Eco. Env. & Cons. 29 (October Suppl. Issue) : 2023; pp. (S149-S159)
Copyright@ EM International
ISSN 0971–765X

DOI No.: http://doi.org/10.53550/EEC.2023.v29i05s.027

Revolutionizing Crop Improvement: The Crucial Role of Genomic Selection in Accelerating Speed Breeding

Chilamakuri Prudhvi Sai Gowtham, Aarti Sharma*, Tumu Sahithi and Shridhar Kalasgond

Lovely Professional University, School of Agriculture, Phagwara, Punjab, India

(Received 21 March, 2023; Accepted 26 May, 2023)

ABSTRACT

The use of GS in crop breeding has emerged as a potent tool to improve the productivity of crops. This process predicts breeding values through genetic data, enabling an efficient and effective way to enhance crop yields. Coupled with speedy breeding techniques, this technology has immense potential to speed up the process of genetic improvement and bolster food security, which is crucial in light of changes in climate patterns and the surging global populace. However, several challenges must be addressed before leveraging its full potential. This review highlights the critical role of genomic selection in speeding up crop breeding for better yields while considering essential factors such as computational power, marker density and trait heritability that influence its efficacy. Furthermore, we delve into recent advances that have been made in this field and how they can revolutionize sustainable agriculture practices. The ultimate goal is to provide insights into how genomics can tackle worldwide agricultural challenges while improving human health and well-being. Genomic selection coupled with speedy breeding techniques provides immense opportunities for farmers worldwide to improve their output significantly. However, before this can be realized on a large scale, careful attention must be given to understanding how these technologies work together effectively and efficiently. With more research being conducted, we look forward to gaining deeper insights into the future possibilities offered by these methods in achieving global food security goals.

Key words : *Speed Breeding, Genomic Selection, SB protocols, Genomic tools, CRISPR-Cas9*

Introduction

As the world's population grows unprecedentedly, i.e., "Expected to hit 9.7 billion by 2050." (Samantara *et al.,* 2022), ensuring everyone can access adequate food has become a significant challenge. Climate change has only exacerbated this problem by causing unpredictable weather patterns that make crop cultivation even more complex and risky (Shivakumar *et al.,* 2018). To try and overcome these challenges, researchers from UQ in Australia have been exploring innovative methods of increasing crop yields and developing new strains of plants that can better withstand harsh environmental conditions. One such method that has shown immense potential is "speed breeding", which involves using advanced lighting systems and other cutting-edge technologies to establish an optimal environment for plant growth (Sharma *et al.*, 2022). Experts can cultivate several generations of crops in a year instead of waiting for several seasons or even years, as with traditional methods. This ground-breaking approach has already yielded promising results in developing novel wheat strains - one of the most crucial staple crops worldwide (Samantara *et al.*, 2022). With speed breeding techniques, scientists could produce new wheat strains in just six months - a stark contrast to the two decades it would have taken using conventional methods (Watson *et al.*, 2018).

The success attained through SB has opened up new horizons for its application across various crops, thus providing renewed hope for global food security. Despite being a relatively new technology, speed breeding holds great promise to combat climate change-induced agricultural challenges (Abdul Fiyaz, *et al.*, 2020). Researchers continue exploring how it can be refined and applied on a broader scale to boost crop yields and global food security (Samantara *et al.*, 2022), and by employing this approach during the inactive period, farmers can obtain one harvest per year for a specific crop and two or three harvests in rare cases. Nevertheless, implementing SB methods can yield up to six crop cycles yearly for common wheat, durum wheat, barley, chickpeas, and peas. Furthermore, this method can has ten cultivation procedures for neglected or underutilized crops while efficiently combating food scarcity problems. (Chiurugwi *et al.*, 2018).

