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REVIEW PAPER

Speed Breeding: A Unique Technology for Accelerated Varietal Development

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ABSTRACT

Speed breeding is a technique that accelerates the development of high-performing crop cultivars by reducing the time, space, and resources needed for selection and genetic advancement. This method allows plant breeders to efficiently produce superior crop types while streamlining processes to reduce costs and minimize revenue losses. By integrating traditional breeding methods with speed breeding, breeders can select elite genotypes with enhanced yields, nutritional qualities, and stress resilience. Effective selection methods such as SSD, SPD, and SPS contribute to quicker homozygosity and evaluation of crops. Although further research is needed to explore potential negative effects on plant development, speed breeding presents a resource-efficient approach to genotyping and phenotyping, adaptable to meet local needs.

HIGHLIGHTS

- Techniques for quick generation of breeding materials.
- Manipulation of temperature, photoperiod and growing environment enhances rapid generation.
- New varieties can be developed in the shortest possible time.

Keywords: Rapid plant advancement, Photoperiod, temperature, plant density adjustment

In recent years, "speed breeding" has emerged as a revolutionary plant breeding strategy aimed at enhancing the turnover of plant generations. This technique modifies growing environments to accelerate flowering and seed setting, facilitating rapid generation advancement during the pre-breeding phase of crop development. As a result, it conserves both breeding time and resources.

Photoperiod, light intensity, and temperature are regulated by speed breeding in controlled environments, enabling rapid generation turnover in plants. This approach overcomes the limitations of seasonal cycles and enhances traditional breeding efficiency, which is hampered by lengthy field selection processes and slow generational advancement in cereals and pulses. Typically, achieving an improved variety using conventional methods takes over ten years due to only two generational cycles per year. Effective management of segregating populations and stable genotypes requires phenotyping expertise alongside fast generation advancement.

Speed breeding techniques, including single seed descent, single pod descent, single plant selection, clonal selection, and marker-assisted selection, enhance breeding efficiency and resource utilization. The integration of genomic technologies is vital to this approach, facilitating advancements in precision agriculture through rapid genetic methods like genome editing and shorter breeding cycles. This review explores the scientific principles of speed

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breeding and its applications across various plant species.

NASA conducted experiments in the 1980s growing crops like potatoes, lettuce, soybeans, and wheat in constant light, revealing that light significantly affects biomass (Wheeler *et al.* 1996). In 2003, Dr. Eric von Wettberg and colleagues at the University of Queensland introduced "speed breeding", inspired by NASA's work on food production for space stations (Fig. 1). This methodology has since been studied by various research organizations, leading to advancements in crop breeding. On January 10, 2024, the International Rice Research Institute announced the launch of Speed Flower, the first rice speed breeding procedure (Table 1).

A Detailed Overview and Comparison for Conventional and Speed Breeding

There are numerous significant distinctions between speed breeding and conventional breeding, ranging from environmental management, resource utilisation, material output, and performance. Table 2 depicts the elements of speed breeding that highlight the differences compared with conventional breeding.

Flexible Speed Breeding (S.B.) Systems

Early SB activities centred on complete in vitro lifecycle turnover or in vivo-in vitro cycling (Varshney *et al.* 2021). However, fully in vivo systems have been employed the most frequently in improvement projects. Watson *et al.* (2018) presented three distinct speed breeding facilities based on resource availability.

Factors Affecting Speed Breeding

The strategy is based on altering photoperiod, light intensity, temperature, soil moisture, soil nutrition, and planting density. These strategies have been used to promote early flowering and seed germination, which reduces the time required for developing each breeding generation and facilitates the production of 3 to 9 breeding generations per year (Fig. 1).

Manipulation of photoperiods

According to Vince-Prue (1994), photoperiod is the period of time during which plants are exposed to controlled levels of light and darkness every day in order to induce rapid growth, development, flowering, and seed germination. Numerous crops have been successfully cultivated under sustained photosynthesis for speed breeding using light sources that emit photosynthetic active radiation (PAR) at wavelengths ranging from 400 to 700 nm and intensities extending between 360 to 650 mol/ m^2 /s (Ghosh *et al.* 2018; Watson *et al.* 2018).

When compared to genotypes grown under 12/12 hr light/dark conditions, Dubcovsky *et al.* (2006) discovered that a photoperiod of 22 hr light and 2 hour dark under PAR of 150-190 E m^2 s1 reduced the number of days to blooming by half. According to Samineni *et al.* (2019), early flowering of chickpea was produced by a photoperiod length of 12/12 hr light/dark using a standard 60 W incandescent lamp with an intensity of 870 lm. Groundnut flowers abnormally early, 25 to 27 days after germination, when exposed to continuous light (24 hr light) from a 450 W PAR lamp (O'Connor *et al.* 2013).

Manipulation of temperature

Changes in soil and air temperatures can have a number of consequences on plant growth rates, including a transition from the vegetative to reproductive phases (Hatfield & Prueger, 2015; McClung *et al.* 2016). According to Samineni *et al.*'s 2019 data, chickpea direct-sown immature seed grew best at 25. 1 °C with a 12/12 hr light/dark cycle. Cold temperature stress may assist as well to speed up the transition from vegetative to reproductive periods (Dubcovsky *et al.* 2006; Yan *et al.* 2004). Temperatures above 33°C promote male sterility in rice, sorghum, and soybean (Hatfield and Prueger, 2015; Wiebbecke *et al.* 2012), allowing blooming, seed germination, and maturity for rapid breeding.

Zheng *et al.* (2013) found that acquiring seeds from plants grown in embryo culture and heated to 20-22°C promotes germination in wheat and barley. Seedlings were shifted to a temperature regime of 25/22°C and a photoperiod of 16/8 hr light/dark to promote rapid plant growth and flowering. Solar/ battery powered air conditioning systems could be a useful, dependable, and long-lasting technology for indoor rapid breeding projects in impoverished countries.

