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SPEED BREEDING: PRINCIPLES, METHODS, AND PROSPECTS FOR INTEGRATION WITH GENOMIC AND BIOTECHNOLOGICAL TOOLS IN CROP IMPROVEMENT

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ABSTRACT

Speed breeding is the novel method of growing plant that exploits and applies the innovative knowledge of the modern technology to accelerate the process of crop varieties through the processes of crop improvement and their successful commercialization. With its help we reduce the time of generation for the cultivar improvement. In addition, speed breeding offers a new paradigm to overcome the major challenges in the present world, including gene specific trait development through plant breeding, resistance against the newly discovered genes conferring pests & disease resistant lines in an efficient manner, mitigation effects against climate change and thus contributes towards enhancing the productivity for sustainable agriculture. This review covers up different aspects for the understanding of the basic principles and techniques involved in speed breeding and key advantage of speed breeding especially faster response to new challenge. Information for the present study was gathered from secondary literature sources such as journal articles and literature. Furthermore, it also covered the prospect of the speed breeding like development of stress tolerate as well as high-yield in new crop varieties and thereby the role of speed breeding as well in future with its application for sustainability in agriculture sector & food security and successful breeding for full maturity peanut variety from 145 days to 89 days by use of speed breeding through development of innovative tools. Collaboration among plant breeders, geneticists and the policy makers should be actively maintained to implement this powerful technique fully and to ensure bright prospect for the world agriculture.

***Keywords*:** Speed Breeding, Crop Improvement, Food Security, Sustainable Agriculture.

Introduction

Plant breeding has been essential to the security and safety of food and has drastically shaped world's food production since early 1900's; However, food security and quality have been an issue globally because the ever-growing human population is consuming excessive foods. Food security issues are becoming an important issue and plant breeders are the ones who are creating varieties which can tolerate environmental stresses, give high yield and improved nutrition value (Gonal *et al.*, 2023). Environmental changes occurring due to global climate change such as heat, drought stress are bringing enormous loss to world's crops farmers. The procedures above are the standard crop breeding procedure for development of improved varieties used in majority of crop cultivar programmes. Nevertheless, those conventional procedures may take over ten years in developing and release an improved variety without integrated pre-breeding programme (Ahmar *et al*., 2020; De La Fuente *et al*., 2013).

Speed breeding is a way of developing a new crop variety rapidly. It works by changing growth environments such as light intensity, photoperiod, temperature and humidity etc. To make time from seed to seed become as short as possible and consequently have rapid breeding cycles (Kumar and Walia, 2024; Blinkov *et al*., 2025). It is a smart and rapid generation advancement technology designed to reduce the long duration needed to breed and advance crop development programmes (Singh *et al*., 2021). Plant breeding is a traditional breeding technology that has taken many years, this needs to catch up with the human population's growing needs. Crop production technology needs to be innovative or enhance by changing breeding technology such as speed breeding which improves traditional planting technique. This concept was conceived when NASA explored the ways of growing crops under alien environment, and later used the technologies such as enclosed environment and lengthened photoperiod in accelerating development in variety of crops. Later, this technique was adapted for rapid cultivation of wheat and barley and hence speed breeding was adopted by University of Queensland. Speed breeding technique adopted by the Australian researchers' allows them quick move of genetic resource (Nayan and Kalyan, 2020). Further, for crop breeding it require skill and resources in phenotyping for continuous field selection and rapid early generation development since homozygous stable breeding line need to be produced and yield and economics traits have to be calculated (Mobini *et al*., 2015).

Last year, Lee Hickey and his team found the answer in 'speed breeding', a technology that does not involve GMO and can result in many generations of selection within multiple variations. This uses regulated environmental conditions to attain four-six generations in a year in long-term crops (e.g. Wheat, barley and canola) (Hickey *et al*., 2017; Ghosh *et al*., 2018).