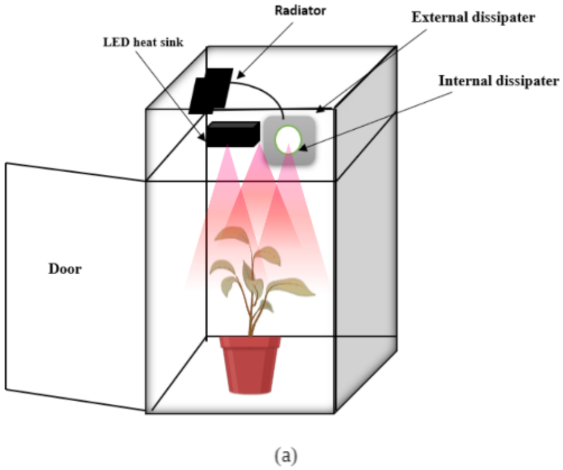
Plants are picked depending on their genetics instead of their physical characteristics in genomic selection (Lorenz *et al.*, 2011). As a result, breeders can detect and choose specific genes that are challenging to identify through conventional breeding methods. By recognizing these genes, they can choose plants withmore potential for disease resistance, high yield, and improved tolerance to environmental stressors such as drought and extreme temperatures. (Greenlee, 2022). As a result, speed breeding has become popular because it reduces the time needed for each generation and accelerates plant breeding (Shanmugavel *et al.*, 2022). Genomic selection has also improved speed breeding's efficiency and accuracy by allowing researchers to initially recognise the most promising off spring in the breeding process without waiting for multiple generations of crossbreeding experiments (Sandhu *et al.*, 2022). This eliminates trial-and-error approaches that may lead to unfavourable outcomes, enhancing precision. Furthermore, genomic selection allows breeders to concentrate on critical traits necessary for crop improvement while avoiding undesirable traits that could harm yield potential or marketability (Budhlakoti *et al.*, 2022).

Consequently, genomic selection has transformed speed breeding into an efficient tool for producing high-yielding and stress-resistant crops within shorter periods than conventional plant-breeding methods (Crossa *et al.*, 2017). Genomic selection holds promise for creating sustainable agricultural systems capable of meeting global food demands now and in the future by increasing accuracy and significantly reducing timelines (Bohra *et al.*, 2020). The interconnection between various farming methods and their overall impact on producing high-quality crops that satisfy the increasing worldwide demand for food will be analyzed. Despite highlighting the benefits of these techniques, this review will discuss the potential breakthroughs and developments in agriculture that may revolutionize crop cultivation and relieve famine in regions experiencing critical food shortages.

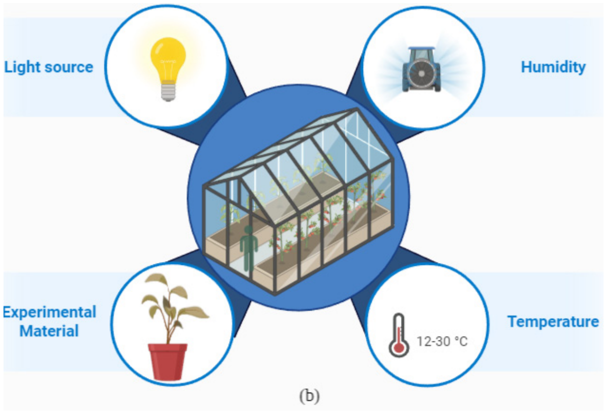
Speed Breeding for Faster Crop Growth: Protocol Design and Setup

NASA has reduced the duration required for crop studies by utilizing a confined growing space with extended light exposure (Abdul Fiyaz *et al.*, 2020). This was achieved using growth slots or greenhouses with LED lights offering optimal light intensity (Osama *et al.*, 2020). Additionally, they have implemented standardized procedures for SB protocols meant for barley, and wheat are examples of crops (Abdul Fiyaz *et al.*, 2020; Sharma *et al.*, 2022). The University of Queensland in Australia has also adopted this fast-breeding method as a norm in cereal research designs. This innovative technology hastens crop experimentation and encourages sustainable farming methods by decreasing breeding cycles and attaining food and industrial crop improvements more quickly (Riga, 2019).

The design created by SB maximises the essential metrological elements necessary for the growth and progress of plants (Swami *et al.*, 2023). These factors include light intensity, temperature regulation, humidity, and CO_2 concentration (Raza *et al.*, 2019; Samantara *et al.*, 2022; Swami *et al.*, 2023). LED lights with a specific wavelength spectrum help promote photosynthesis while reducing energy consumption (Rahman *et al.*, 2021). Temperature is regulated by air conditioning units and heaters that maintain optimal conditions throughout the day and night (Ghosh *et al.*, 2018; Wanga *et al.*, 2021). Humidity levels are monitored in real-time using misting systems that adjust accordingly. Additionally, an automated system maintains CO_2 concentrations higher than those in the atmosphere to stimulate plant growth rates (Soussi *et al.*, 2022). This technique has successfully accelerated crop generation cycles within controlled environments such as greenhouses or growth chambers while maintaining high-quality



(a) A diagram illustrating the process of Speed breeding within a Growth chamber.



