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Integrating speed breeding with artificial intelligence for developing smart varieties

R. Muthuvijayaragavan[1*] and E. Murugan[2]
[1]Department of Plant Biotechnology, Centre for Molecular Biology and Biotechnology, Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu, India – 641 003
[2]Department of Plant Breeding and Genetics, Agricultural College and Research Institute, Tamil Nadu Agricultural University, Madurai, Tamil Nadu, India – 625 104
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Introduction

Global climate changes have severely impacted agricultural productivity worldwide. The severe repercussions of climate change range from extreme temperatures (high and low), excess sunlight, and elevated CO2 altering rainfall's geographical nature, making crops more prone to disease (Wang *et al.,* 2018). Several researchers have well-advocated climate change has become a prime aspect that tremendously affects plant growth, development, and productivity by provoking biotic and abiotic stresses (Hasegawa *et al.,* 2018). The conventional plant breeding approach has been the saviour for ensuring food and nutritional security worldwide. It does it by strengthening genetic diversity and unravelling novel genes (Ahmar *et al.,* 2020). The gain in genetic diversity and identification of novel genes through classical breeding is a time-consuming process involving hybridization/inter-crossing of elite/wild cultivars with common landraces (Al-khayri *et al.,* 2015).

The new crop varieties developed through the classical breeding approach possess superior agronomic traits that help increase their yield potential and stress resilience. Speed breeding technology has emerged as a versatile suite for manipulating the growing environment of crop plants to accelerate their breeding generation by enhancing the rate of flowering and seed set under the influence of AI (Razzaq *et al.,* 2021). In addition, speed breeding instigates rapid generation advancement via reducing breeding time and resources by accelerating essential cellular and metabolic processes (Ghosh *et al.,* 2018).

Speed Breeding

Speed breeding mainly works by modifying the light, intensity, and duration, which, upon subsequent perception by photoreceptors, triggers rapid reproductive development in plants. These photoreceptors, upon perceiving light, regulate the natural circadian rhythm, which is the first and rapid responder to changing environmental conditions (Leal Filho *et al.,* 2022). The researchers have

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devised speed breeding protocols by categorizing plants into three groups' viz. short-day plants (SDP), long-day plants (LDP), and day-neutral plants (DNP). The speed breeding instigates rapid generation advancement in SDP and DNP by providing light for more extended and LDP for a shorter duration (Godwin *et al.,* 2019). The main objective of any plant breeders is to increase the yield and resistance of crop plants by predicting which line/cultivars will produce the best hybrids upon their subsequent hybridization.

Traditional breeding: the liberator

Initially, ancient farmers practiced plant breeding to increase the domestication of plants within their surroundings. Its subsequent evolution has become one of the acclaimed approaches for improving yield and disease susceptibility in crop plants. Later, plant breeders started exploiting molecular/genetic markers that allow robust and quick assessment of genetic variation among the progenies. In addition, molecular markers also serve as an indispensable tool for underpinning genetic variation and structure more efficiently than the morphological and biochemical markers, which help in accelerating breeding programs and greatly facilitate their efficient conservation. Furthermore, an amalgamation of molecular techniques with classical breeding helps to untapped the hidden genetic potential of common landraces, wild relatives, and varieties by expediting the identification of quantitative trait loci (QTLs), thereby identifying new alleles/genes that may be absent in the local cultivars (Gupta *et al.,* 2010). These novel genes/alleles can be integrated into elite cultivars/varieties via the gene pyramiding/accumulation approach to increase the scope of genetic variation for given agronomic traits (Rana *et al.,* 2019).

Various genetic/linkage/QTL maps have been made for multiple agriculturally essential crops that have helped plant breeders unlock favourable genetic variations in crop species by using a specific set of molecular markers. Conventional breeding has been most prominently used to develop and breed new perennial crops by domesticating wild/superior cultivars from one place to another or mediating its crossing or hybridization with cultivated genotypes. Conversely, domestication of any line/variety involves its establishment at the desired place, followed by rigorous phenotyping for selecting superior cultivars with desired traits. In contrast, hybridization is more realistic and practical than domestication because if the hybridization of two contrasting cultivars is successful, it can develop hybrids having superior agronomical traits.