The breeding procedure of a crop such as wheat is very time-consuming. It thus required a more rapid and readily available breeding method and these finally result in the development of a novel technology "speed breeding". This technology, developed and practically completed by the University of Queensland, the University of Sydney and the John Innes Centre, involves using controlled environmental condition/glasshouse with 24-hour light to promote plant growth. This breeding technique was inspired when the world's food crisis had led NASA to devise means of growing foods in space, and even though NASA's attempts in space did not come to fructify, but their contribution lead to development of rapid breeding technology. Their hypotheses are that since the foods we derive from plants are made through light, giving plants light for longer hours will allow them to produce food faster. The researchers have been working incessantly on perfection of this technique for over eight years. This remarkable innovation totally depended on artificial controlled environment in which conditions such as light intensity, temperature, relative humidity, photoperiod etc. Are controlled with little adjustment required for use in a glasshouse. The light source comes from standard LEDs highly modified to boost photosynthesis up to 22 hours per day (Devi *et al*., 2023).

Speed breeding speeds up breeding plant generations using optimized LED lighting and a photoperiod of up to 22 hours per day to enhance photosynthesis and growth. It accelerates the breeding period so that six generations of wheat plants can be bred in one year instead of two by using traditional methods. It hastens genetic development such as crop yield improvement, disease resistance and climate resilience in several crops including wheat, barley and oat. The speed breeding concept was praised and developed further in wheat crops by Dr. Hickey and Amy Watson and released some breeds (Watson *et al*., 2018).

One generation for cereal or legume crop is of around 3–6 months in general, in a particular crop, generation and year. However, for cassava it may take a minimum of 15–18 months to get one generation ready; erratic rainfall distribution, poor rainfall amount, high temperature and day length in some agro-ecologies only allows one generation per year whereas in other crops the maximum is two generations (Laux *et al*., 2010). In the past, premature seed of fast germinating pigeonpea cultivars was harvested 21 days after pollination and showed rate of germination from 73 to 100% without any pre-treatment (Saxena *et al*., 2017). Use of premature seed has been considered effective in indoor as well as field cultivation for rapid generation development.

Speed breeding is a group of techniques that utilize specific growth conditions in crop plants, in order to promote flowering and seeds formation, to hasten development of breeding generation. Speed breeding helps to save time and resources because of rapid generation development. It can be incorporated with different selections like SSD, SPD, SPS, marker-assisted selection (MAS) and clonal selection to shorten cycle and use resources efficiently (Hickey *et al*., 2017; Samineni *et al*., 2020; Watson *et al*., 2018).

A novel 'Speed Breeding' (SB) methodology was lately developed, allowing rapid generation development, which helps in reducing the breeding cycle length and expediting crop breeding programmes. In this process there are number of ways to perform the SB, the key aspect being enhancing plant's daily light exposure combined with early seed harvest, decreasing generation time. Australian researchers' have successfully utilized the technique to develop a pre-harvest sprouting resistant wheat variety DS Faraday (Hickey *et al*., 2019).

Procedure of Speed Breeding:

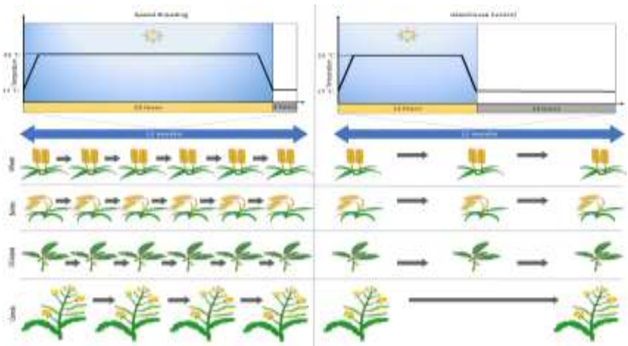
1. Initially, the seeds are prepared for sowing by providing the proper treatment and Environmental conditions.
2. The significant growing stages are taken into consideration and specific emphasis is given to phenotyping of only those stages. Like the time of anthesis or flowering is observed and their associated parameters are observed.
3. Majorly seed is harvested at an immature stage and then given specific cold treatment for maturation. Although the seed produces this process somewhat shrivelled on hydration, they regain their shape and vigour and germinated. But this process reduces the time from 15 days to 3 days.
4. The energy monitoring helps us to be specific while providing light, temperature and other biological setups. (Tiwari *et al.*, 2020).

