Speed Breeding: Accelerated Crop Improvement

G. Eswara Reddy, K. Sadaiah, G. Madhuri, N. Nalini, V. Divya Rani, S. Vanisri and C. Sudhakar
Regional Agricultural Research Station, Palem, Nagarkurnool, Telangana, Professor Jayashankar Telangana Agricultural University-509215
Corresponding Author: akashparuthi2003@gmail.com

The current world human population is around 7.8 billion and is estimated to reach nearly 9.9 billion by 2050 (IISD, 2022). Climatic changes involving rising temperatures, frequent floods and drought are predicted to lead to novel diseases and frequent pest outbreaks, requiring an agile plant breeding response (Hussain, 2015). Many researchers quoted the importance of enhancing the genetic gain of primary crops at a faster rate to meet the global food demands (Hussain, 2015). Traditional plant breeding is a slow process, attributed partly to the time required to complete the plant life cycle (Fiyaz *et al.,* 2020). Further developing stable lines, plants are grown for many generations, and each new generation is targeted to breed out undesirable traits while keeping the desirable ones (Nawade *et al.,* 2018). The quicker they can take a generation from seed-to-seed, the quicker they can remove undesired traits while promoting wanted ones (Ghosh *et al.,* 2018; Watson *et al.,* 2018). Indeed, it is apparent that generation time in most plant species has become a new bottleneck in crop breeding. This has driven intense efforts by the scientific community of agriculture researchers and engineers to adapt newer technologies for generation advancement (Ghosh *et al.,* 2018; Watson *et al.,* 2018). Speed Breeding concepts are now being adopted at large/small units for realizing a rapid genetic gain in many crop species. Speed Breeding (SB) is a plant breeding technology that accelerates the generation time of crops by controlled environments with manipulation provisions for the light duration, intensity and temperature.

Historical Context of Speed Breeding

Origins and Early Development

Speed Breeding, a revolutionary technique in plant science, has its roots in space exploration. The concept was initially developed by National Aeronautics and Space Administration (NASA) in the 1980s as part of their Controlled Ecological Life Support Systems (CELSS) program. The primary goal was to find efficient ways to grow crops in space, where resources are limited and time is of the essence. Dr. Gary Stutte, a principal investigator for NASA, played a crucial role in these early experiments. His team demonstrated that by manipulating light cycles, they could significantly reduce the time between wheat generations.

- **1980s**: NASA scientists begin experimenting with accelerated plant growth cycles.
- **1992**: First successful implementation of extended photoperiods to speed up wheat breeding.
- **Late 1990s**: Australian scientists, inspired by NASA's work, begin adapting the technique for Earth-based crop improvement.
- **2001**: Dr. Lee Hickey and his team at the University of Queensland started developing speed breeding protocols for various crops.
- **2007**: First published results demonstrating the successful application of speed breeding in wheat.
- **2010-2015**: Development of optimized light spectra and intensities for different crop species.
- **2017**: Publication of a landmark paper in Nature Plants, detailing a standardized speed breeding protocol.
- **2018-present**: Integration with other breeding technologies like genomic selection and CRISPR gene editing.

Global Adoption and Impact

Speed breeding has gained traction worldwide, with research institutions and companies adopting the technique:

- **Europe**: John Innes Centre in the UK becomes a hub for speed breeding research.
- **Asia**: Adoption of the speed breeding technique by IRRI (International Rice Research Institute) for rice breeding.
- **Africa**: ICRISAT (International Crops Research Institute for the Semi-Arid Tropics) incorporates speed breeding in its legume improvement programs.

Current State and Future Outlook

Today, speed breeding is recognized as a valuable tool in addressing global food security challenges, especially in the face of climate change. Its ability to accelerate crop development cycles has made it an integral part of many breeding programs worldwide. As we move forward, the technique continues to evolve, with ongoing research focusing on:

- Optimizing protocols for a wider range of crop species
- Reducing energy costs and improving sustainability
- Integrating artificial intelligence for more efficient breeding decisions

The historical journey of speed breeding from a space-focused experiment to a widely adopted agricultural technique underscores its importance in modern plant science and its potential to revolutionize crop improvement strategies for years to come.