(b) SB requirements in a Green House

yield standards (Samantara *et al*., 2022).

Speed breeding is an innovative solution that has emerged to improve traditional methods of plant propagation and introduce new techniques. This technique accelerates the breeding cycle, reduces generation time, and enables multiple generations annually. According to Jasmitha and Sandhyarani, crop breeding can benefit significantly from speed breeding. High-intensity lighting is critical to achieving optimal results in growth chambers or greenhouses for SB. In 2018, Watson *et al.* observed that Light Emitting Diodes equipped in growth chambers provide precisely regulated light intensities at different stages of plant growth, resulting in high-quality crops. Temperature control is another crucial factor when establishing a greenhouse or growth chamber for speed breeding because temp plays anessential role in determining the success rate of any experiment. Therefore, it is necessary to choose HVAC systems that maintain precise temperature ranges at every stage of plant development from germination to maturity. Hickey *et al*., 2019, proposed another approach involving small, low-cost units to expedite gene introgression related to grain dormancy inhibition and increase tolerance towards preharvest sprouting while enhancing protein levels within milling wheat varieties resulting in the overall improvement in nutritional value.

In plant breeding, there is an inherent need for efficient and comprehensive speed breeding strategies (Ghosh *et al*., 2018). These techniques have proven revolutionary in recent years by significantly reducing the time required to develop new plant species without compromising genetic variation. This novel approach has helped scientists expedite growth, saving time while ensuring optimal quality. An essential aspect of this method involves effectively controlling the metrological elements,such as temp and light intensity, to produce robust and healthy plants resistant to diseases and pests (Samantara *et al.*, 2022). The effectiveness of this procedure is primarily based on appropriate planning and installation methods that aim to establish simulated conditions suitable for amplifying plant ge-

Table 1. Protocols for Speed Breeding:

Sr.No	Methodologies	Uses	References
1.	Single seed descent (SSD)	SSD is the optimal choice for selecting crops quickly with speed breeding.	Samantara *et al.*, 2022
2.	Harvesting immature seeds	Harvesting premature seeds is done to decrease the time it takes for crops to reproduce.	Ghosh *et al.*, 2018
3.	Parallel testing	Multiple environments are simultaneously experimented with in order to refine the variables.	Ghosh *et al.*, 2018
4.	High throughput	The rSSD technology is employed for breeding on a large scale.	Samantara *et al.*, 2022

netic diversity while maintaining optimal growth rates throughout each phase of the process. If successfully executed, this advancement could enhance global food security by swiftly producing better crop varieties, abating the adverse effects of environmental pressures on productivity, and maximizing agricultural land yields per acre.

Enhancing Crops: Traditional Breeding vs. Genomic Selection

One way to enhance crops is by using traditional breeding techniques or genomic selection methods (Wang *et al*., 2018). Conventional breeding has been used for many years and relies on phenotypic selection to identify superior progenies based on physical attributes, which requires much expertise and patience (Anand *et al.,* 2023). Genomic selection is a more recent method that seeks to speed up genetic progress by utilizing markers found throughout the genome to approximate the impact of all loci, which allows for a broader and more trustworthy selection process (Budhlakoti *et al.,* 2022). However, while conventional breeding can maintain diversity within populations and select specific traits not identified through genomics, it is less accurate and efficient than genomic selection (Strandén *et al.,* 2019). Therefore, crop breeders seeking to improve yield, disease resistance or nutritional value may prefer the latter approach as it offers a quicker and more precise way of identifying desirable traits (Wang *et al.,* 2018).