Speed breeding photoperiodism method:

A) Speed breeding, I - Conviron BDW chamber conditions: The Conviron BDW chamber (Conviron, Canada) was programmed to run a 22-hr photoperiod, with a light/dark set of 2200 to the chamber with a temperature of 22 degrees in the day/photoperiod phase of the chamber with 17 degrees to in the dark. The light and temperature were ramped to and down for 1 hr 30 mins to simulate dawn and dusk conditions, and a humidity of 70% was used throughout. Lighting consisted of a combination of white LED bars (Valoya, 6 units per 3.67 m^2), far-red LED lamps (Valoya; 12 units per 3.67 m^2), and Metal HQI lamps (Valoya; 32 units per 3.67m^2) light quantity (photoperiodisms; PPFD) at bench height, the point where the plants were positioned to mimic 360-380 mol m^{-2} s^{-1} (highest PPFD achieved following ramping) and for adult plants 490-500 mol m^{-2} s^{-1} (highest PPFD achieved following ramping).

B) Speed breeding II - Glasshouse conditions: The chamber was set to run for an 18-hr photoperiod to 22°c (with high pressure sodium vapor lamps - Phillips SONT 400W E E40 to light conditions in Sylvan High Bay housing and glass diffuser), with 6 hr dark to 17°c (with lights off). All conditions except for dark and temperature change did not include a ramping up/down function Light intensity was for adult plants was around 440- 650 mol m^2 /s) at the point that was approx 45cm from the plant. The spectrum quality consisted of metal HQI lamps.

C) Speed breeding III -Homemade growth room design for low-cost speed breeding: A growth room was prepared from a commercial sandwich panel building, 3 m × 3 m × 3 m, fitted with 7 LB-8 growth light boxes from “Grow Candy” (http://www.growcandy.com) (1 light box per 0.6 m^2, 1.5 hp inverter split system air-conditioner) as an attempt at a cheaper alternative than a Conviron BDW. Light details are in supplementary data. The light conditions for ‘adult plant' range from 340–590 µmol $m^{-2}s^{-1}$ (at 50 cm from bench to nearest plant crown at height of 140cm), while those for younger plants (bench to closest pot crown, approx.20 cm from nearest plant crown to pot 23.04±6.79%) were 210–260 µmol m^{-2} s^{-1}. Plants can be grown on individual shelves and a 90 × 8-inch diametre x 5-L pots may fit on the bench of this size growth room. It was irrigated with a 13 mm line with spike emitters by using a Hunter 10 Station Irrigation Controller with a single solenoid per room; a single irrigation line was fitted into this and attached to a single room air solenoid and, using the 8-inch diameter pots, up to 90 single spike drippers per room could be utilized. Conditions consisted of a initial light-dark period regime of 12 hour days and 12 hours nights over four weeks until reproductive growth was initiated then a shift to 18 hours of daylight and six hours of dark. The room did not light / temperature up and down; in fact this had occurred with both systems b and c until this point. Average night-time temperatures were 18 degrees and days a temperature of 21 degrees could fluctuate no more than10 degrees celsius, this however again occurred with systemb and notac 10 ºC change. This system was used for speed breeding of wheat (*Triticum aestivum* cv. Morocco and Avocet), barley (*Hordeun vulgare* cv. Gus and Baudin), oat (*Avena sativa* cv. Swan), and triticale.



Speed breeding: a powerful tool to accelerate crop research and breeding (Amy Watson *et al*., 2017), (Source: www.nature.com/natureplants).

Fig. 1: Here, you can see that a standard glasshouse provides you with only 2 to 3 generations per year for crops like wheat, barley, chickpeas and canola (right), compared with a speed breeding facility that yields four to six generations per year (left).