Several perennial crops have been improved using a comprehensive hybridization approach, such as sorghum (*Sorghum bicolor* × *S. halepense*), wheat (*Triticum spp.* × *Thinopyrum spp.*), rice (*Oryza sativa* × *O. longistaminata*) and buckwheat (*Fagopyrum spp.* × *Fagopyrum spp.*) (Crews and Cattani 2018). However, both the conventional techniques are time-consuming and often involve robust data collection; researchers have now incorporated various molecular breeding techniques that

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have significantly expedited the traditional breeding approaches to develop and breed improved cultivars, which have been comprehensively discussed in the following section.

How plant breeding can benefit from AI

The application of Next-Gen AI in plant breeding requires intelligent and efficient mining of breeding datasets by employing relevant models and definitive algorithms [10]. Researchers are constantly working to innovate and improve the efficiency of AI to enable high-definition image recognition for analysing complex data sets and therefore has become a prime target for accelerating the crop improvement process (Harfouche *et al.,* 2019). AI, such as neural networks (NN) and deep learning (DL), are currently being exploited to improve the efficiency and accuracy of multi-omics data. The mechanisms by which these two AI functions are often opaque involve multiple nonlinear hierarchical methods to build nodes for easy classification of datasets mimicking brain neurons.

Conversely, plant breeders are conceptualizing a Next-Gen AI that will analyse breeding values and provide a comprehensive analysis of complex traits under changing environmental conditions (Niazian and Niedbala 2020). Furthermore, AI will also be learned and improved iteratively to improve data mining accuracy and efficiency to predict better the factors underlying disease resistance/agronomic traits, thereby accelerating breeding programs. Extensive hybridization and rigorous selection parameters have significantly altered the phenotypic plasticity of crop plants (Parmley et al., 2019). In addition, phenotypic plasticity of economically important traits is also substantially reduced upon genotypic variation occurring among the genotypes as a direct consequence of their interaction with the environment. Therefore, current breeding programs aim extensively to improve the abiotic stress tolerance of crop plants by bridging the genotype-phenotype gap that has occurred due to alteration in the phenotype plasticity.

AI for Plant Breeding: Speed Breeding

Speed breeding is like a speed dating for plant genes, in controlled environmental conditions and within special scientific programs. This method can incorporate marker-assisted selection and advanced gene-editing tools for early selection and manipulation of crops with superior agronomic traits. Scientists are utilizing next-generation AI to explore the complex biological and molecular mechanisms influencing plant functions under environmental conditions. Let's consider just a few researchers published by Indian IN scientists - this will be a nice way to celebrate our new series "AI for Plant Breeding".

Speed Breeding for Major Crops: Time Savings

Speed breeding concept was successfully employed for the improvement of various crops *viz.,* wheat, barley, rice, canola, soybean, chickpea, lentil, pigeon pea, tomato, and pea. The following numerical insights, which can be enhanced with AI:

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1. Speed breeding can achieve **4-6 generations per year** in various crops compared to 1-2 generations per year using conventional methods.
2. Maintaining temperatures around 20-22°C for wheat and barley allows for up to **eight generations per year**.
3. Using a 10-hour photoperiod with specific light conditions can result in soybean plants maturing in 77 days, enabling **five generations per year**.
4. In studies with rice, a germination rate of 95-100% was achieved by **optimizing seedling tray conditions and thinning processes**.
5. Speed breeding coupled with genomic selection and other advanced techniques can **reduce the breeding cycle of wheat** from 3-7 years to just 1-2 years