Comparison with other breeding methods:

The development of the new climate-resilient elite varieties takes several years in most of the crops. Traditional plant breeding is a slow process, attributed partly to the time required to complete the plant life cycle (Fiyaz *et al.*, 2020). Further developing stable lines, plants are grown for many generations, and each new generation is targeted to breed out undesirable traits while keeping the desirable ones (Nawade *et al.*, 2018). After hybridization of selected parental lines and even in the case of the advancement of transgenic lines, it requires four to six successive cycles of inbreeding to achieve desirable homozygosity (Watson *et al.*, 2018). Earlier, the shuttle breeding, developed by Norman Borlaug in the 1950s, was the most known approach in wheat to harvest about two generations per year (Ghosh *et al.*, 2018). Other approaches were also being used like physiological stress for early flowering, embryo rescue to shorten generation cycle, and embryo rescue coupled with the application of plant-growth regulators and double haploid (DH) to obtain homozygous lines only in two generations, which otherwise takes six or more generations (Ghosh *et al.*, 2018). Among these approaches, DH was most extensively used in breeding programs for a number of plant species (Hooghvorst *et al.*, 2020). However, DH technology has some disadvantages: it can be expensive, it requires specialist skills, it restricts recombination to single round of meiosis, and it has a variable success rate that may be genotype dependent. The approach can also be labour intensive for larger populations especially those requiring removal of the embryos from the seed coat. Notably, there is the potential for speed breeding to further accelerate the production of DH lines by speeding up the crossing, plant generation and seed multiplication steps.

Speed-breeding components

Speed-breeding techniques consist of setting up a controlled environment that meets all the plant needs and influences its growth at every stage of its development (Ghosh *et al.*, 2018). The basic components of speed breeding include the use of growth chambers with supplemental LED for prolonged photoperiods, controlled temperature, and humidity. Environmental factors such as light, temperature, and humidity are significant in relation to determine plant's growth and health levels. Optimization of plant growth involves controlling these environmental factors to encourage and boost photosynthesis there by speeding up vegetative and reproductive growth.

Light

Light is the source of energy for plant photosynthesis and growth. Light characteristics such as intensity, duration, spectral wavelengths, and direction can influence plant growth and development (Bayat *et al.*, 2018). Light intensity influences photosynthesis, stem length, leaf color, and flowering (Yoshida *et al.*, 2012). Artificial light is provided as a photoperiodic light to control flowering and to reduce the plant development time and to obtain higher quality and quantity (Bergstrand and Schussler, 2013). The advent of advanced LED lighting systems complemented efforts to accelerate lifecycle turnover, enabling manipulation of wavelength composition to trigger light responses, such as shade avoidance and encourage rapid progression to flowering.

The immature seeds (37 days after post anthesis) from plants grown under CO2 supplementation exhibited a high germination rate similar to control in soybean (Nagtoshi, 2019). Around 7–8 generations/ year is achieved in lentils by integrating early harvest with the application of plant growth regulators (Mobini, 2014). O'Connor *et al.*,

(2013) reported a speed breeding protocol for peanut (*Arachis hypogaea* L.) that used controlled temperature and continuous light to accelerate plant development and fast-track a SSD breeding program. They succeeded in reducing the generation time from 145 to 89 days.

In pigeonpea, Broad spectrum light (5700 K LED) hastened early vegetative growth and pod formation. Whereas far red (735 nm) light favoured early flowering. According to the recommendation of Ghosh *et al.* (2018), any light that produces a spectrum that covers photosynthetic active radiation (PAR: 400-700 nm), consisting blue, red, and far-red ranges, is suitable to use for speed breeding. The LEDs, or a combination of LEDs, could be used to get an appropriate spectral range.

Photoperiodic regime: A photoperiod of 22-hour light and 2-hour darkness in diurnal cycle of 24 hours is ideal photoperiodic regime in most of the crops for speed breeding. Another alternative is continuous light but slight period of darkness is known to improve the health of plant. The immature seeds obtained from plants grown under speed breeding protocols with an extended duration of photoperiod (22 h of light) proved to be viable in wheat and barley (Watson 2018). A similar finding on early seed harvest was reported in wheat cultivars (Ferrie, 2020). According to (Samineni et al. 2020) research, exposing chickpea plants to 12/ 12 h of light/dark cycle using a 60 W incandescent bulb emitting 870 lm of light intensity resulted in early flowering. Similar photoperiod regimes utilizing light sources that emit Photosynthetically Active Radiation (PAR) ranging from 400–700 nm and a light intensity of 360–650 µmol/m2/s was effectively employed in numerous crops, such as wheat, rice, pea, canola, and chickpea, to expedite speed breeding processes (Watson et al. 2018). In pigeonpea, a photoperiod of 13 h: 8 h: 13 h at vegetative, flowering and pod filling stages is ideal for shortened the breeding cycle. A significant difference between the photoperiods, genotypes as well as photoperiod x genotype interaction for both days to flowering and plant height was noted (Prakash Gangisetty *et al.,* 2024).