Adjusting the soil's moisture content

Early flowering and maturity are triggered by soil moisture issues like as dryness and submergence, which can be used for speed breeding (Anjum *et al.* 2017; Hussain *et al.* 2018). According to Vadez et al. (2012), dryness causes pearl millet to flower early in order to promote subsequent generation through a "escape mechanism to achieve 8 and 9 generations per year in wheat and barley, respectively, watering regimes were combined with embryo rescue by photoperiod and temperature modifications (Zheng *et al.* 2013). It has been employed in fast breeding of numerous crops, including wheat, barley, canola, and gram, to reduce watering frequency from daily to twice per week beginning one month after flowering, with no watering in the final week before harvest.

Modifying the plant population density

Tall plants that quickly progress from the vegetative to the reproductive growth stages are produced by high-density planting because there is less competition, which increases the number of generation cycles annually and yields (Warnasooriya and Brutnell, 2014). Rahman *et al.* 2019 observed that high-density planting of 400 plants/m^2 (with intra-row spacing of 5 cm and inter-row spacing of 5 cm [5 × 5 cm]) encouraged four generations per year and shortened the time of a crop cycle by 15 to 40 days in contrast to the typical 25 plants m^{-2} (20 × 20 cm). Similar to sorghum, genetic differences influence how plants react to high-density planting in the field. While Jones and Johnson (1991) revealed that plant density of four to eight plants/m^2 had no discernible effects on plant growth and grain yield, Villar *et al.* (1989) noted that increasing plant density from 16 to 38 plant/ m^2 shortened the days to blooming from 59 to 50 days. High planting density is one of the low-cost, quick generation advancement strategies for maintaining a substantial population size for advanced selections.

Varying the carbon dioxide concentrations

The way that various crop species respond to increasing CO_2 levels varies. A 2016 study by Jagadish *et al.* (2016) suggested that increased CO_2 concentrations might speed up some plants' transition from the vegetative to the reproductive stage. At higher CO_2 levels of 400/700, 350/700, and 350/650/100 ppm, the days to blooming in cowpea, rice, and soybean were shortened by 2, 7, and 12 days, respectively (Springer and Ward, 2007).

Yet, Bunce *et al.* (2015) discovered that when CO_2 was kept at 20 mol/mol^2, soybean flowering behaviour was delayed by 11 days. The soybean (cv "Enrei") crop cycle was shortened in growth chambers by up to 62 days by combining a 14-hour light (30°C)/10-hour dark (25°C) cycle with > 400 ppm CO_2 supplementation. This also encouraged three more generations to be produced annually in the field or a greenhouse while increasing the number of blooms which led to a large number of crosses (Nagatoshi and Fujita, 2019). Tanaka *et al.* (2016) found that increased CO_2 (600 ppm) in growth chamber conditions reduced the number of days to heading in the rice cultivars Yamadawa and Nipponbare from 80 to 88 days to 48 to 49 days and 70 to 74 days, respectively. The proper facilities and safety measures must be followed when handling and using CO_2 cylinders and valves in order to adjust CO_2 levels.

Modification of hormones and nutrients in vegetation

Plant hormones and nutrients play a crucial role in promoting seed set, flowering, and in vitro germination, as noted by Bermejo *et al.* (2016). To enhance in vitro flowering and seed setting in faba bean, Mobini *et al.* (2015) found that auxin and cytokinin, combined with flurprimidol, indole-3-acetic acid, and zeatin, are effective. To reduce the generation cycle of faba beans and lentils from 102 and 107 days to 54 and 45 days respectively, Mobini and Warkentin (2016) applied temperature adjustments and plant growth regulators, achieving 80–90% flowering and seed set. Additionally, Yao *et al.* (2016) reported that raising wheat embryos on a modified MS medium led to high flowering rates of 100% and 92% in the cultivars "Emu Rock" and "Zippy."

Early harvested wheat seed dormancy can be broken by dehydrator treatment at 22°C for three days, followed by 4°C chilling to enhance germination. Implementing long photoperiods (22/2 hr light/ dark) and temperature regulation (22/17°C light/ dark) allows for 4-6 generation cycles annually for wheat, barley, chickpea, pea, and canola (Watson *et al.* 2018). Additionally, using immature seeds with optimal hormonal, nutritional, and environmental conditions is essential for rapid generational advancement.

Potential Applications of Speed Breeding Techniques in Agricultural Crops

SB can be used to address double haploid (DH) technology challenges, such as low vigour and germination rates (Ferrie *et al.* 2007). Recombinant inbred lines (RILs), resulting from self-fertilization across generations, may be preferable for genetic mapping due to enhanced recombination. Conversely, SSD offers a more cost-effective and efficient approach to creating segregating generations under SB conditions compared to traditional pedigree breeding. This method reduces generation time significantly and yields three times more generations in rice than shuttle breeding (Sinha *et al.* 2021).

Accelerated homozygous line development

Speed breeding techniques are effectively combined with conventional hybridization to accelerate the development of homozygous lines in various crops. This integration optimizes factors such as planting density, photoperiod, light intensity, temperature, soil moisture, and nutrition, significantly reducing the time needed for breeding generations. According to El-Hashash and El-Absy (2019), this method can yield 3 to 9 breeding generations per year through techniques like single seed descent (SSD), single pod descent (SPD), and single plant selection (SPS), making it suitable for rapid breeding and population assessment in targeted ecosystems.

Adaptability to selection criteria

Speed breeding emphasizes quick generation turnover without focusing on phenotypic selection. To improve breeding efficiency, it's essential to maintain a breeding population that optimizes output while minimizing plant growth. Effective strategies include single plant selection (SPS), single pod descent (SPD), and single seed descent (SSD). SSD, which aims to develop homozygous populations through continuous inbreeding, is applied under high-density conditions in controlled environments. It has been effective in conjunction with Rapid Generation Technology (RGT) for creating notable cultivars like 'Nipponbare'(Tanaka *et al.* 2016). Studies show minimal yield differences among inbred lines from the same parent genotypes using doubled-haploid (DH) and SSD techniques, supporting SSD as a viable method for speed breeding (Bordes *et al.* 2007).