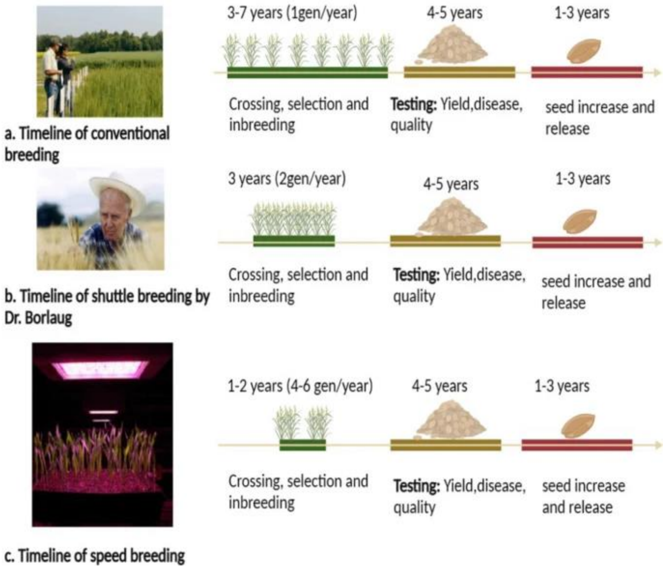

Fig 1. Timeline comparison of speed breeding with other breeding techniques.

Photo credit: Chaudhary and Sandhu (2024)

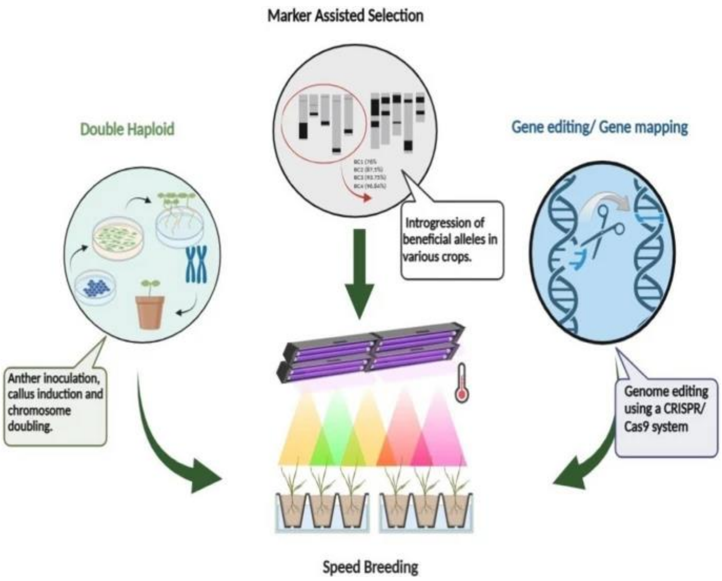

Fig 2. Speed breeding coupled with modern breeding techniques.

Photo credit: Chaudhary and Sandhu (2024)