Plant breeding has produced a wide variety of plant species through traditional methods. However, it is essential to note that these methods have not yielded the same genetic advancements as conventional techniques (Breseghello and Coelho, 2013; MacNeil, 2021). Phenotypic selection, for instance, has resulted in three times more genetic progress than customary breeding practices. However, when dealing with complex traits controlled by intricate genetic systems characterized by low heritability and high levels of epitasis, Genome Selection (GS) is an effective tool for accelerating crop improvement efforts. In addition, modern genomic technology and data analysis can be utilised in GS to swiftly identify and select desirable genetic traits in crops without requiring time-consuming phenotyping methods (Budhlakoti *et al.,* 2022). GS offers a hopeful chance to improve farming output and maintain food security in the face of climate change and population growth affecting worldwide food supply

Table 2. A depiction of the arrangement and configuration of SB is presented below:

S. No.	Procedures of SB	Requirement and Methodologies	Uses	References
1.	Optimal SB protocol layout:	Speed breeding boxes	Speed breeding boxes are installed in the climate chamber to optimize parameters through parallel testing.	IRRI, 2022
		Surfaces that reflect	The boxes have reflective interiors for optimal light usage.	Queensland, 2018
		LED lighting	LED lights are used for crops that need shorter days to grow. Therefore, the rapid single seed descent rSSD system's effectiveness is influenced by light quality factors.	Ghosh *et al*., 2018
2.	Speed breeding arrangement:	Photoperiod	There are three photoperiod protocols commonly used: 1. 22 hours of daylight followed by 2 hours of darkness. 2. 16 hours of daylight and 8 hours of darkness. 3. Equal amounts of daylight and darkness, totaling 24 hours.	Pereira *et al*., 2021
		Temperature	Set temperature from 12 ^{0}C to 30 ^{0}C and gradually increase brightness and temperature for 90 minutes to simulate natural transitions of dawn and dusk.	Swami *et al*., 2023
		Light sources	Red and blue LEDs and SVL.	Ghosh *et al*., 2018
		Humidity	The ideal humidity for plant growth and breeding is 60-70%.	Samantara *et al*., 2022

chains (He and Li, 2020; MacNeil, 2021).

GS is broadly used in crop breeding practices. However, it can be challenging to implement due to the abundance of genetic markers compared to observable traits (Wang *et al.,* 2018; Stewart-Brown *et al*., 2019; Anilkumar *et al.,* 2022). Algorithms and models such as GBLUP, Bayesian analysis, and ML (Machine learning) have been employed to improve prediction accuracy (Tong and Nikoloski, 2021). Despite these challenges, GS has already shown its potential in improving crop breeding by maximizing genetic gain while minimizing time and cost. Additionally, integrating GS with other innovative breeding techniques has accelerated its adoption in crop improvement programs. This approach enables breeders to identify hard-to-detect traits using traditional methods. With continuous advancements in genomic tools and technologies, GS is expected to become crucial for achieving sustainable crop production and ensuring food security (MacNeil, 2021).

One way to evaluate the breeding and genetic values of untested individuals in a testing population (TST) is by using genomic estimated breeding values (GEBVs). This method, called GS, combines molecular and phenotypic data from a training population (TRN) to determine the GEBVs, as Crossa *et al.* (2017) described. This technique can replace multiple selection cycles that require phenotyping, reducing costs and shorter development times for new varieties. According to Crossa *et al.* (2017), GS offers several advantages over phenotype-based selection, including cost reduction and faster variety development (Crossa *et al*., 2017). Furthermore, according to Sood (2022), a promising technique called genomic selection can enhance polygenic characteristics, especially crop yield, and lead to better genetics and higher crop production. This method has replaced the traditional marker-assisted selection approach with more accurate forecasts and quicker, less expensive breeding gains. Utilizing GS in breeding offers a significant advantage as it establishes a framework that considers all molecular markers to evaluate the genetic potential of candidate performance for selection. This reduces time and costs per cycle compared to phenotypic-based selection when producing varieties (Sood, 2022).

Advantages of utilizing Genomic Selection in SB

By utilizing markers with high density and analyzing phenotypes, genomic selection can enhance complicated traits controlled by various genes with minor effects (Bhat *et al.,* 2016). Furthermore, it permits breeders to anticipate the breeding capabilities of specific lines, resulting in quicker identification of exceptional genotypes and fewer selection cycles needed, ultimately reducing cycle time (Crossa *et al*., 2017). The ability of genomic selection to target multiple traits is a notable benefit as it allows for attaining several advantages at once. For example, breeders can improve selection accuracy by focusing on characteristics such as disease resistance or high yields and choosing plants with favourable qualities (Swami *et al*., 2023). Additionally, this approach reduces the time of selecting plants by decreasing the number of selection cycles required.By adopting genomic selection, breeders in agriculture and plant breeding industries can save considerable time and money by phenotyping half of the population without the need for physical measurement of each plant (Xu *et al*., 2020).

