

Rapid Generation Advancement in the Genomic Era: Unlocking Breeding Efficiency

Vinodh Kumar P.N.*, Sahana Police Patil and Keerthi G.M.

Division of Genetics, ICAR-Indian Agricultural Research Institute, New Delhi, India.

(Corresponding author: Vinodh Kumar P.N.*)

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ABSTRACT: Global food production must increase significantly to feed the projected 10 billion people by 2050, despite challenges such as climate change, land degradation, and emerging pests and diseases. Traditional plant breeding methods, while successful in developing high-yielding varieties, are time-consuming and require multiple growing seasons, often taking 8–12 years to develop new varieties. This slow pace is inadequate given the urgency of food security and rapidly changing environmental conditions. Recent advances in rapid generation advancement techniques combined with genomic tools such as genomic selection, marker-assisted selection, and genome editing offer unprecedented opportunities to accelerate breeding cycles and increase genetic gain. This review explores the principles of rapid generation advancement by manipulating environmental conditions to shorten generation times, the integration of genomic approaches to enhance selection precision, and the application of multi-omics for comprehensive trait dissection. Real-world successes in key crops and the challenges ahead are discussed, highlighting the potential of these integrated technologies to revolutionize crop improvement and address global food security challenges.

Keywords: climate-resilient breeding, drought and heat tolerance, genomic selection, marker-assisted selection, and genome editing.

INTRODUCTION

Global food production must increase significantly to feed the projected 10 billion people by 2050, despite challenges like climate change, land degradation, and the emergence of new pests and diseases. Traditional plant breeding methods, although successful in developing high-yielding varieties, are time-consuming, often requiring 8–12 years for variety development due to lengthy generation cycles and multi-seasonal evaluations (Tester & Langridge 2010; Cobb *et al.* 2019). This slow pace is inadequate in the face of rapidly changing environmental conditions and urgent food security demands.

To address this, rapid generation advancement has emerged as a breakthrough strategy to reduce generation time by manipulating environmental conditions such as photoperiod, temperature, and humidity. By enabling up to 4–6 generations per year, this approach significantly accelerates the development of homozygous lines and trait fixation in crops like wheat, barley, chickpea, and canola (Watson *et al.*, 2018; Hickey *et al.*, 2019). It has transformed breeding pipelines by enabling year-round crop cycles under controlled conditions.

Concurrently, the genomics revolution in plant science has led to the availability of whole-genome sequences, high-density single nucleotide polymorphism markers, genotyping platforms (e.g., genotyping-by-sequencing, SNP arrays), and advanced bioinformatics tools. These

resources facilitate the use of genomic selection, which predicts breeding values using genome-wide marker data; marker-assisted selection, which selects for known trait-associated loci; and genome editing, particularly CRISPR/Cas9, to directly modify target genes (Varshney *et al.*, 2021; Jaganathan *et al.*, 2018). Together, these genomic tools have enhanced selection precision and reduced dependency on multi-seasonal phenotyping.

The integration of rapid generation advancement with genomics-based approaches presents a synergistic opportunity to both accelerate and enhance genetic gain in crop improvement. Rapid generation advancement provides a rapid generation turnover system, while genomics allows early and accurate selection of superior genotypes making it possible to fast-track the development of climate-resilient, high-yielding, and nutrient-rich crop varieties (Ghosh *et al.*, 2018; Watson *et al.*, 2018). Moreover, rapid generation advancement facilitates faster fixation of edited alleles in genome-edited populations and accelerates backcrossing in marker-assisted introgression.

Principles and Methodologies of Rapid Generation Advancement. Rapid generation advancement refers to a set of controlled-environment techniques designed to accelerate plant growth and shorten generation time, enabling the completion of 4–6 generations per year, compared to the typical 1–2 generations under field conditions (Watson *et al.*, 2018). This approach allows breeders to rapidly advance generations and fix desired

traits more efficiently, significantly reducing the time required to develop new cultivars. The concept was inspired by NASA's plant growth protocols for space agriculture and was first adapted to wheat breeding at the John Innes Centre and the University of Queensland. It represents a shift from traditional season-bound breeding to year-round, rapid-cycle advancement.