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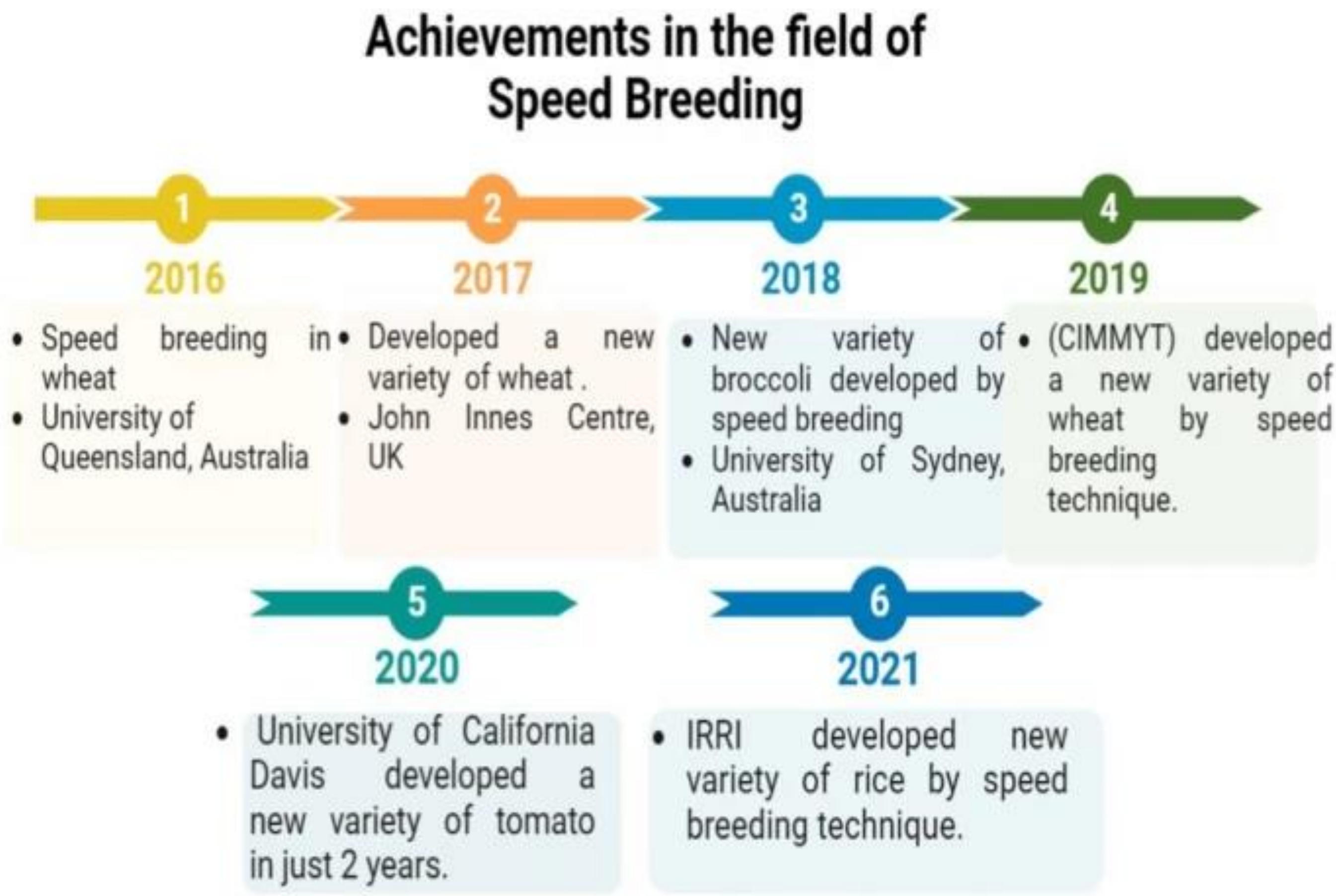

Fig 3. Achievements of speed breeding. ***Photo credit: Chaudhary and Sandhu (2024)***

Speed Breeding Concept: Where is AI Applied?

The consortium of Indian agriscience research institutions have reviewed the state of plant breeding for the following crop species:

- Cereals
- Legumes
- Vegetables and Other Horticultural Crops
- Oilseed Crops
- Fibre

Advanced techniques like CRISPR-based gene editing, high-throughput phenotyping, and genomic selection can further optimize speed breeding protocols, enabling rapid development of crop varieties with desired traits. The use of **AI-driven control systems to optimize environmental conditions** will increase efficiency, allowing for simultaneous cultivation of multiple generations and diverse crops.

