Speed Breeding in Pigeonpea: Revolutionizing Crop Improvement

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Introduction

Pigeonpea (*Cajanus cajan*) is a vital grain legume crop in rainfed agriculture, serving as a staple protein source across Asia, Africa, Latin America, and the Caribbean. Known for its protein-rich grains, pigeonpea is a significant contributor to food security, offering a healthier alternative to soybeans and peas. Despite its importance, breeding progress for pigeonpea has been notably slow, constrained by its photosensitivity, long maturation period, and seasonal specificity.

Traditionally, developing a new pigeonpea variety takes about 12 to 13 years, limiting the number of improved cultivars released over the past six decades. However, the advent of speed breeding techniques offers a transformative approach to reduce this lengthy breeding cycle. This article delves into the potential of speed breeding and seed/pod chip-based genotyping to accelerate pigeonpea improvement, enhancing yield, nutritional value, and adaptability to changing climates.

Background

Achieving genetic uniformity in inbred lines is a primary goal for plant breeders, typically accomplished through growing segregating populations in the main cropping season to highlight genetic differences for selection. This simultaneous approach to generation advancement and selection is time-consuming. To address this, Goulden (1941) suggested postponing selection until populations reach homozygosity. Techniques like the "single seed descent" method, where a single seed per plant is harvested and bulked for generational advancement, were developed. Modifications followed, such as Brim’s (1966) "modified pedigree method" and Fehr’s (1991) "multiple seed descent," enhancing efficiency.

While these approaches have accelerated breeding in some crops, traditional pigeonpea germplasm remains constrained by photoperiod sensitivity, making off-season cultivation difficult. However, early maturing, photo-insensitive pigeonpea genotypes can reproduce off-season, making rapid generation turnover a viable strategy for developing early-maturing cultivars.

The Need for Speed Breeding

The time required to develop new varieties of economically important crops like rice, wheat, maize and pigeonpea is often too slow to keep pace with a rapidly changing environment. Climate change—characterized by delayed monsoons, droughts, excessive rainfall, and emergent pests—has disrupted cropping cycles, leading to declining food security.

In traditional breeding, it can take 8 to 9 years to develop a new rice variety, and even longer for the variety to reach farmers. Similar timelines apply to pigeonpea. However, the adoption of speed breeding techniques has significantly reduced this period to about 2–4 years for pigeonpea, ensuring quicker access to improved varieties that can better withstand environmental challenges.

Speed breeding, initially developed for long and day-neutral crops, leverages environmental manipulations like extending daily light exposure to shorten the time to flower and mature. This approach has now been adapted for short-day crops like pigeonpea, offering promising results. The evolution of speed breeding traces back to NASA's research on dwarf wheat, and the integration of LED technology in the 1990s allowed for controlled, efficient breeding environments, further accelerating crop improvement.

Optimizing Photoperiods and Light Wavelengths

Speed breeding exploits-controlled environments to manipulate the photoperiod and light wavelength, enhancing flowering and reducing the time to maturity. The optimized protocol includes a photoperiod of 13 hours of light followed by 8 hours of darkness during vegetative growth and pod filling, complemented by a shorter 8-hour light period during the flowering stage. Broad-spectrum white light (5700 K LED) accelerates vegetative growth, while far-red light (735 nm) triggers early flowering.

Temperature control plays a critical role as well, with day/night temperatures maintained at 25–27°C and 16–18°C, respectively, during flowering, and 32–35°C/22–25°C during other growth stages. The integration of these environmental factors facilitates rapid growth, early flowering, and improved seed set, contributing to faster breeding cycles.

Speed Breeding Approach

Speed breeding has emerged as a valuable strategy to accelerate the development of inbred cultivars, significantly reducing the time needed to advance breeding materials from one generation to the next. Optimizing environmental conditions and, in some cases, applying plant hormones, rapid plant growth and early flowering can be achieved. This approach has demonstrated success across cereals, legumes, and oilseed crops (Watson *et al.*, 2017).

In legumes, speed breeding techniques have shown notable results. For instance, chickpea (Cicer arietinum L.) can produce three generations per year under extended photoperiods (Gaur *et al.*, 2007). Advanced methods like applying growth regulators and using immature seeds enabled faba bean (Vicia faba L.) and lentil (Lens culinaris Medik) to achieve up to seven and eight generations annually (Mobini *et al.*, 2015).

In pigeonpea, rapid generation turnover has been explored using greenhouses with natural light and evaporative air coolers (Saxena *et al.*, 2017). Under controlled conditions, immature seeds harvested about 35 days after flowering demonstrated high germination rates and could produce four generations per year. This strategy has successfully shortened the breeding cycle, providing a viable method for developing early maturing pigeonpea cultivars efficiently.

Effective speed breeding requires maintaining optimal environmental conditions, especially temperature control. Areas with mild winters and summers are ideal, while regions with extreme temperatures may need advanced facilities. Early breeding tasks, like parent selection and hybridization, can occur in the field, with subsequent generations advanced in controlled glasshouses. Additionally, marker-based screening for target traits can help refine breeding populations, expediting the development of stable, improved varieties. A major breakthrough in pigeonpea speed breeding is the use of immature seed germination combined with the "single pod descent" method. Typically, immature seeds are harvested 35 days after flowering, ensuring successful germination with minimal defects. These methods allow breeders to achieve four generations per year, accelerating the development of homozygous lines.