Selection method of speed breeding

Historically, speed breeding has been utilized primarily to accelerate generation turnover without focusing on phenotypic evaluation. However, the integration of edge technologies such as marker-assisted selection (MAS) and high-throughput genotyping now allows breeders to select for specific traits simultaneously. Johnston *et al*. (2019) note that combining speed breeding with these efficient selection strategies is crucial for maintaining genetic diversity and ensuring high yield potential, even within restricted growth environments. Traditional breeding methodologies, including bulk, mass, pedigree, and pure line selection, are generally ill-suited for speed breeding protocols. These conventional approaches depend on genetically stable populations and necessitate lengthy selection cycles that negate the time-saving benefits of speed breeding. Consequently, the most compatible method for rapid generation advancement are Single Seed Descent (SSD), Single Pod Descent (SPD), and Single Plant Selection (SPS). The specific applications of these methods are detailed below."

(a) Single Seed Descent (SSD) Method:

Single seed descent (SSD) is a breeding method mainly used to develop highly homozygous (pure) lines through continuous self-pollination. In this method, only one seed from each plant in the F2 generation is selected and grown in the next generation. Each inbred line produced can be traced back to a single F_2 plant (Fehr, 1991). The time required to produce pure inbred lines through SSD is almost similar to the doubled haploid (DH) technique (Yan *et al*., 2017). One of the major benefits of SSD is that it needs less space and less labour, especially in the early generations. It is very useful because plants can be grown in high-density conditions in small nurseries, greenhouses, or growth chambers (Arbelaez *et al*., 2019; Funada *et al*., 2013). However, one drawback of SSD is that it may carry forward many weak or inferior progenies, since selection is not done at early stages. For example, in common bean, Urrea and Singh (1994) reported that seed yield of SSD-developed lines was lower compared to lines developed through pedigree or mass selection. To apply SSD effectively, a large number of plants are required. Generally, around 50–100 F1 plants are needed to produce about 2000–3000 F2 plants, which are advanced up to the F3–F4 generations (Priyadarshan, 2019).

SSD has been successfully used in many crops. For instance, Pignone *et al*. (2015) rapidly developed hundreds of durum wheat inbred lines using SSD. In rice, SSD combined with rapid generation technology helped develop the popular variety ‘Nipponbare’ (Tanaka *et al*., 2016). In maize, studies showed that grain yield performance of SSD-derived lines was similar to DH lines (Bordes *et al*., 2007). Additionally, Ma *et al*. (1999) found that SSD lines had better grain yield and kernel weight compared to anther culture-derived lines. Overall, SSD is considered one of the most suitable methods for speed breeding, as it can be practiced under both field and controlled indoor environments.

(b) Single Pod Descent (SPD) Method

Single pod descent (SPD) is a breeding method in which one pod from each plant is selected and advanced from the F2 to F4 generations, instead of selecting only one seed as done in SSD. Since most legume crops produce multiple seeds per pod, SPD helps in maintaining more genetic material from each F2 plant and increases the chance of preserving superior genotypes in later generations. Funada *et al*. (2013) reported that soybean progenies developed from crosses between ‘OAC Atwood’ and ‘RG600RR’ showed an increase in population size because each pod contained an average of 2.4 seeds. Their study found no major differences in selection efficiency among SSD, SPD, and bulk methods.

A key advantage of SPD is that it allows early pod-based selection, which means fewer plants may be needed to advance populations. Destro *et al*. (2003) observed that SPD-derived soybean lines produced higher mean yield (7.96 g $plant^{-1}$) compared to SSD lines (6.42 g $plant^{-1}$). However, the effectiveness of

SPD may vary depending on the crop and selection objective. For example, Khosla *et al*. (2019) reported that bulk selection resulted in greater yield improvement (72.6%) than pedigree (33%) and SPD (10.4%) in soybean. Overall, SPD is a useful approach for speed breeding in legumes, but preliminary evaluation trials are necessary to confirm its suitability for specific traits and environments (Priyadarshan, 2019)