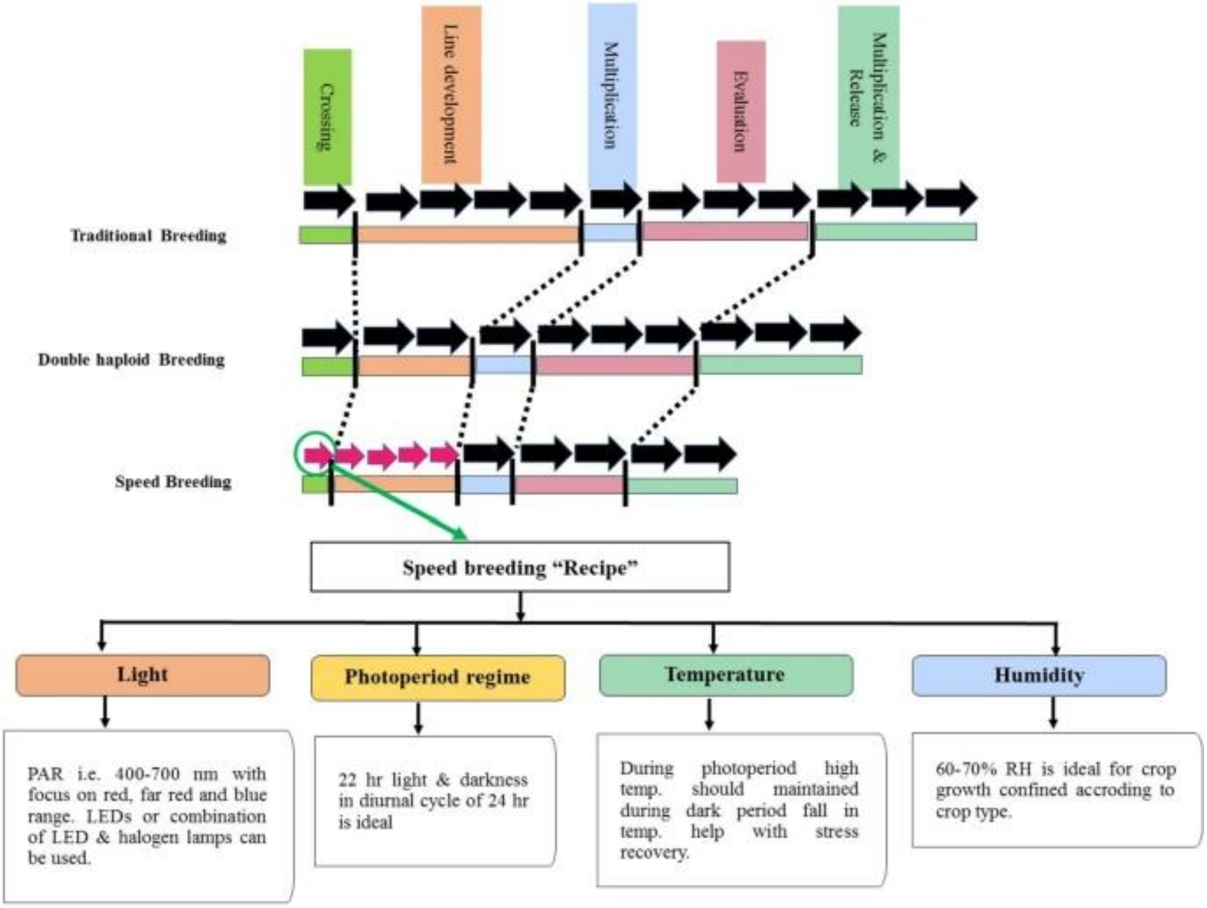

Fig 4. Visual representation of different breeding methods for varietal development (Each colour represent different steps of varietal development); Black arrow - single generation, field condition; pink arrow - single generation, speed breeding. ***Photo credit: Imam et al., 2024***

Plant breeding with AI vs. Conventional Breeding

Conventional breeding technologies are limited, time-consuming, and labour intensive, necessitating the acceleration of plant breeding cycles through AI to monitor plant responses to environmental changes in real-time. Next-generation AI facilitates the exploration of complex plant mechanisms and the analysis of OMICS datasets, essential for developing high-yield, adaptable crop plants.