Temperature: Ideal temperature for each crop should be applied. During photoperiod higher temperature should be maintained, while during dark period fall in temperature can help with stress recovery. Temperature control plays an important role in promoting flower growth, seed production, and maturation, all of which are essential for expediting breeding processes. In the instance of wheat and barley, embryo cultures were used to obtain immature seeds that were subsequently germinated at a temperature range of 20–22 ℃ (Zheng *et al.,* 2013). It has been found that temperatures exceeding 33℃ can result in reduced anthesis time and elevated male sterility in crop such as soybean (Hatfield and Prueger 2015; Singh *et al.,* 2015). Using a 10-h photoperiod enriched with blue light and deprived of far-red light, soybean plants matured in 77 days of sowing, for five generations to be grown in a year (Harrison *et al.,* 2021).

Humidity: Control over humidity even in controlled environment chambers is limited, but 60–70% RH is ideal for crop growth, this level can be modified according to type of crop. For crops more adapted to arid conditions, lower humidity level is recommended.

Applications of Speed Breeding

1. Accelerating the crop improvement programmes by achieving up to six generations of long-day or day-neutral crops in a year, while traditional techniques only enable one to two generations.
2. Facilitates the development and testing of genetically modified crops by shortening the time required for their creation.
3. Ability to rapidly generate and assess multiple generations of plants, breeders can efficiently create and evaluate multi-trait combinations.
4. Speeding up the process of genomic selection.
5. Generate diverse segregating populations for genetic mapping in less time
6. It can be extended to study physiological traits of importance in crop plants.

Limitations of Speed Breeding

1. The early harvest of immature seeds before completing normal ripening process interferes with the phenotyping of some seed traits.
2. There is no universal protocol of speed breeding because of diverse response of plant species to photoperiodic conditions.

3. Differential responses of various plant species when exposed to extended photoperiodic conditions.
4. The lack of advanced controlled environment facilities and skilled personnel decreases genetic gain by limiting the ability to create ideal growth conditions.

References

IISD- International Institute for Sustainable Development. World Population to Reach 9.9 Billion by 2050. Available online: https://sdg.iisd.org/ news/ world-population-to-reach-99-billion-by-2050.

Hussain, B. Modernization in plant breeding approaches for improving biotic stress resistance in crop plants. Turk. J. Agric. For. 2015, 39, 515–530. [Cross Ref]

Fiyaz, R.A., Ajay, B.C., Ramya, K.T., Kumar, J.A., Sundaram, R.M., Rao, L.S., 2020. Speed breeding: methods and applications, Accelerated Plant Breeding, 1. Springer, Cham, pp. 31_49.

Ghosh, S., Watson, A., Gonzalez-Navarro, O.E., Ramirez-Gonzalez, R.H., Yanes, L., Mendoza-Sua´rez, M., et al., 2018. Speed breeding in growth chambers and glasshouses for crop breeding and model plant research. Nat. Protoc. 13 (12), 2944_2963.

Nawade, B., Mishra, G.P., Radhakrishnan, T., Dodia, S.M., Ahmed, S., Kumar, A., et al., 2018. High oleic peanut breeding: achievements, perspectives and prospects. Trends Food Sci. Tech. 78, 107_119.

Watson A, Ghosh S, Williams MJ, Cuddy WS, Simmonds J, Rey MD, et al. Speed breeding is a powerful tool to accelerate crop research and breeding. Nature Plants. 2018; 4(1):23-29.

Hooghvorst, I., Torrico, O., Hooghvorst, S., Nogue´s, S., 2020. In situ parthenogenetic doubled haploid production in melon "Piel de Sapo" for breeding purposes. Front. Plant Sci. 11, 378.

Bayat, L., Arab, M., Aliniaeifard, S., Seif, M., Lastochkina, O., Li, T., 2018. Effects of growth under different light spectra on the subsequent high light tolerance in rose plants. AoB Plants 10 (5), 052.

Yoshida, H., Hikosaka, S., Goto, E., Takasuna, H., Kudou, T., 2012. Effects of light quality and light period on flowering of ever bearing strawberry in a closed plant production system. Acta Hortic. 956, 107_112.

Mobini SH, Lulsdorf M, Warkentin T, Vandenberg A. Plant growth regulators improve in vitro flowering and rapid generation advancement in lentil and faba bean. Invitro cellular and developmental biology. Plant. 2014; 51: 71-79

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

Nischay Chaudhary, Rubby Sandhu 2024. A comprehensive review on speed breeding methods and applications. Euphytica (2024) 220:42.