Rapid generation advancement relies on optimized environmental parameters within growth chambers, greenhouses, or controlled-field facilities. The core strategies include:

- **Extended Photoperiod:** Typically, 22 hours of light and 2 hours of darkness per 24-hour cycle using LED or high-pressure sodium lamps, which accelerates photosynthesis and vegetative growth (Watson *et al.*, 2018).

- **Controlled Temperature:** Maintaining warmer day/night temperatures (22–25°C during day, 17–20°C at night) promotes uniform growth and flowering.

- **Humidity and Irrigation Control:** Controlled humidity (60–70%) and precision watering systems help avoid abiotic stress and ensure uniform development.

- **Early Seed Harvesting:** Seeds are harvested at physiological maturity, often 2–3 weeks post-anthesis, and treated (e.g., drying or chilling) to induce rapid germination for the next cycle (Ghosh *et al.*, 2018).

- **Soil-less or Accelerated Growth Media:** Use of nutrient-rich media or hydroponics speeds up early seedling growth.

In wheat (*Triticum aestivum* L.), for example, an extended photoperiod of 22 hours light and 2 hours dark is commonly used, allowing up to six generations per year (Watson *et al.*, 2018). Early seed harvesting is practiced about 14 to 21 days post-anthesis, with subsequent seed drying or chilling treatments to promote rapid germination. Hydroponic systems or nutrient-rich soil media further enhance early seedling growth and uniform development.

In chickpea (*Cicer arietinum*), which naturally has a longer growth cycle, similar extended photoperiod and controlled temperature regimes are employed to achieve up to four generations annually (Dixit *et al.*, 2022). Controlled humidity and precise irrigation prevent moisture stress during critical flowering stages. Early seed harvesting combined with seed chilling improves

germination rates, enabling faster cycling. Tomato (*Solanum lycopersicum*) rapid generation advancement takes place primarily in controlled greenhouse environments with LED lighting providing extended photoperiods, allowing four to five generations per year. Use of nutrient-enriched soilless media accelerates seedling vigor and flowering. Early fruit harvesting and seed extraction speed up trait pyramiding and transformation recovery.

Barley (*Hordeum vulgare*) breeding programs manipulate temperature and photoperiod to rapidly develop populations (Hickey *et al.*, 2019). Seeds are dried and harvested early to allow generation cycling in 8 to 10 weeks. Precision irrigation supports optimal moisture levels, ensuring uniform growth and aiding disease management.

These crop-specific examples demonstrate how carefully controlled environmental factors such as photoperiod, temperature, humidity, and growth media are applied in rapid generation advancement to significantly shorten generation times across diverse crops.

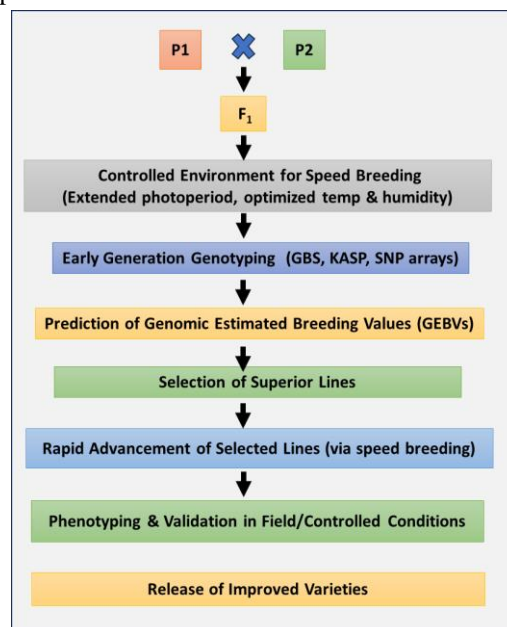


Fig. 1. Schematic representation of rapid generation advancement pipeline integrated with genomic selection, marker-assisted selection, and genome editing.

Table 1: Crop-specific Generation Advancement Potential and Applications.