(c) Single Plant Selection (SPS) Method

Single plant selection (SPS) is a breeding method where each selected plant in the F2 generation is advanced by harvesting all seeds from that single plant. In the next generation, progenies are grown using the plant-to-row system, which helps breeders evaluate individual plant performance more effectively. This method is especially useful in speed breeding because it allows early selection from smaller populations compared to SSD and SPD. SPS has been successfully applied in modified backcross programmes to rapidly develop introgression lines (ILs). For example, Hickey *et al*. (2017) developed barley ILs within two years by crossing the European barley cultivar 'Scarlett' with donor parents carrying resistance to leaf rust, net blotch, and spot blotch. Under speed breeding conditions of continuous light and controlled temperature (22°C), Hickey *et al*. (2010) selected 87 superior plants from about 5,000 BC1F2 individuals. The resulting Scarlett introgression lines showed significantly higher yield and improved multiple disease resistance compared to the original cultivar. Similarly, in bread wheat, Alahmad *et al*. (2018) used SPS to improve several important traits such as foliar disease resistance, grain dormancy, crown rot tolerance, leaf rust resistance, root architecture, and plant height. Their study reported stronger selection responses in SPS-derived lines compared to unselected populations.

Overall, SPS is an efficient method for speed breeding as it supports rapid improvement of agronomic and disease resistance traits through early-generation plant selection (Acquaah, 2020; Priyadarshan, 2019).

Challenges of speed breeding

The application of speed breeding is an important approach to speed up traditional breeding. The technology, however requires know-how, efficient and synergized phenomics facilities that complement each other and appropriate infrastructure with ongoing financial commitment toward research and development (Shimelis *et al.*, 2019). For this to happen the speed breeding methods will have to be understood as critically important for conventional plant breeding, marker assisted-selection and genetic engineering. In addition, the combined tool kit will requires staff expertise and technical knowledge of plant breeding and biotechnology, long-term financial commitments and supportive government policy and, inSSA (Sub-Saharan Africa), more than the common approaches of conventional plant breeding will have to be used. The traditional methods applied at most of SSA public research institutions are constrained by economic, institutional and technical limitations (Morris and Bellon, 2004). The application of the latest breeding tool could increase the rate of breeding and release of both conventional and GMO crop varieties in SSA. The most pertinent hindrances to application are: (a) the appropriate facility (b) staff that can follow the protocol (c) adoption of major program redesign (d) need for long-term funding.

a) **A lack of trained plant breeders and breeding technicians:** The problem of the lack of skilled and actively working plant breeders and breeding technicians in many developing countries is identified as a significant impediment in wide spread use of speed breeding at public sector (Morris *et al*, 2006 and Shimelis *et al*, 2019). The Public Sector Breeding programs suffers greatly from high turnover of staff as they seek employment from the private sector companies and Training Institutions that offer competitive salaries that the public sector fails to match. Few Scientists are Specializing as Plant breeders since Postgraduate specialization program in plant breeding programs are conducted only few Universities. Furthermore, In few cases, the legal and administrative structure required to support the promotion of plant breeding in the whole value-chain-from farmers to consumers -is weak/absent to protect the IP rights of the breeders (Tripp *et al.*, 2007). Hence, policy-makers in the developing world need to facilitate and reorganize policies for investment of resources in to plant breeding research and training and ensure staff retention, which will enable future success in the improve men to various crops through innovative methods of technology as speed breeding.

b) **Inadequate infrastructure:** Inadequate Infrastructure. High-level infra-structure, which control the water (soil moisture), temperature and photo period, are very crucial in a speed breeding facility. Public Sector Breeding projects in many of the developing countries Lack enough institutional supports for adopting state of art breeding technology, which includes speed breeding and other biotechnologies (Byerlee and Fisher, 2002). Also, limited technical skills to run innovative breeding research and insufficient scientific equipment (like tools and materials to screen selection of trait in the early stages) hinder the use of speed breeding method and related modern technologies (Ribaut *et al.*, 2010). A strong dependence over donors (donor minded) in majority cases and poor coordination of regional breeding programs often lead to the duplication of efforts and resources. Thus, active collaboration on resources, technology, infrastructure, and training is needed between national and regional organizations. We need to think of a cheaper mechanism to build similar in frats rapturising localized innovative materials like modified and converted shipping containers with solar driven temperature and light control technologies (Chiurugwi *et al*., 2018).