The integrations of multiple disciplines such as, high-throughput genotyping and phenotyping with speed breeding to rapidly improve orphan crops and bring them to the forefront of the quest for a well-nourished world population, in the context of unpredictable environmental and socioeconomic conditions. Speed breeding must, therefore be integrated with other breeding techniques as well as cost-efficient high-throughput genotyping and phenotyping to speed up the generation. Therefore, speed breeding could be a pivotal tool for accelerating crop growth and reproduction, through which breeders around the world will be able to breed plants and generate improved cultivars that are better adapted to changing climate to feed the increasing population.

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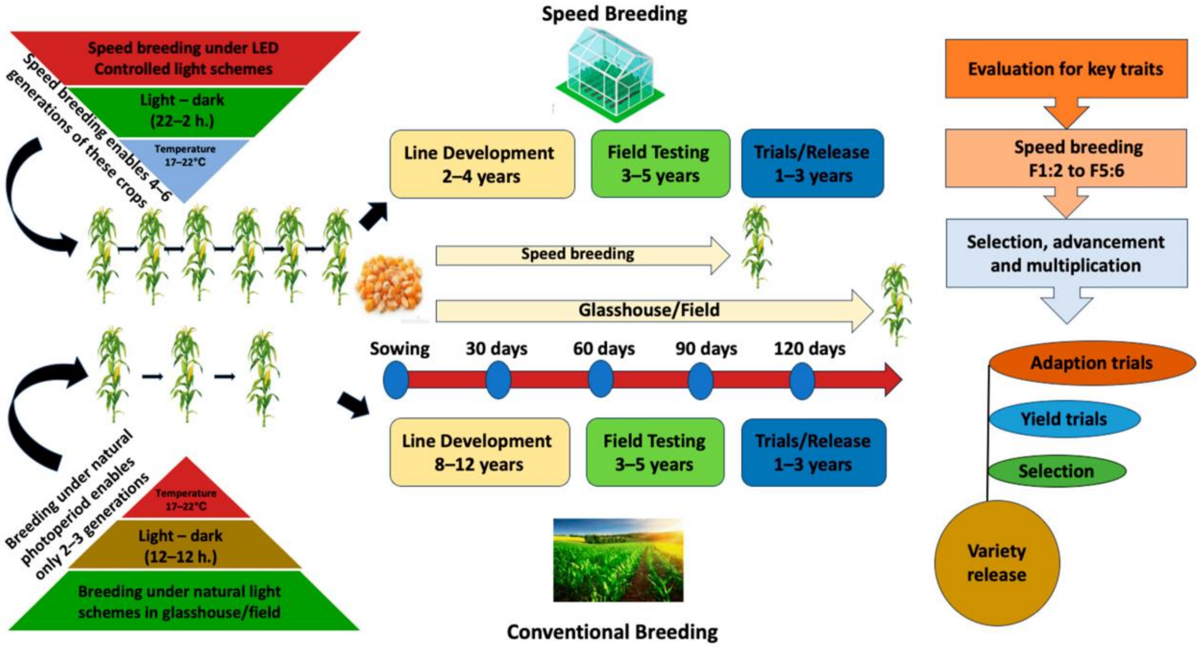

Fig 6. Overview of conventional and speed breeding. *Photo credit: Jesse Potts et al., 2023*

Challenges and Future Prospects:

Speed breeding is a phenomenal technique for accelerating crop improvement programmes. One of the best features of SB set up is its flexibility to combine with high throughput breeding tools such as MAS and Genomic selection. Since it can substantially reduce generation intervals, genetic gain from this approach could be greatly increased by applying genomic selection at each generation to select the parents for the next generation (Hickey *et al.,* 2019). However, the technology requires expertise, effective and complementary plant phenomics facilities, appropriate infrastructure and continuous financial support for research and development. Integrating genome editing and speed breeding without tissue culture requires a number of technological breakthroughs. The existing restrictions, on the other hand, can be overcome by further optimising SB methods for essential food crops and ensuring their efficient incorporation into plant breeding pipelines.

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