Combination with Technologies for High-Throughput Genotyping

Cost-Effective Genotyping*:* High-throughput technologies are more cost-effective because of the automation and parallelisation of genotyping operations. This efficiency is especially helpful for speed breeding projects, as they produce plenty of plants that need to be genotyped quickly (Jighly *et al.* 2019).

Genome-Wide Association Studies (GWAS) and Marker-Assisted Selection (MAS)

High-throughput genotyping significantly enhances genome-wide association studies by identifying connections between specific behaviours and genetic markers. This advancement aids in developing accurate prediction models for genomic selection and streamlines marker-assisted selection, which utilizes specific DNA markers to inform breeding decisions. By focusing on individuals possessing the desired genetic profiles, this targeted approach accelerates the breeding process.

Using SB with the Available Tools for Phenotyping and Genome Editing

In the twenty-first century, advances in genomics and genetic marker technology have revolutionized agricultural breeding methods. Recent discoveries reveal that site-specific nuclease-based genome editing can produce enhanced plant varieties for improved agriculture. By integrating selection breeding (SB) into genome editing, researchers can boost homozygosity and accelerate genetic gains, as modified plants mature into new seeds more rapidly. As this technology spreads to other species, the CRISPR/Cas9 system paired with SB is expected to become increasingly prevalent. The first generation (T1) can be utilized for selecting desirable edited lines, while the second generation (T2) serves to thoroughly evaluate and eliminate off-target genotypes. This approach has been effectively applied in crops such as *Brassica napus, B. oleracea*, and soybean (Bao *et al.* 2020).

MAS/MABC and other genomic tools

The use of SB in marker-assisted selection (MAS) and marker-assisted back-crossing (MABC) facilitates the incorporation of beneficial genes into crops, reducing biotic and abiotic stresses (Varshney *et al.* 2021). For instance, the Pi21 gene, known for its resistance to rice blast, has been integrated into multiple rice cultivars (Angeles-Shim *et al.* 2020) DNA markers help avoid unwanted alleles through linkage dragging, and while backcrossing can be slow, SB speeds up the transfer of desirable traits. SB has also been employed to evaluate plant breeding strategies, such as genomic selection (GS), particularly in spring wheat, where it assisted in identifying candidates and traits, achieving prediction accuracies for traits like plant height and flowering time similar to direct field selection under specific SB conditions Voss-Fels *et al.* (2018).

Speed breeding (SB) accelerates genetic gain predictions beyond traditional phenotyping (Watson *et al.* 2019) by employing advanced multi-trait methods to assess wheat's resistance to leaf rust and crown root issues. It promotes early generation selection, enhancing the integration of desirable traits into breeding populations (Croser *et al.* 2021), and increases operational efficiency in creating resistant wheat varieties. SB also enables rapid development of new mapping populations from multi-parental sources, underlining its value in modern breeding practices (Kitony *et al.* 2021). Speed breeding's possible applications are illustrated in Fig. 2.

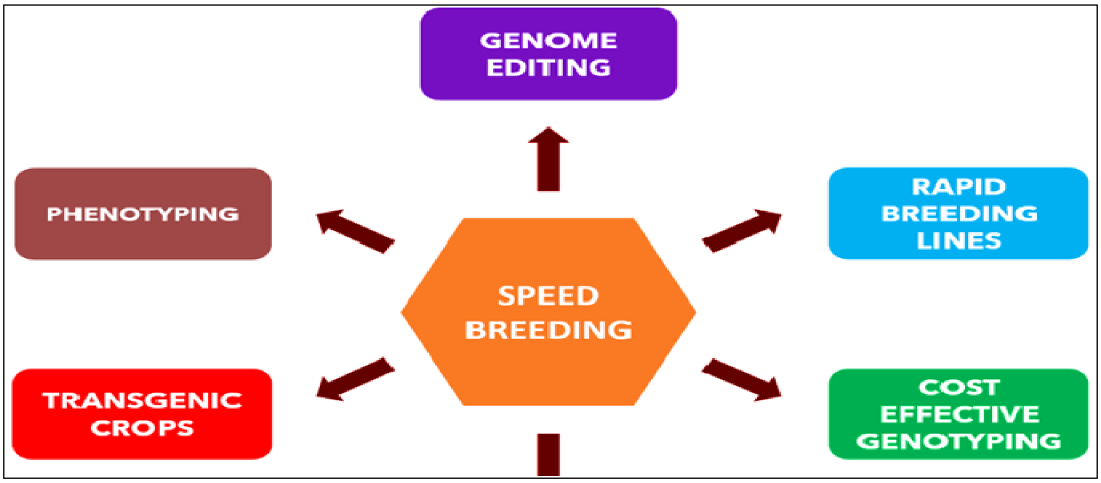

Fig. 1: A comparative chronology of speed breeding and conventional plant breeding