Speeding up breeding by shortening the time between crosses and reducing cycles can help breeders and researchers. Newer breeding techniques like genetic manipulation, genomic selection, and doubled-haploid technology have also helped improve crops such as wheat, rice, and maize. (Hickey *et al.,* 2017). By manipulating the duration of light exposure and temperature, along with effective breeding methods, the impact of these technologies can be significantly enhanced (Wolter *et al.,* 2019).

The formula utilized by the breederis used to predict changes in a trait resulting from selection, and evolutionhelps determine genetic gain in breeding programs. The equation can be expressed as $R= (\ddot{a}g\times i\times r)/L$. This formula examines how traits change over time. The yearly change in the trait (R) is influenced by genetic differences within the population ($\ddot{a}$ g), selection intensity (i), the accuracy ofselection (r), and length of the breeding cycle (L). Shortening the breeding cycle using SB protocols can improve genetic gain in crop improvement programs. This technique quickly advances through many plant generations, speeding up the breeding process. Crossing and line improvement are particularly beneficial prior to field valuation, resulting in more successful and timely achievements of desired genetic advancements (Begna, 2022).

Utilization of Genetic Tools in SB Programs

Advancements in genetic tools like MAS (Rai, 2022), HTP(Ahmar *et al*., 2020; Begna, 2022), GS (Jighly *et* *al*., 2019; Ahmar *et al*., 2020; Varshney *et al*., 2021), gene editing (Ahmar *et al*., 2020). The utilization of optical contribution selection and haplotype-based breeding has brought about a significant change in SB techniques (Varshney *et al*., 2021). It has allowed for the rapid development of crop varieties that yield high amounts to meet the increasing demand for food and tackle climate change issues. Moreover, genomics-assisted breeding has allowed plant breeders to reduce the generation time, enhance breeding effectiveness, and hasten genetic improvement.

Begna (2022) pointed out that a revolution in crop breeding has occurred using SB, The technique of SB is used to speed up plant growth rates by adjusting the duration and intensity of light. This method allows for six generations per year instead of just one or two using conventional methods. Additionally, genotyping-by-sequencing (GBS) is a crucial tool during the process. GBS helps researchers identify thousands of genetic markers across the genome, which provides valuable information on quantitative trait loci (QTLs), single nucleotide polymorphisms (SNPs), and copy number variations (CNVs). These insights are essential in improving our understanding of complicated traits such as disease resistance, yield potential, and stress tolerance.

Rehman *et al.* (2020) further elaborated on how genomic tools can be leveraged more effectively through speed cloning from wild relatives and genome editing using CRISPR-Cas9 technology. Speed cloning enables the quick production of genetically identical clones from wild relatives with desirable characteristics. At the same time, CRISPR-Cas9 makes it possible to precisely target genes responsible for specific traits without affecting other parts of the DNA sequence. As Rehman *et al.* noted, this combination could eventually lead to SB, which may lead to faster advancement of crops in half the standard time frame than conventionally bred crops.

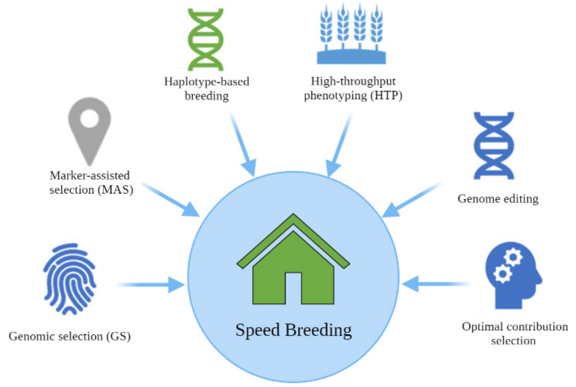


Fig. 2. Schematic representation of genomic tools used in Speed breeding.

Leng *et al.* (2017) emphasized that genomics-assisted selection provides a promising way to expedite crop improvement cycle times using molecular biology techniques. Leng *et al.* noted that the method allows for a better understanding of trait inheritance and genomic architecture, which helps identify QTLs associated with critical traits such as yield potential. With this information, breeders can use marker-assisted selection to identify plants with favourable alleles or associated with desirable phenotypes, resulting in a faster genetic gain. Genomics tools such as GBS and CRISPR-Cas9 have revolutionized SB by reducing generation time and improving breeding efficiency. These advancements provide valuable insights into crop genetics and offer opportunities for sustainable food production amidst global climate change challenges.