Crop	Scientific Name	Generations per Year	Applications	References
Wheat	<i>Triticum aestivum</i>	Up to 6	Trait fixation, genomic selection, genome editing	Watson <i>et al.</i> (2018); Ghosh <i>et al.</i> (2018)
Barley	<i>Hordeum vulgare</i>	Up to 6	Early-stage screening, mapping populations	Watson <i>et al.</i> (2018); Hickey <i>et al.</i> (2019)
Chickpea	<i>Cicer arietinum</i>	Up to 4	Rapid generation advancement in long-duration legumes	Dixit <i>et al.</i> (2022)
Canola	<i>Brassica napus</i>	Up to 4–5	Accelerated backcrossing, trait introgression	Watson <i>et al.</i> (2018); Hickey <i>et al.</i> (2019)
Tomato	<i>Solanum lycopersicum</i>	Up to 4–5	Trait pyramiding, recovery of edited/transgenic lines	Ghosh <i>et al.</i> (2018); Hickey <i>et al.</i> (2019)
Emerging Crops	Lentil, peanut, maize, groundnut	Varies	Protocol optimization for photoperiod-sensitive or longer-cycle crops	Ghosh <i>et al.</i> (2018); Watson <i>et al.</i> (2018)

Advantages of Rapid Generation Advancement

- **Time Efficiency:** Reduces breeding cycle duration by 2–3 times.
- **Scalability:** Compatible with marker-assisted and genomic selection strategies.
- **Flexible Infrastructure:** Can be implemented in growth chambers, polyhouses, or glasshouses.
- **Integration with Modern Tools:** Serves as a foundational platform for integrating CRISPR/Cas, transgenic validation, and high-throughput phenotyping.

Enabling Genomics in Rapid Generation Advancement Pipelines. Integrating genomics with rapid generation advancement holds immense potential for accelerating genetic gains in crop improvement. Rapid generation advancement not only reduces generation time but also complements genomic tools that enable early and accurate selection. Major genomic approaches synergistically working with rapid generation advancement include:

Genomic Selection. Genomic selection relies on genome-wide marker information to predict the genetic value of individuals, known as genomic estimated breeding values (GEBVs). In rapid generation advancement-integrated pipelines, GEBVs can be calculated early in the plant's life cycle, allowing breeders to select superior lines without waiting for full phenotypic data.

Genomic selection offers several advantages when integrated with rapid generation advancement, such as reducing breeding cycles, accelerating trait fixation, and enabling early generation selection particularly in F₂ or F₃ stages. This integration also enhances selection accuracy for complex polygenic traits like yield and stress tolerance. In wheat, the combination of genomic selection and rapid generation advancement has been effectively used to fast-track the development of lines with improved drought tolerance and rust resistance (Watson *et al.*, 2018; Crossa *et al.*, 2017). Similarly, in chickpea, Varshney *et al.* (2021) demonstrated the successful application of this approach to rapidly select for traits such as flowering time and seed weight.

Marker-Assisted Selection. Marker-assisted selection enables precise identification and selection of individuals carrying target alleles through the use of molecular markers. When applied within a rapid generation advancement framework, marker-assisted selection allows for the rapid introgression and fixation of key genes across fewer breeding cycles. Notable target genes include *Rht* for dwarfing in wheat, *Sub1* for submergence tolerance in rice, and *Lr34* for leaf rust resistance. Molecular tools such as Kompetitive Allele Specific PCR (KASP) markers support high-throughput and cost-effective genotyping. SNP chips like the wheat 35K and 90K arrays are widely used for background selection and trait tracking.

Genome Editing. Genome editing technologies, especially CRISPR/Cas9, allow for targeted modification of specific genes. When integrated with rapid generation advancement platforms, genome editing can accelerate the development of homozygous edited lines and significantly reduce the time required

for validation and trait fixation. This also facilitates multi-trait genome editing, particularly in complex polyploid crops like wheat and in transformation-recalcitrant species such as tomato (Gao, 2021).