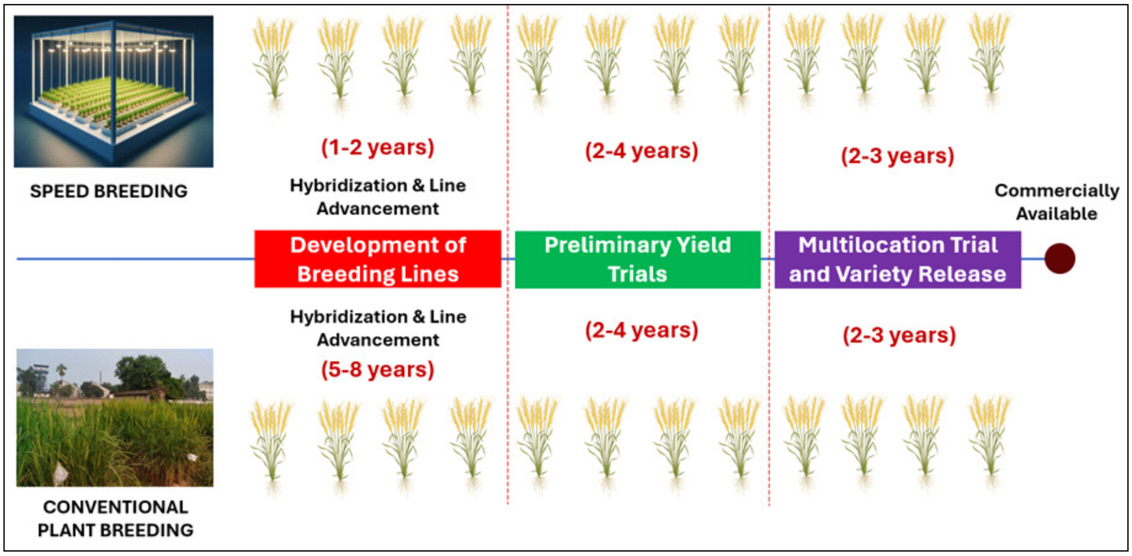

Fig. 2: Possible applications of Speed Breeding in crop improvement

Table 1: A brief timeline, depicting some important achievements in Speed Breeding

Year	**Crops**	**Institute Involved**	**Achievement**	**Reference**
1980s	Potato, lettuce, soybean, and wheat	National Aeronautics and Space Administration (NASA)	Light exposure significantly affects plant biomass.	Bugbee and Koerner, 1997
2013	Groundnut	Queensland Dept. of Agriculture, Fisheries and Forestry	Outlined a speed breeding method for reducing the generation time of full-season maturity groundnut cultivars.	O'Connor *et al.*, 2013
2018	Wheat	University of Sydney	Application of speed breeding to various crop species for enhanced productivity	Alahmad and associates, 2018
2018	Wheat, Barley, Chickpea and Pea	John Innes Centre	Optimization of growth conditions for speed breeding in controlled environments	Watson and colleagues, 2018
2020	Soybean, Rice and Amaranth	State Plant Breeding Institute, University of Hohenheim, Germany	Development of a technique to adjust the photoperiod to 10 hours and modifies the light intensity and quality for the short-day crops	Jähne *et al.*, 2020
2021	Rice	International Rice Research Institute at IRRI South Asia's Regional Centre (ISARC) in Varanasi	Development of speed breeding unit for growing rice plants under controlled environment to facilitate fertigation called "SpeedBreed"	IRRI, 2021
2022	Hot Pepper	South China Agricultural University and Hunan Xiangyan Seed Industry	Development of a speed breeding programme for hot peppers by altering the light environment.	Liu *et al.* 2022

Table 2: Comparison between conventional and accelerated breeding

Aspect	**Speed Breeding**	**Conventional Breeding**
Time Frame	Shortened growth cycles, allowing multiple generations in a single year.	Typically longer growth cycles, with one or two generations per year.
Environmental Control	Highly controlled environments, often using artificial lighting and optimal temperature conditions.	Dependent on natural environmental conditions, which may lead to longer breeding cycles.
Resource Efficiency	Requires more controlled environments, energy, and resources to maintain optimal conditions.	Generally, uses natural resources and relies on outdoor conditions, which may be less resource-intensive.
Precision	Offers precise control over environmental factors, facilitating more predictable outcomes.	Relies on natural processes, which may introduce more variability in outcomes.
Risk of Contamination	Environments under control may lessen the chance of cross-contamination.	Cross-contamination may be prevalent in open-field situations.
Nutrient Control	Allows precise control over nutrient availability, optimizing for plant growth.	Nutrient availability is subject to natural soil conditions, potentially requiring additional supplementation.
Plant Hardiness	May result in plants that are adapted to specific controlled conditions, potentially less hardy in diverse environments.	Plants may exhibit greater adaptability and hardiness as they are exposed to varying environmental conditions.
Performance at F_6 generation	Rapid breeding may allow for quicker identification of desired traits; however, potential concerns about stability and adaptability to diverse environments.	Generally, traits may take longer to identify and stabilize, but resulting plants may exhibit greater adaptability and stability in diverse conditions.

Significant achievements and the establishment of the SB protocol in important crops

Rice

Significant advancements in rice breeding have been achieved through the Rapid Generation Advancement (RGA) and the recently developed Speed-Flowering protocol (Collard *et al.* 2017). At IRRI, RGA was successfully implemented, showing improved phenotypic traits such as flowering time and yield. The Speed-Flower protocol, created in 2023 by Kabade *et al.* enhances breeding efficiency by enabling the development of four to five rice generations annually under optimized light, photoperiod, and temperature conditions, demonstrating the potential to accelerate rice cultivar production.

Wheat

In 2022, Schoen *et al.* improved a speed breeding method for winter wheat, finding that a 22-hour photoperiod at 25°C/22°C could reduce generation time by four generations, expediting seed breeding. Concurrently, Riaz *et al.*'s 2016 method for phenotyping adult plant resistance to leaf rust, tested on 21 spring wheat genotypes, showed a strong correlation ($R^2 = 0.77$) with field results. This efficient approach requires less time, area, and labour while enabling the early selection of desirable gene combinations, thus facilitating the incorporation of adult plant resistance genes into breeding programs.

Pulses and Oilseeds

In 2020, Samineni *et al.* introduced a method to extend photoperiods for chickpea, facilitating the achievement of seven generations of early-maturing accessions each year. Similarly, Mobini *et al.* (2015) highlighted that plant growth regulators could accelerate generation advancement in lentils and faba beans, effectively doubling their annual output. Furthermore, Cazolla *et al.* (2020) evaluated rapid generation technologies for pea breeding, determining that a controlled in vivo hydroponic system enabled cultivation of up to five generations per year, optimizing cost-effectiveness and breeding efficiency by lowering labour and land costs.

