]. Biofortified crops with better protein quality, higher micronutrients and reduced anti-nutrients have been created using speed breeding [43]. This has promise for alleviating malnutrition.

- **Adaptation to Climate Change:** Speed breeding under simulated climatic scenarios helps examining phenology shifts, heat tolerance and drought responses to find resilient lines [44,45]. Traits including shortened growth period, early vigor, lower transpiration and improved carbon absorption can be selected [11]. This permits breeding climate-ready crops.

- **Accelerating Breeding in Orphan Crops:** Many orphan or under-utilized crops lack optimized breeding strategies. Speed breeding can overcome limits of long generation durations to speed trait mapping and introgression in these neglected species [4,10]. This expands resources available for diversification agriculture.

- **High-Throughput Trait Evaluation:** Integration with automated phenotyping provides massively parallelized characterization of features including growth, morphology, yield metrics, physiology and metabolite profiles [30,11]. This permits speeding selection for complicated trait combinations underlying productivity and resilience.

In summary, speed breeding provides a comprehensive toolkit to handle varied crop improvement concerns encompassing biotic and abiotic stressors, yield potential, climatic resilience, nutritional quality and breeding efficiency. Continued study into genotype-by-environment interactions and translating speed breeding benefits from controlled environments to target agro-ecological situations will be crucial to optimize effect.

4. BENEFITS OF SPEED BREEDING

Speed breeding gives various advantages that enhance the precision, efficiency, and speed of crop improvement. By shortening breeding cycles, speed breeding delivers major benefits including quick genetic gain, year-round breeding, regulated conditions for precision

Table 1. Ways for quick generation advancement with matching flowering days, the number of generations attained annually, and the selection strategies applied to various crops

Crop	Days to flowering	Number of generations per year	Techniques	References
Amaranthus	28	6	Temperature and photoperiod	[46]
Arabidopsis thaliana	20–26	10	Photoperiod, immature seed germination and plant hormones	[47]
Hordeum vulgare	24 – 36	9	Temperature, photoperiod, soil fertility, immature seed germination and embryo rescue	[48-50]
Brassica napus	73	4	Temperature, light intensity, photoperiod, immature seed germination and soil moisture	[3]
Cicer arietinum	33	7	Immature seed germination and photoperiod	[51]
Vicia faba	29–32	7	Light intensity, photoperiod, plant hormones and immature seed	[52]
Arachis hypogaea	25–27	3	Temperature and photoperiod	[53]
Lens culinaris	31–33	8	Light intensity, photoperiod, plant hormones and immature seed	[52]
Pisum sativum	33	5	Photoperiod, plant hormones and immature seed germination	[54]
Cajanus cajan	50–56	4	Temperature, photoperiod, immature seed germination	[55]
Oryza sativa	75–85	4	Temperature, photoperiod and high-density planting	[56]
Sorghum bicolor	40–50	6	Temperature, photoperiod and immature seed germination	[57]
Glycine max	23	5	Temperature, photoperiod and immature seed germination	[58]
Triticum Aestivum	28–41	7.6	Temperature, photoperiod, soil fertility, immature seed germination and embryo rescue	[48]
Avena sativa	45-52	4.9	Temperature, early seed harvest and photoperiod	[59]

selection, adaptability across varied crops, and seamless integration of molecular breakthroughs.

- **Rapid Genetic Gain:** The ability to accomplish several generations each year permits faster accumulation of positive features and production of superior varieties [4,6]. Rapid cycling paired with early generation selection permits additional rounds of recombination and selection annually, speeding genetic gain [60,61]. Estimates imply 2-4 times improvements in some crops employing speed breeding [3].

- **Season-Independent Breeding:** Photoperiod modification removes seasonal limits, enabling year-round breeding and optimization of resources [3]. Multiple generations can be cultivated continuously rather than waiting for specific planting windows. This allows ongoing advancement in breeding projects.

- **Precision Phenotyping and Selection:** Controlled environments provide reliable definition and selection for target features by minimizing confounding influences [6,38]. Automated phenotyping offers massively parallelized characterization of different attributes [30,62]. This boosts the precision of phenotyping and selection.

- **Enhancing Trait Introgression:** Speed breeding provides more efficient introgression of desirable features from exotic germplasm into elite adapted material by faster backcrossing [63,64]. Fewer backcross generations are required to recover the recurrent parent genome.

- **Accelerated Hybrid Breeding:** The quick generation cycling permits development and testing of different parental combinations to identify ideal crossings for hybrid production [65,10]. Once found, hybrid populations can be expanded faster.

- **Flexibility Across Diverse Species:** The strategies of speed breeding successfully transferred across cereals, legumes, fodder crops, vegetables, fruits and ornamentals, displaying adaptability across plant species [4,6]. This offers extensive utility for varied breeding schemes.

- **Integration of Genomic Tools:** Molecular markers, genomic selection and genome editing can be readily integrated with speed breeding for increased precision and efficiency [66,67]. High-throughput genotyping keeps pace with rapid cycling.

- **Accelerating Research:** The ability to create many generations annually also assists researchers in disciplines including genetics, physiology, pathology and entomology by conducting tests over compressed timescales [5,38]. This accelerates hypothesis testing and research.

In summary, speed breeding delivers multifarious advantages encompassing rapid genetic gain, year-round breeding, precision selection, trait introgression, hybrid development, flexibility, and integration of contemporary genomic technologies. Continued improvement of methods and addressing obstacles will further augment the benefits of speed breeding for varied plant breeding and research applications.