c) **Unreliable water and electricity supplies for sustainable operations:** The Manipulation of environmentally variables (in particularly) water, temperature, and photoperiod in indoor system is dependent on sustained supply of water and electricity resources. Indoor speed breeding requires Affordable sustainable power to operate temperature, lighting and fan systems. Temperature-controlled grow room in QLD in winter accounted for>50 % cost of plants maintenance (O'Connor *et al.*, 2013). Poor supply of electricity contributes significantly the ineffable cost of operation for the control of temperature and light on a day to day basis in speed breeding in Public Sector breeding program. On Farm Management of field varieties will require land preparations, the use of fertilizer, irrigation and several agronomic practices that costs resources and demand the use of the infrastructure (labor to carry out agronomic practices etc). We must seek inexpensive ways to operate indoor seed breeding that utilizes efficient light source and a temperature control system driven by locally-sourced power such as solar, supplemented with battery power system, to minimize the cost. Alternatively we could utilize the "speed-growing" concept of field growing by creating highly density planting under managed moisture stress conditions or using some other stress-forcing agronomic techniques with suitable resources in a system in a relatively cheaper way.

Applications:

1) Useful in developing multiple disease resistance crops
2) Can collaborate with new technology like CRISPER CAS9 and give result in a shorter period.
3) Spring wheat, durum wheat, barley and Brachy podium dictation has given amazing result by decreasing the time of progression to anthesis to just half.
4) According to some protocols, even 8-9 generations of barley were found.
5) There are many opportunities to combine it with transgenic and genomic selections to get good results.
6) The first varieties originated through speed breeding are "DS Faraday" using speed breeding with high protein, milling and tolerant to post-harvest sprouting.
7) The disentangling of photoperiod revealed that vernalization and dormancy, two plant traits previously considered necessary to the proliferation of *Hamulus lupulus* L. (hop flowers), do not influence hop flower yield and quality, this finding paves the way for speed breeding and controlled-environment production to achieve 4 hops generation cycles per year, as opposed to 1 under field-grown conditions. (Bauerle *et al*., 2019).
8) In Peanut: - Speed breeding was successful in reducing generation time of full-season maturity cultivars from 145 to 89 days. Speed breeding can rapidly progress the inbreeding of F2, F3 and F4 generations in less than 12 months, and potentially accelerate the development of the first cross to commercial release in around six to seven years. (O'Connora *et al*., 2013)
9) Application of a high-speed breeding programme for disease resistance in apple. (Flachowsky *et al*., 2011)
10) Multiple quantities traits in durum wheat.
11) Mutant transformation for waxy traits in barley.

Achievements:

1) Speed breeding (SB) is essential for genetic progress in winter wheat. Unlike spring wheat, winter wheat requires vernalization, extending generation time. We optimized SB for 48 diverse soft red winter wheat cultivars, achieving rapid advancement using a 22-hour photoperiod (25°C/22°C) in high-density trays. This approach enables four generations per year, reducing generation time by about 30 days compared to previous SB methods for winter wheat, expediting the development of experimental genotypes for field testing.

2) Although advances in crop breeding help us to face up to feeding the worlds 10 billion people can crop improvements be introduced quickly enough? The current environmental and rapid increase in global population necessitate the exploitation of emerging technologies like Genotyping, Marker Assisted Selection, High Throughput Phenotyping, Genome Editing, Genomic Selection and 'de novo' Domestication; all of which could be greatly accelerated by using Speed breeding technology to make plants faster at adapting. The earliest Wheat species to successfully be bred via Speed breeding, called 'DS Faraday' by Dr Lee Hickey features superior protein content, the traits of increased grain pre harvest and has quality grain properties required for milling. While Speed breeding technique is mostly used for research purposes, the industry use of this technology is becoming increasing more popular.