Case Study: IRRI SpeedBreed

In December 2021, the IRRI South Asia Regional Centre (ISARC) opened the IRRI SpeedBreed facility in Varanasi to tackle long generation times in rice breeding. This facility includes controlled growth chambers that optimize temperature, humidity, CO_2 levels, and light to speed up vegetative development

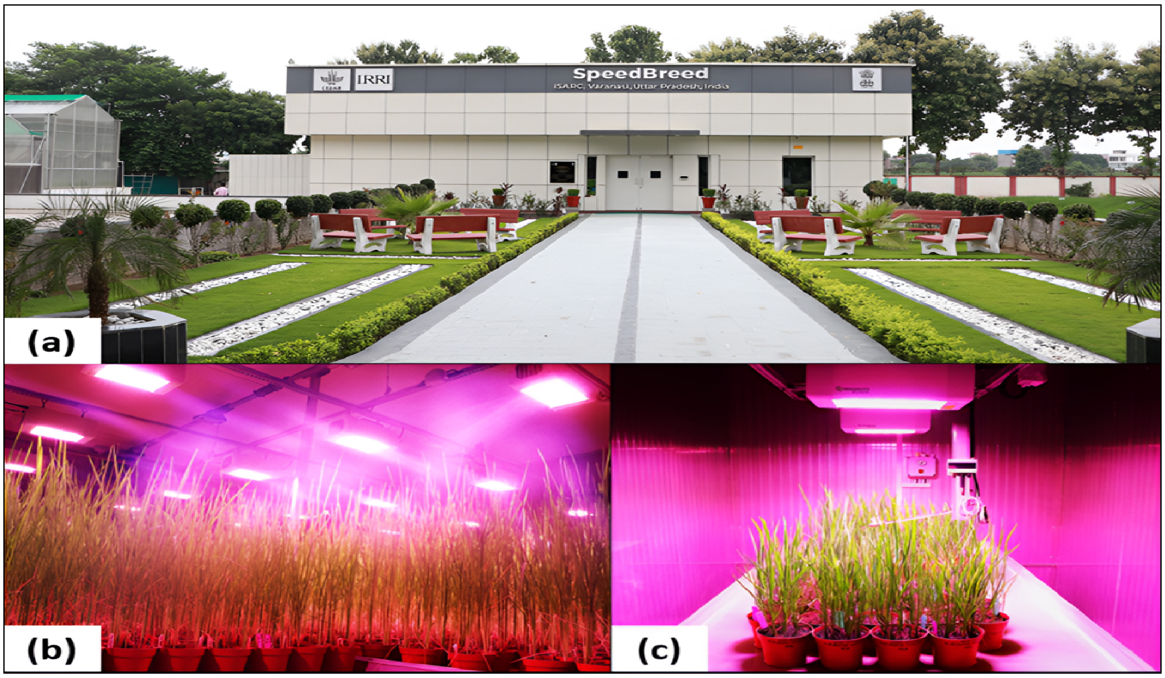

Fig. 3: (a) SpeedBreed setup at IRRI, ISARC, Varanasi **(b)** Multiplication Chamber **(c)** Optimization Chamber
Image Source: *IRRI.* https://www.irri.org/news-and-events/news/speedbreed-crop-breeding-center-built-speed

and grain maturity. It aims to produce four to five generations of rice annually, with plans to also cultivate other crops like wheat and chickpeas, targeting six generations per year. The setup allows simultaneous advancement of over 39,000 rice plants and may enhance protocols with additional chambers and media preparation areas.

Speed Breeding: Constraints and Restrictions

Speed breeding strategies can significantly accelerate traditional breeding processes. To effectively utilize this technology, expertise, efficient phenomics facilities, proper infrastructure, and continuous funding for research are essential (Shimelis *et al.* 2019). Yet, the main barriers to implementing rapid breeding include insufficient facilities, inadequate training for workers, the need for substantial changes in breeding program operations, and a lack of long-term financial support.

Absence of environmentally regulated circumstances

Maintaining key environmental factors in indoor growth facilities hinges on stable electricity and water supplies. Reliable energy is crucial for lighting and heating, with nearly half of plant management costs in Queensland related to winter temperature regulation. Public breeding initiatives struggle with unstable electrical sources, impacting temperature and photoperiod management. Additionally, fertilization and irrigation practices, essential for agricultural preparation, incur significant infrastructure costs.

Significant Losses

Severe growing conditions can cause genotypic variations in species after SB establishment, leading to low seed yields that obstruct field evaluations. Extended photoperiods may increase starch production and stress hormones, negatively affecting plant growth. Harvesting immature seeds complicates seed trait assessments. Pushing plant growth beyond physiological limits to speed results can weaken their stress defences and result in significant losses of valuable breeding materials if not managed properly.

Inadequately Qualified Personnel

A significant challenge for public sector speed breeding initiatives in developing countries is the shortage of qualified plant breeders and technicians (Morris *et al.* 2006). This issue is exacerbated by high turnover rates as workers migrate to private seed companies offering better pay and benefits. Furthermore, the lack of postgraduate programs in plant breeding limits the number of researchers in this field. In addition, ineffective legislative frameworks in some countries hinder the management of plant breeders' rights and seed regulations (Tripp *et al.* 2007), ultimately disrupting the value chain from farmers to consumers.

Improper Infrastructure

Speed breeding platforms require complex infrastructure to manage environmental factors like soil moisture, temperature, and photoperiod. In many impoverished countries, public plant breeding efforts lack sufficient institutional support, hindering the adoption of modern techniques such as speed breeding and biotechnology. The tools available for early generation trait selection are also limited. Furthermore, dependence on donor organizations and poorly coordinated regional breeding programs result in duplicated efforts and inefficient resource use.

Plant Hardiness and Adaptability after F5 or F6

Speed Breeding may result in plants after F5 or F6 that are adapted to specific controlled conditions, potentially less hardy in diverse environments, as field level selection for stability and adaptability is not possible in each segregating generation.

CONCLUSION

Speed breeding accelerates the creation of high-performing crop varieties by reducing the time, space, and resources needed for genetic selection. This approach allows for the efficient production of superior crops while minimizing costs and maximizing facility usage. By blending traditional breeding with speed breeding, it identifies elite genotypes with improved yield, nutritional value, and resilience to stress. Key selection methods include SSD, SPD, and SPS, and the method also enhances breeding cycles via environmental adjustments, promoting faster homozygosity and transgenic crop assessment. Although more research is necessary to understand potential negative effects on plant growth, speed breeding serves as a resource-efficient strategy for crop evaluation tailored to local needs.