5. LIMITATIONS AND CHALLENGES OF SPEED BREEDING

While speed breeding has enormous potential, there are significant constraints and obstacles that need considered for its best implementation. Key challenges requiring consideration include infrastructure costs, protocol optimization, genetic diversity consequences, phenotypic data management, and significantly, making speed breeding accessible internationally.

- **Infrastructure Costs:** Specialized facilities including growth chambers and greenhouses with precision climate control, lighting systems and hydroponics/aeroponics setups incur substantial capital and maintenance expenditures [3]. Optimizing methods to minimize resource requirements could enhance affordability.

- **Protocol Optimization Needs:** Response to speed breeding conditions differs between genotypes, necessitating optimization for different crops [68,6]. Understanding genotype-environment interactions using multi-environment trials is crucial [69]. Physiological and epigenetic implications of fast cycling require additional characterization [35,70].

- **Impacts on Genetic Diversity:** High selection pressure paired with rapid turnover of generations could degrade genetic variety during speed breeding [71,6]. Monitoring diversity and enrichment measures may be essential to avoid sensitivity to biotic and abiotic stressors.

- **Phenotyping and Data Challenges:** The data created during rapid phenotyping and selection demands robust systems for storage, access and analysis [72,14]. Effective data management is crucial to generate insights and breeding decisions.

- **Ethical Considerations:** Responsible deployment of technologies boosting access to quality seed while respecting rights of farmers and breeders is vital [14]. Transparency and participatory approaches engaging stakeholders are crucial.

- **Accessibility Constraints:** Many public breeding programs and small enterprises, especially in developing countries, lack the infrastructure and resources to conduct speed breeding [14,7]. Improving affordability and access will be important for worldwide adoption.

- **Making Speed Breeding Truly Global:** Platforms supporting international collaboration, capacity building efforts, and technological transfers can promote greater adoption of speed breeding [73,6]. Multi-stakeholder collaborations addressing restrictions are needed to realize the full potential of this method.

In short, capitalizing on the great potential of speed breeding while appropriately addressing its problems would need multi-disciplinary initiatives. Continued research, global cooperation, participatory techniques and fair access can enable this breakthrough technology to sustainably advance agricultural development worldwide.

6. FUTURE PROSPECTS FOR SPEED BREEDING

While speed breeding has already showed tremendous influence, new developments and advancements can boost its efficiency and usefulness. Key areas giving future prospects include integration of cutting-edge genomics techniques, advanced phenotyping, sustainable speed breeding approaches, worldwide consortiums to promote cooperation, and capacity building to improve access.

- **Integration with Advanced Genomics:** Approaches including genomic selection, gene editing utilizing CRISPR-Cas and targeted mutagenesis can be merged with speed breeding for rapid and accurate trait integration [66]. High-throughput genotyping keeps pace with rapid breeding cycles [4].

- **Next-Generation Phenotyping:** Emerging phenotyping breakthroughs including remote sensing, radiomics, robotics, machine learning and metabolomics allow high-resolution, non-invasive characterization of complex traits [62,74]. These can promote trait selection in fast breeding.

- **Sustainable Speed Breeding:** Approaches boosting sustainability include renewable energy systems, optimal growth medium recycling, and aeroponics lowering water usage, and merging speed breeding with organic practices [7]. Multi-location trials ensure adaption.

- **Global Consortiums and Networks:** Platforms that enable international collaboration and exchange of germplasm, protocols, data and technology can stimulate innovation and optimization of speed breeding [2,6]. These networks help distribute speed breeding widely.

- **Capacity Building and Training:** Efforts to enhance technical competence and infrastructure for speed breeding in developing countries through training programs and participative techniques can improve access and worldwide adoption [14,11]. This allows localized adaptability.

- **Broadening Crop Base:** Protocols designed for distinct cereals, legumes, vegetables, fruits and orphan crops might enhance the applicability of speed breeding for varied breeding aims and agro-ecologies [4].

- **Multidisciplinary Integration:** Insights from genetics, physiology, pathology, metabolomics, microbiome investigations and climate science can inform ongoing refining of speed breeding techniques and ensure genetic gain realization in target conditions [75,35].

- **Responsible Governance:** Regulatory frameworks and participatory techniques that appropriately manage the use of biotechnologies can guarantee wider access to the benefits of rapid breeding while ensuring rights [76]. Realizing these prospects demands persistent investments and multi-stakeholder engagement. Advancing speed breeding through integration of cutting-edge innovations, collaborative networks, capacity building, multidisciplinary research and responsible governance can enable this technique to meet its tremendous potential in sustainably accelerating crop improvement worldwide [77].

7. CONCLUSION

In conclusion, speed breeding represents a transformational approach that can accelerate crop improvement through optimized growth conditions to achieve rapid generation turnover. This technique has diverse applications for enhancing yield, abiotic stress resilience, disease resistance, nutritional quality, and climate adaptation in a range of crops. The key benefits include accelerated genetic gain, year-round breeding, precision introgression of traits, and integration with genomic innovations. However, aspects like infrastructure costs, protocol optimization needs, phenotyping challenges, and crucially, improving global access, require consideration. Continued research into genotype-by-environment interactions, impacts on genetic diversity, and sustainable speed breeding techniques will be important [6,35]. Platforms enabling international collaboration, capacity building and responsible governance can drive widespread adoption [2]. Integrating speed breeding with next-generation genomics tools, phenotyping technologies, multidisciplinary science and participatory approaches can enable unlocking its full potential sustainably [78,62]. In summary, speed breeding provides a versatile toolkit to accelerate crop improvement programs and address diverse agricultural challenges. Realizing its immense potential through collaborative efforts can contribute significantly to global food and nutritional security. This review highlights the principles, applications, opportunities, and responsible pathways for harnessing speed breeding to create resilience in a changing climate.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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