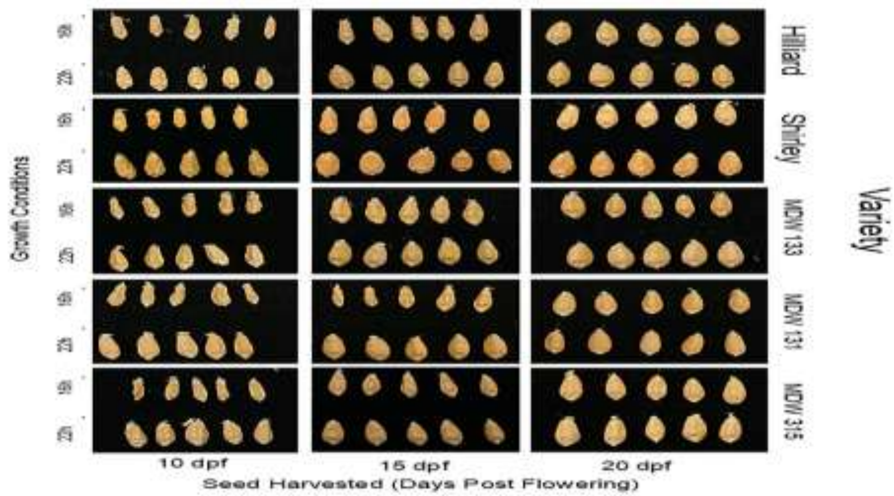


Fig. 2: (Source: Schoen, A., Wallace, S., Holbert, M. F., Brown‐Guidera, G., Harrison, S., Murphy, P., ... and Tiwari, V. (2023). Reducing the generation time in winter wheat cultivars using speed breeding. *Crop Science*, *63*(4), 2079-2090)

3) When this technology was applied to peanut breeding the 'time taken between the two generations' was reduced from 145 days to 89 days. Within the 12-month period, 2 to 3 generations from F2 to F4 can be obtained, the potential commercializing cultivar time can now be 6 - 7years instead of the more usual period which was 9 – 10 years for new commercialize cultivation (Connor, 2013 *et al*).

4) The research by Schoen *et al*, (2023) aimed to optimise the process for Speed breeding Winter wheat, which reduced time between seeding and flower to as short as ~105 days and from seeding to harvesting ~ 123 days, therefore, at 4 to 5 generations per year were attainable and feasible using this Speed Breeding process under optimum growing conditions in controlled environment

Table 1: The techniques for rapid generation advancement with corresponding days to flowering, number of generations achieved per year and selection methods used in different crops though speed breeding method.

Crop Species	Acceleration Protocol	Time to Anthesis / Maturity (Days)	Annual Generations	Breeding Strategy	Source
Amaranth	Regulation of thermal conditions and daylength	28	6	SSD	Stetter *et al*. (2016)
Arabidopsis	Hormonal priming, embryo rescue, and light control	20–26	10	—	Ochatt and Sangwan (2008)
Barley	Extended daylength (22h), temp. control, and nutrient optimization	24–36	9	SSD	Zheng *et al*. (2013); González-Barrios *et al*. (2021)
Canola	High-intensity light, thermal stress, and immature seed germination	73	4	SSD	Watson *et al*. (2018)
Chickpea	Continuous light (24h) and	33	7	SPD	Samineni *et al*. (2019)

	immature seed germination				
Faba bean	Growth regulators, extended photoperiod, and immature seed culture	29–32	7	SPD	Mobini *et al*. (2015)
Groundnut	Photoperiod extension and temperature modulation	25–27	4–5	SPD	O'Connor *et al*. (2013);
Lentil	Light intensity modulation and hormonal application	31–33	8	SPD	Mobini *et al*. (2015)
Oats *(Avena sativa)*	Early harvest combined with 22h photoperiod	~88 (seed-to-seed)	5	SSD	González-Barrios *et al*. (2021)
Pea	Hormonal induction and controlled photoperiod	33	5	—	Mobini and Warkentin (2016)
Pearl Millet	Optimized pot density, CO_2 enrichment, and ABA hormone	47–64	4–5	SSD	Terada *et al*. (2025);
Pigeon pea	Temperature regulation and immature seed germination	50–56	4	SPD	Saxena *et al*. (2019)
Rice	High-density planting and extended photoperiod	75–85	4	SSD	Collard *et al*. (2017)
Sorghum	Photoperiod manipulation and embryo rescue	40–50	6	SSD	Forster *et al*. (2014)
Soybean	CO_2 supplementation and light quality modification	23	5	SSD	Jähne *et al*. (2020)
Tomato	LED spectrum customization (Red/Blue ratio)	60–63	6	—	Li *et al*. (2025)
Wheat	Extended photoperiod (22h), early seed harvest	28–41	6–7.6	SSD	Zheng *et al*. (2013); Watson *et al*. (2018)

Abbreviations: SPD, single pod descent; SSD, single seed descent; SPS, single plant selection; not available information.