REFERENCES

Alahmad, S., Dinglasan, E., Leung, K.M. *et al.* 2018. Speed breeding for multiple quantitative traits in durum wheat. *Plant Methods*, **14**: 36.

Angeles-Shim, R.B., Reyes, V.P., del Valle, M.M., Lapis, R.S., Shim, J., Sunohara, H., Jena, K.K., Ashikari, M. and Doi, K. 2020. Marker assisted introgression of quantitative resistance gene pi21 confers broad spectrum resistance to rice blast. *Rice Science*, **27**: 113–123.

Anjum, S.A., Ashraf, U., Zohaib, A., Tanveer, M., Naeem, M., Ali, I., Tabassum, T. and Nazir, U. 2017. Growth and developmental responses of crop plants under drought stress: A review. *Zemdirbyste-Agriculture*, **104**(3): 267–276.

Arbelaez, J.D., Tandayu, E., Reveche, M.Y., Jarana, A., van Rogen, P., Sandager, L., Stolt, P., Ng, E., Varshney, R. K., Kretzschmar, T. and Cobb, J. 2019. Methodology: Ssb-MASS: A single seed-based sampling strategy for marker-assisted selection in rice. *Plant Methods*, **15**(1): 78.

Bao, A., Zhang, C., Huang, Y., Chen, H., Zhou, X. and Cao, D. 2020. Genome editing technology and application in soybean improvement. *Oil Crop Science*, **5**: 31–40.

Bermejo, C., Gatti, I. and Cointry, E. 2016. *In vitro* embryo culture to shorten the breeding cycle in lentil (*Lens culinaris* Medik). *Plant Cell, Tissue and Organ Culture*, **127**(3): 585–590.

Bordes, J., Charmet, G., Vaulx, R.D., Lapierre, A., Pollacsek, M., Beckert, M. and Gallais, A. 2007. Doubled-haploid versus single-seed descent and S1-family variation for testcross performance in a maize population. *Euphytica*, **154**: 41–51.

Bunce, J.A. 2015. Elevated carbon dioxide effects on reproductive phenology and seed yield among soybean cultivars. *Crop Science*, **55**(1): 339–343.

Byerlee, D. and Fischer, K. 2002. Accessing modern science: Policy and institutional options for agricultural biotechnology in developing countries. *World Development*, **30**(6): 931–948.

Choi, H., Back, S., Kim, G.W., Lee, K., Venkatesh, J., Lee, H.B., Kwon, J.K. and Kang, B.C. 2023. Development of a speed breeding protocol with flowering gene investigation in pepper (*Capsicum annuum*). *Frontiers in Plant Science*, **14**: 1151765.

Collard, B.C.Y., Beredo, J.C., Lenaerts, B., Mendoza, R., Santelices, R., Lopena, V., Verdeprado, H. *et al.* 2017. Revisiting rice breeding methods–evaluating the use of rapid generation advance (RGA) for routine rice breeding. *Plant Production Science*, **20**(4): 337–352.

Croser, J., Mao, D., Dron, N., Michelmore, S., McMurray, L., Preston, C., Bruce, D., Ogbonnaya, F.C., Ribalta, F.M., Hayes, J. *et al.* 2021. Evidence for the application of emerging technologies to accelerate crop improvement—A collaborative pipeline to introgress herbicide tolerance into chickpea. *Frontiers in Plant Science*, **12**: 779122.

Dadu, R.H.R., Bar, I., Ford, R., Sambasivam, P., Croser, J., Ribalta, F., Kaur, S., Sudheesh, S. and Gupta, D. 2021. Lens orientalis contributes quantitative trait loci and candidate genes associated with ascochyta blight resistance in lentil. *Frontiers in Plant Science*, **12**: 703283.

Dubcovsky, J., Loukoianov, A., Fu, D., Valarik, M., Sanchez, A. and Yan, L. 2006. Effect of photoperiod on the regulation of wheat vernalization genes VRN1 and VRN2. *Plant Molecular Biology*, **60**(4): 469–480.

El-Hashash, E.F. and El-Absy, K.M. 2019. Barley (*Hordeum vulgare* L.) breeding. *In* J. Al-Khayri, S. Jain and D.V. Johnson (Eds.), Advances in Plant Breeding Strategies: Cereals (pp. 1–45). Springer International Publishing. https://doi.org/10.1007/978-3-030-23108-8_1

Ferrie, A.M.R. 2007. Doubled haploid production in nutraceutical species: A review. *Euphytica*, **158**: 347–357.

Funada, M., Helms, T.C., Hammond, J.J., Hossain, K. and Doetkott, C. 2013. Single-seed descent, single-pod, and bulk sampling methods for soybean. *Euphytica*, **192**(2): 217–226.

Ghosh, S., Watson, A., Gonzalez-Navarro, O.E., Ramirez-Gonzalez, R.H., Yanes, L., Mendoza-Suárez, M., Simmonds, J. *et al.* 2018. Speed breeding in growth chambers and glasshouses for crop breeding and model plant research. *Nature Protocols*, **13**(12): 2944–2963.

Gudi, S., Kumar, P., Singh, S., Tanin, M.J. and Sharma, A. 2022. Strategies for accelerating genetic gains in crop plants: Special focus on speed breeding. *Physiology and Molecular Biology of Plants*, **28**(10): 1921–1938.

Hatfield, J.L. and Prueger, J.H. 2015. Temperature extremes: Effect on plant growth and development. *Weather and Climate Extremes*, **10**: 4–10.

Hussain, H.A., Hussain, S., Khaliq, A., Ashraf, U., Anjum, S.A., Men, S. and Wang, L. 2018. Chilling and drought stresses in crop plants: Implications, cross talk, and potential management opportunities. *Frontiers in Plant Science*, **9**: 393.