The single pod descent approach involves selecting one healthy immature pod from each plant to advance generations rapidly. This strategy conserves genetic variability while expediting the breeding process. It has successfully reduced the breeding cycle from 10–12 years to just 4–5 years, a significant milestone for pigeonpea improvement. Comparision among conventional breeding approach and speed breeding has been given below (Figure 1).

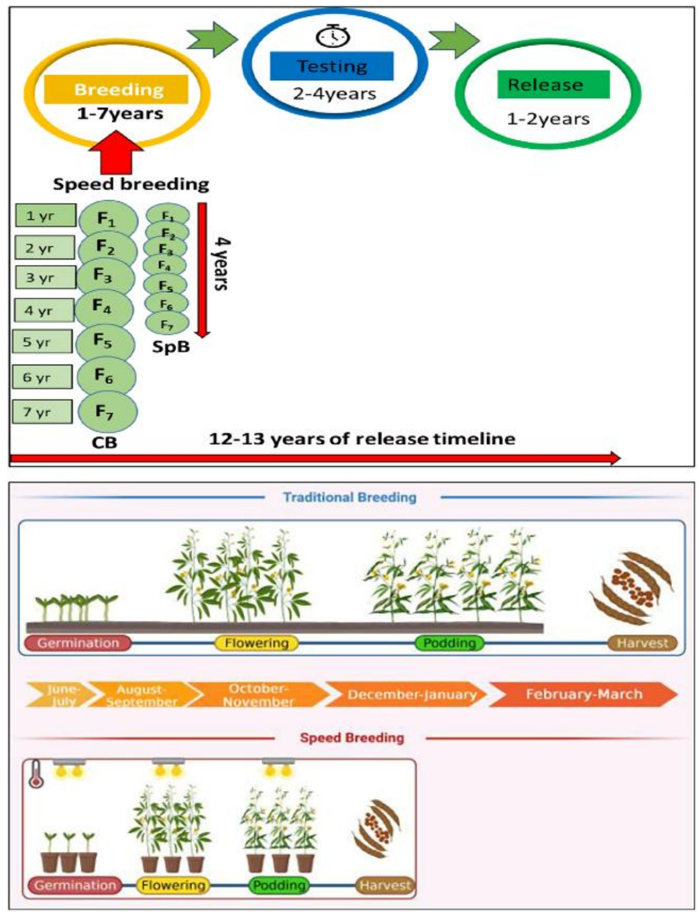

Fig. 1. Diagram representing speed breeding in comparison with conventional breeding pipeline (Gangashetty *et al.*, 2024)

Seed/Pod Chip-Based Genotyping: Enhancing Precision

A notable advancement accompanying speed breeding is the use of seed and pod chip-based genotyping for early marker-assisted selection. This approach enables researchers to assess genetic purity and select desirable traits at an early stage, expediting breeding efforts. By sampling a small portion of the seed or pod, researchers can perform DNA analysis without damaging the embryo, allowing for early-generation selection.

The efficiency of this method has been demonstrated by Gangashetty *et al*., (2024) through genotyping of leaf, seed, and pod chips using Kompetitive Allele-Specific PCR (KASP) markers. With high-quality genotyping calls—98.1% for leaf samples, 95.6% for seeds, and over 90% for green and dry pods—this technique has proven valuable for maintaining genetic integrity and accelerating varietal development.

Impact and Future Prospects

Speed breeding in pigeonpea has shown promising results, enabling breeders to screen larger populations in less time, enhancing the chances of identifying superior cultivars. By combining this approach with modern genomic tools like AI-based prediction models, the potential for achieving substantial genetic gains is immense.

A study by the International Rice Research Institute (IRRI) showed that reducing a breeding cycle by two years could translate to an economic benefit of approximately USD 18 million over the variety's useful life. If applied widely to pigeonpea, similar economic and food security gains are anticipated. The rapid generation advancement facilitated by speed breeding is crucial for meeting the increasing demand for pigeonpea, driven by its nutritional benefits, including protein, vitamins, minerals, and a low glycemic index. With the capacity to integrate methods like high-density planting, physiological stress induction, and controlled environments, speed breeding maximizes the turnover of generations. This technique is being adapted to other crops, such as wheat, barley, and maize, with promising results of achieving multiple generations per year.

Challenges and Limitations

Despite its potential, speed breeding faces limitations, including the need for specialized infrastructure, high-energy consumption, and technical expertise. Excessive photoperiods or temperature deviations can hinder growth, reduce flowering, and result in genetic instability. In developing regions, inadequate facilities and limited technical support may restrict the widespread adoption of speed breeding.

Conclusion

Speed breeding and seed/pod chip-based genotyping represent a paradigm shift in pigeonpea breeding, offering a practical and efficient path to developing improved cultivars in record time. As breeders and researchers continue to refine these methods and integrate advanced technologies, the future of pigeonpea cultivation appears promising—poised to meet the dietary needs of a growing global population.

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