Future prospects

The future prospects of speed breeding are highly promising and have the potential to transform modern agriculture and crop improvement programs worldwide. By accelerating the development of new crop varieties, speed breeding can play a major role in helping agriculture adapt to climate change through the rapid production of heat-, drought-, and stress-tolerant crops. It also enables faster responses to emerging pests and diseases by facilitating the quick development of resistant cultivars. In addition, speed breeding can contribute to nutritional security by supporting the development of crops with enhanced nutritional quality and improved health benefits. The technology also promotes environmental sustainability by reducing the time, space, and resources required for crop improvement, thereby increasing breeding efficiency. Speed breeding offers opportunities to develop region-specific crop varieties suited to diverse agro-climatic conditions and market demands. Furthermore, its integration with advanced technologies such as precision agriculture, biotechnology, genomic selection, and gene-editing tools like CRISPR-Cas9 can significantly improve breeding accuracy and efficiency. Another important future application of speed breeding lies in advancing scientific understanding of plant genetics, physiology, and trait inheritance. As breeding cycles become shorter, researchers can evaluate genetic traits more rapidly and efficiently. Ultimately, speed breeding is expected to play a crucial role in ensuring global food security by accelerating the production of high-yielding, resilient, and sustainable crop varieties capable of meeting the food demands of a growing world population.

Limitations and Challenges of Speed Breeding

Although speed breeding has emerged as a promising approach for accelerating crop improvement, several limitations and challenges restrict its widespread application in plant breeding programs. One of the major constraints is the high cost associated with establishing and maintaining controlled environment facilities such as growth chambers, greenhouses, LED lighting systems, and temperature regulation units. These infrastructural requirements may limit the adoption of speed breeding, particularly in developing countries and resource-limited institutions.

Another important challenge is the crop-specific response to speed breeding conditions. While many cereal and model crops respond effectively to extended photoperiods and controlled environments, some crops with complex photoperiod sensitivity, perennial growth habits, or long juvenile phases may not perform efficiently under accelerated conditions. In certain cases, rapid growth cycles may negatively influence plant morphology, flowering behavior, seed set, or fertility.

The success of speed breeding also depends heavily on precise environmental management, including light intensity, temperature, humidity, and nutrient availability. Any fluctuation in these factors can affect plant growth and experimental outcomes. Furthermore, the artificial conditions used in speed breeding may not fully replicate natural field environments, which can influence the expression of agronomically important traits and genotype × environment interactions.

Integration of speed breeding with modern breeding tools such as genomic selection, marker-assisted breeding, and genome editing requires advanced technical expertise, molecular infrastructure, and skilled manpower. This increases the complexity of breeding programs and may create barriers for large-scale implementation.

In addition, limited information is available regarding the long-term genetic stability, adaptability, and field performance of varieties developed through accelerated breeding cycles. Energy consumption and operational sustainability of controlled growth facilities are also emerging concerns, particularly under increasing global energy demands.

Therefore, despite its tremendous potential, further research, technological advancements, and cost-effective innovations are needed to overcome these limitations and enhance the practical applicability of speed breeding for sustainable crop improvement.

Conclusion

The Modern breeding is undergoing an unparalleled paradigm shift with the dawn of speed breeding a revolutionized crop breeding process that drastically speeds up crop development to deliver better crop varieties that cater to diverse demands, largely due to a warming world and an increasing global population. It leverages environmental interventions like high intensity lighting, optimized temperatures, and varied photoperiod, to enable the cycle for plant generations in half time than conventionally and remarkably increases productivity. Although speed breeding has a limited number of applications particularly in developing nations, especially among public sector programs, its fusion with additional breeding technologies holds enormous promise. For effective implementation, there is an emphasis on boosting technological and infrastructure capacities, and an expansion of international cooperation as an R&D partnership with speed breeding taking center stage as an anticipatory practice that would deliver the most climate resilient, high performing and commercially viable cultivars in a post covid-world.

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