IRRI. 2022. SpeedBreed: A crop breeding center built for speed. International Rice Research Institute. https://www.irri.org/news-and-events/news/speedbreed-crop-breeding-center-built-speed

Jagadish, S.V.K., Bahuguna, R.N., Djanaguiraman, M., Gamuyao, R., Prasad, P.V.V. and Craufurd, P.Q. 2016. Implications of high temperature and elevated CO_2 on flowering time in plants. *Frontiers in Plant Science*, **7**: 913.

Johnston, H.R., Keats, B.J.B. and Sherman, S.L. 2019. Population genetics. *In* R.E. Pyeritz, B.R. Korf and W.W. Grody (Eds.), Emery and Rimoin's Principles and Practice of Medical Genetics and Genomics (Foundations, pp. 359–373). Academic Press. https://doi.org/10.1016/B978-0-12-812537-3.00012-3

Jones, O.R. and Johnson, G.L. 1991. Row width and plant density effects on Texas high plains sorghum. *Journal of Production Agriculture*, **4**(4): 613–621.

Kabade, P.G., Dixit, S., Singh, U.M., Alam, S., Bhosale, S., Kumar, S., Singh, S.K. *et al.* 2024. SpeedFlower: A comprehensive speed breeding protocol for indica and japonica rice. *Plant Biotechnology Journal*, **22**(5): 1051–1066.

Khoo, K.H.P., Sheedy, J.G., Taylor, J.D., Croser, J.S., Hayes, J.E., Sutton, T., Thompson, J.P. and Mather, D.E. 2021. A QTL on the Ca7 chromosome of chickpea affects resistance to the root-lesion nematode *Pratylenchus thornei*. *Molecular Breeding*, **41**: 78.

Kitony, J.K., Sunohara, H., Tasaki, M., Mori, J.-I., Shimazu, A., Reyes, V. and Yasui, H. *et al.* 2021. Development of an Aus-derived nested association mapping (Aus-NAM) population in rice. *Plants*, **10**: 1255.

McClung, C.R., Lou, P., Hermand, V. and Kim, J.A. 2016. The importance of ambient temperature to growth and the induction of flowering. *Frontiers in Plant Science*, **7**: 1266.

Mobini, S.H., Lulsdorf, M., Warkentin, T.D. and Vandenberg, A. 2015. Plant growth regulators improve *in vitro* flowering and rapid generation advancement in lentil and faba bean. *In Vitro Cellular and Developmental Biology - Plant*, **51**(1): 71–79.

Mobini, S.H. and Warkentin, T.D. 2016. A simple and efficient method of in vivo rapid generation technology in pea (*Pisum sativum* L.). *In Vitro Cellular and Developmental Biology - Plant*, **52**(5): 530–536.

Morris, M., Edmeades, G. and Pehu, E. 2006. The global need for plant breeding capacity: What roles for the public and private sectors? *HortScience*, **41**(1): 30–39.

Nagatoshi, Y. and Fujita, Y. 2019. Accelerating soybean breeding in a CO_2-supplemented growth chamber. *Plant and Cell Physiology*, **60**(1): 77–84.

O'Connor, D.J., Wright, G.C., Dieters, M.J., George, D.L., Hunter, M.N., Tatnell, J.R. and Fleischfresser, D.B. 2013. Development and application of speed breeding technologies in a commercial peanut breeding program. *Peanut Science*, **40**(2): 107–114.

Phyu, P., Islam, M.R., Cruz, P.C.S., Collard, B.C.Y. and Kato, Y. 2020. Use of NDVI for indirect selection of high yield in tropical rice breeding. *Euphytica*, **216**: 74.

Rahman, M.A., Quddus, M.R., Jahan, N., Rahman, A., Hossain, M.R.A.S. and Iftekharuddaula, K.M. 2019. Field rapid generation advance: An effective technique for industrial scale rice breeding program. *The Experiment*, **47**(2): 2659–2670.

Rana, M.M., Takamatsu, T., Baslam, M., Kaneko, K., Itoh, K., Harada, N., Sugiyama, T., Ohnishi, T., Kinoshita, T., Takagi, H. *et al.* 2019. Salt tolerance improvement in rice through efficient SNP marker-assisted selection coupled with speed-breeding. *International Journal of Molecular Sciences*, **20**: 2585.

Riaz, A., Periyannan, S., Aitken, E. and Hickey, L. 2016. A rapid phenotyping method for adult plant resistance to leaf rust in wheat. *Plant Methods*, **12**: 1–10.

Ribaut, J.-M., de Vicente, M.-C. and Delannay, X. 2010. Molecular breeding in developing countries: Challenges and perspectives. *Current Opinion in Plant Biology*, **13**(2): 213–218.

Ribalta, F.M., Pazos-Navarro, M., Nelson, K., Edwards, K., Ross, J.J., Bennett, R., Munday, C., Erskine, W., Ochatt, S.J. and Croser, J. 2017. Precocious floral initiation and identification of exact timing of embryo physiological maturity facilitate germination of immature seeds to truncate the lifecycle of pea. *Plant Growth Regulation*, **81**: 345–353.

Samantara, K., Bohra, A., Mohapatra, S.R., Prihatini, R., Asibe, F., Singh, L., Reyes, V.P., Tiwari, A., Maurya, A.K., Croser, J.S. *et al.* 2022. Breeding more crops in less time: A perspective on speed breeding. *Biology*, **11**: 275.

Samineni, S., Sen, M., Sajja, S.B. and Gaur, P.M. 2019. Rapid generation advance (RGA) in chickpea to produce up to seven generations per year and enable speed breeding. *Crop Journal*, **8**(1): 164–169.

Samineni, S., Sen, M., Sajja, S.B. and Gaur, P.M. 2020. Rapid generation advance (RGA) in chickpea to produce up to seven generations per year and enable speed breeding. *The Crop Journal*, **8**(1): 164–169.

Schoen, A., Wallace, S., Holbert, M.F., Brown-Guidera, G., Harrison, S., Murphy, P., Sanantonio, N. *et al.* 2023. Reducing the generation time in winter wheat cultivars using speed breeding. *Crop Science*, **63**(4): 2079–2090.