Genotyping Platforms. High-throughput genotyping underpins all genomic breeding approaches, offering fast and cost-effective analysis of large populations in each rapid generation cycle. Key platforms include genotyping-by-sequencing, which enables low-cost, genome-wide SNP discovery; SNP arrays, essential for marker-trait association and background selection; and KASP assays, ideal for routine marker-assisted selection workflows. These genotyping outputs guide selection decisions at every stage of the rapid generation advancement pipeline.

Integration with Other Omics. The integration of rapid generation advancement with advanced omics platforms represents a transformative step in accelerating both the understanding and manipulation of complex traits in crop plants. Multi-omics approaches, transcriptomics, metabolomics, and phenomics complement rapid generational turnover and enhance selection precision and trait dissection.

Transcriptomics provides insights into early gene expression patterns under stress or during trait selection. Combined with rapid generation advancement, transcriptomic analysis at early growth stages facilitates identification of candidate genes and regulatory networks involved in yield, stress adaptation, and development. Metabolomics offers a biochemical snapshot of cellular responses, especially under nutritional or abiotic stress. Coupling metabolomics with rapid generation advancement allows selection of lines with favorable metabolic profiles related to stress resilience or nutrient use efficiency. Phenomics involves high-throughput, non-destructive phenotyping using advanced imaging technologies, such as RGB imaging, hyperspectral cameras, and LiDAR, enabling objective trait data collection in controlled environments (Fiorani and Schurr 2013).

Together, these omics enhance the precision and efficiency of rapid generation advancement pipelines, creating a systems biology framework for next-generation crop improvement.

Applications and Success Stories. Rapid generation advancement combined with genomics has demonstrated remarkable success in key crops. Wheat breeding programs have accelerated development of rust-resistant lines by achieving up to six generations per year, reducing breeding timelines from years to months (Watson *et al.*, 2018). Chickpea breeders at ICRISAT implemented rapid generation advancement coupled with genomic selection to enhance breeding efficiency for early flowering and drought tolerance traits (Varshney *et al.*, 2021). Barley programs integrate rapid generation advancement with functional genomics for rapid gene function screening.

Beyond stress tolerance, rapid generation advancement has been instrumental in biofortification efforts, accelerating introgression and pyramiding of micronutrient traits such as iron and zinc in staple

crops, thereby contributing to food security and nutritional quality (Bouis and Saltzman 2017).

Advantages of Integrating Rapid Generation Advancement with Genomics

- Reduces breeding cycle duration by two to three times, dramatically accelerating new variety release.
- Facilitates early fixation of elite alleles and efficient backcrossing/pyramiding of favourable genes.
- Enhances population improvement strategies with rapid response to emerging climate stresses, pests, and diseases.
- Provides critical responsiveness under rapidly changing environmental conditions.

Limitations and Challenges

Despite its potential, implementation faces challenges:

- Infrastructure intensive: Requires controlled environment facilities with LED lighting, temperature, and humidity controls, which can be cost-prohibitive in resource-limited settings.
- Genotype-by-environment interactions under artificial conditions may not always represent field performance, raising external validity concerns.
- Requires skilled personnel for managing complex datasets and breeding protocols.
- Scaling technology in developing countries remains difficult due to costs and expertise requirements.

CONCLUSIONS

Rapid generation advancement and genomics are complementary forces that, when integrated, revolutionize crop improvement by significantly shortening breeding cycles and enhancing selection accuracy. This synergy is critical under climate change scenarios, enabling rapid development of resilient and nutrient-rich varieties. The future lies in fully integrated, automated pipelines combining speed, precision, and sustainability to meet global food demands.

FUTURE SCOPE

Artificial intelligence and machine learning offer promise for optimizing breeding pipelines by predicting optimal genotype combinations and guiding selection. Integration with digital breeding platforms such as Breeding Insight and Excellence in Breeding System will facilitate data management and increase efficiency. Community seed banks could leverage rapid generation advancement to adapt local varieties quickly to changing climates and emerging stresses. Moreover,

these technologies hold potential for orphan and underutilized crops, critical for regional food security and biodiversity.

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