Bergstrand, K.J., Schussler, H.K., 2013. Growth, development and photosynthesis of some horticultural plants as affected by different supplementary lighting technologies. Eur. J. Hortic. Sci. 78, 119_125.

Ferrie AM, Polowick PL. Acceleration of the breeding program for winter wheat. In: Accelerated Plant Breeding. Berlin: Springer; 2020. pp. 191-215.

Hatfield, J.L., Prueger, J.H., 2015. Temperature extremes: effect on plant growth and development. Weather. Clim. Extrem. 10, 4_10

O'Connor DJ, Wright GC, Dieters MJ, George DL, Hunter MN, Tatnell JR, Fleischfresser DB (2013) Development and application of speed breeding technologies in a commercial peanut breeding program. Peanut Sci 40:107–114

Ochatt, S.J., Sangwan, R.S., Marget, P., Ndong, Y.A., Rancillac, M., Perney, P., et al., 2002. New approaches towards the shortening of generation cycles for faster breeding of protein legumeshh. Plant Breed. 5, 436-440.

Zheng, M., Tao, Y., Hussain, S., Jiang, Q., Peng, S., Huang, J., et al., 2016. Seed priming in dry direct-seeded rice: consequences for emergence, seedling growth and associated metabolic events under drought stress. Plant Growth Regul. 78, 167_178.

Samineni S, Sen M, Sajja SB, Gaur PM (2020) Rapid generation advance (RGA) in chickpea to produce up to seven generations per year and enable speed breeding. Crop J 8:164–169.

Watson A, Ghosh S, Williams MJ, Cuddy WS, Simmonds J, Rey MD, Asyraf Md Hatta M, Hinchliffe A, Steed A, Reynolds D, Adamski NM, Breakspear A, Korolev A, Rayner T, Dixon LE, Riaz A, Martin W, Ryan M, Edwards D, Hickey LT (2018) Speed breeding is a powerful tool to accelerate crop research and breeding. Nat Plants 4:23–29.

Kabade PG, Dixit S, Singh UM, Alam S, Bhosale S, Kumar S, Singh SK, Badri J, Varma NRG, Chetia S, Singh R, Pradhan SK, Banerjee S, Deshmukh R, Singh SP, Kalia S, Sharma TR, Singh S, Bhardwaj H, Kohli A, Kumar A, Sinha P, Singh VK. SpeedFlower: a comprehensive speed breeding protocol for indica and japonica rice. Plant Biotechnol J. 2024 May;22(5):1051-1066.

Prakash G., Shruthi H. B., Naresh B, Vinutha K., Sobhan Babu S., Sunita Choudhary, Ramanagouda G., Deekshitha Bomireddy, V. Anil Kumar, Jwala Pranati, Mamta Sharma and Manish K. Pandey (2024) Optimizing speed breeding and seed/ pod chip based genotyping techniques in pigeonpea: A way forward for high throughput line development, Plant Methods 20:27.

Table 1. Speed breeding protocols optimized for shortening the breeding cycle

Crop	Type of Plant	Growth parameters under Speed Breeding				Generation Time (days)		References
		Photo period	Temperature	Light and other parameters	Humidity (%)	Field condition	Speed Breeding	
Rice	Short Day	24-h long day (LD) for the initial 15 days of the vegetative phase and 10-h short day (SD) in the later stage	32°C/30°C (light/dark)	high light intensity (800 µmol m^{-2} s^{-1})	65	122	80	Pramod Gorakhanath Kabade *et al.* (2024)
Peanut	Short Day	Continuous light (SVLs)	28°±3°C/ 17±3°C (day/night)	Continuous	65	145	89	Ochatt *et al.* (2002)
Soy bean	Short Day	14 h	30°C/25°C (light/dark)	220 µmol m^{-2} s^{-1} at the canopy level (CO_2 supplementation at .400 p. p.m)	50-80	102-132	70	Nagatoshi and Fujita (2019)
Pigeon pea	Short Day	13 h: 8 h: 13 h at vegetative: flowering and pod filling stages	25–27°C/ 16–18°C (Day/ Night	Broad spectrum light (5700 K LED) hastened early vegetative growth and pod formation. Whereas far red (735 nm) light favoured early flowering.	70 - 80% during flowering stage, 60 - 70% during the rest stages	150-180	120-140	Prakash I. Gangashetty *et al.*, 2024

* * * * * * * * *