Shimelis, H. and Laing, M. 2012. Timelines in conventional crop improvement: Pre-breeding and breeding procedures. *Australian Journal of Crop Science*, **6**(11): 1542–1549.

Sinha, P., Singh, V.K., Bohra, A., Kumar, A., Reif, J.C. and Varshney, R.K. 2021. Genomics and breeding innovations for enhancing genetic gain for climate resilience and nutrition traits. *Theoretical and Applied Genetics*, **134**: 1829–1843.

Springer, C.J. and Ward, J.K. 2007. Flowering time and elevated atmospheric CO_2. *New Phytologist*, **176**(2): 243–255.

Tanaka, J., Hayashi, T. and Iwata, H. 2016. A practical, rapid generation advancement system for rice breeding using simplified Biotron breeding system. *Breeding Science*, **66**(4): 542–551.

Taylor, C.M., Garg, G., Berger, J.D., Ribalta, F.M., Croser, J.S., Singh, K.B., Cowling, W.A., Kamphuis, L.G. and Nelson, M.N. 2021. A trimethylguanosine synthase1-like (TGS1) homologue is implicated in vernalisation and flowering time control. *Theoretical and Applied Genetics*, **134**: 3411–3426.

Tripp, R., Louwaars, N. and Eaton, D. 2007. Plant variety protection in developing countries: A report from the field. *Food Policy*, **32**(3): 354–371.

Varshney, R.K., Bohra, A., Yu, J., Graner, A., Zhang, Q. and Sorrells, M.E. 2021. Designing future crops: Genomics-assisted breeding comes of age. *Trends in Plant Science*, **26**: 631–649.

Vadez, V., Hash, T., Bidinger, F.R. and Kholova, J. 2012. Phenotyping pearl millet for adaptation to drought. *Frontiers in Physiology*, **3**: 386.

Villar, J.L., Maranville, J.W. and Gardner, J.C. 1989. High density sorghum production for late planting in the central Great Plains. *Journal of Production Agriculture*, **2**(4): 333–338.

Vince-Prue, D. 1994. The duration of light and photoperiodic responses. *In* R.E. Kendrick & G.H.M. Kronenberg (Eds.), Photo morphogenesis in Plants (1st ed., pp. 281–311). Dordrecht: Springer. https://doi.org/10.1007/978-94-011-1884-2_17

Voss-Fels, K.P., Herzog, E., Dreisigacker, S., Sukurmaran, S., Watson, A., Frisch, M., Hayes, B.J. and Hickey, L.T. 2018. Speed GS to accelerate genetic gain in spring wheat. *In* T. Miedaner & V. Korzun (Eds.), *Applications of Genetic and Genomic Research in Cereals* (1st ed.). Cambridge, MA: Woodhead Publishing. https://doi.org/10.1016/B978-0-08-102163-7.00014-4

Wanga, M.A., Shimelis, H., Mashilo, J. and Laing, M.D. 2021. Opportunities and challenges of speed breeding: A review. *Plant Breeding*, **140**: 185–194.

Watson, A., Ghosh, S., Williams, M.J., Cuddy, W.S., Simmonds, *et al.* 2018. Speed breeding is a powerful tool to accelerate crop research and breeding. *Nature Plants*, **4**(1): 23–29.

Watson, A., Hickey, L.T., Christopher, J., Rutkoski, J., Poland, J. and Hayes, B.J. 2019. Multivariate genomic selection and potential of rapid indirect selection with speed breeding in spring wheat. *Crop Science*, **59**: 1945–1959.

Jähne, F., Hahn, V., Würschum, T. *et al.* 2020. Speed breeding short-day crops by LED-controlled light schemes. *Theoretical and Applied Genetics*, **133**(11): 2335–2342.

Jighly, A., Lin, Z., Pembleton, L.W., Cogan, N.O.I., Spangenberg, G.C., Hayes, B.J. and Daetwyler, H.D. 2019. Boosting genetic gain in allogamous crops via speed breeding and genomic selection. *Frontiers in Plant Science*, **10**: 1364.

Liu, K., He, R., He, X., Tan, J., Chen, Y., Li, Y. *et al*. 2022. Speed breeding scheme of hot pepper through light environment modification. *Sustainability*, **14**(19): 12225.

Warnasooriya, S.N. and Brutnell, T.P. 2014. Enhancing the productivity of grasses under high-density planting by engineering light responses: From model systems to feedstocks. *Journal of Experimental Botany*, **65**(11): 2825–2834.

Wheeler, R., Mackowiak, C., Stutte, G., Sager, J., Yorio, N., Ruffe, L. *et al.* 1996. NASA's biomass production chamber: A testbed for bioregenerative life support studies. *Advances in Space Research*, **18**(4–5): 215–224.

Wiebbecke, C.E., Graham, M.A., Cianzio, S.R. and Palmer, R.G. 2012. Day temperature influences the male-sterile locus ms9 in soybean. *Crop Science*, **52**(4): 1503–1510.

Yan, L., Loukoianov, A., Blechl, A., Tranquilli, G., Ramakrishna, W., SanMiguel, P., Bennetzen, J.L., Echenique, V. and Dubcovsky, J. 2004. The wheat VRN2 gene is a flowering repressor downregulated by vernalization. *Science*, **303**(5664): 1640–1644.

Yao, Y., Zhang, P., Liu, H., Lu, Z. and Yan, G. 2016. A fully in vitro protocol towards large scale production of recombinant inbred lines in wheat (*Triticum aestivum* L.). *Plant Cell, Tissue and Organ Culture*, **128**: 655–661.

Zaman, S.U., Malik, A.I., Kaur, P., Ribalta, F.M. and Erskine, W. 2019. Waterlogging tolerance at germination in field pea: Variability, genetic control, and indirect selection. *Frontiers in Plant Science*, **10**: 95.

Zheng, Z., Wang, H.B., Chen, G.D., Yan, G.J. and Liu, C.J. 2013. A procedure allowing up to eight generations of wheat and nine generations of barley per annum. *Euphytica*, **191**(2): 311–316.