Challenges of Implementing Genomic Selection in SB

GS has shown great promise in advancing the genetic advancements of various species, particularly crops. GS allows breeders to predict an individual's genetic worth using their genomic data, resulting in the selection of superior individuals early in breeding and accelerating genetic gain. However, incorporating GS into SB presents significant challenges that require innovative solutions. For example, high-throughput genotyping technologies produce massive amounts of genomic data quickly and accurately, which requires a significant investment in infrastructure and equipment for breeding programs with limited resources. Also, managing extensive genomic data is computationally challenging and requires specialized skills and software (Juliana *et al*., 2018; Wartha and Lorenz, 2021). Another challenge is accurately evaluating trait heritability when implementing GS in SB due to discrepancies between enclosed settings like growth chambers or greenhouses in contrast toopen-field cultivation conditions that may impact yield potential (Begna, 2022).

Furthermore, farmers must consider the cost-benefit ratio before adopting this technology because they require cost-effective commodities from reliable sources that meet quality standards mandated by regulations such as equitable trade practices worldwide (Xu *et al.,* 2023). Finally, it is crucial to consider ethical concerns when using advanced technologies like gene editing or other biotechnological tools for crop improvements because they carry potential risks regarding biodiversity and public perception fears about GMOs' safety if consumers perceive them as unsafe or pose long-term health effects (Begna, 2022). Implementing genomic selection in SB requires creative solutions due to substantial challenges such as genotyping costs and data administration, trait heritability estimation accuracy, fiscal constraints, and ethical considerations that must be pondered upon before adopting this technology for crop improvement. While the benefits of using GS are apparent, weighing the advantages against these challenges is critical before implementing them into existing breeding programs (Begna, 2022).

An appropriate equilibrium between the quantity of markers and feasible genomic selection is essential, as inadequate markers can lead to inaccurate results.On the other hand, using too many can lead to increased expenses and computational complexity. This is a significant consideration for genomic selection (Krishnappa *et al.*, 2021). Wheat breeding programs face difficulty in forecasting the genotypic values of individuals for genomic selection. This arises from additive and nonadditive effects determining the final breeding value. Rapid-cycle recurrent genomic selection (RCRGS) strategies can potentially enhance genetic gain for wheat grain yield (GY), but their practical implementation is limited. Studies show that RCRGS has boosted genetic gain for GY in wheat by 12.3% after three cycles of recombination (Dreisigacker *et al.*, 2023). However, critical agronomic attributes such as days to heading, days to maturity, and height of the plant were altered, which were not selected for. As a result, the authors suggest implementing GS and multi-trait prediction models to account for these changes.

Future Avenues for Genomic Selection in SB

The application of GS has the potential to accelerate crop breeding and increase output, particularly for quantitative characteristics like crop yield. Moreover, it can reduce the duration needed for selection cycles, resulting in expedited crop genetic improvement. (Watson *et al.,* 2019). A significant benefit of using genomic markers is their ability to provide more precise assessments of genetic similarity between individuals than conventional lineage connections. (Habier *et al.*, 2007). Additionally, genome-wide markers can capture Mendelian sampling effects, further boosting the precision of these estimations. With increased accuracy, breeders can make well-informed decisions about which plants to select and how to pair them for optimal results (Watson *et al.,* 2019).

GS can potentially speed up the breeding process for crops such as Intermediate wheatgrass (IWG) and other perennial plants with a lengthy breeding timeline. This could be particularly important in light of food security concerns and a rapidly changing climate. The research suggests significant opportunities to apply GS techniques to improve breeding efforts in various agricultural contexts. One key advantage is reducing selection cycles and accurately estimating relatedness between individuals, leading to sustainable agriculture and greater food security during times of urgency (Crain *et al.,* 2021).

Undoubtedly, GS has the potential to update agricultural development, despite a few challenges that must first be tackled. One of the biggest hurdles in implementing GS for agricultural purposes is managing complex trait architectures, which can make identifying specific genes problematic due to numerous gene variants underlying phenotypic variation. However, it isessential to note that previous studies have shown significant strides towards unlocking the full potential of GS for agricultural use. With more research and development, we may soon see widespread implementation of this innovative technology in agriculture, unlocking unparalleled benefits for farmers and consumers (Wartha and Lorenz, 2021).

Next-generation sequencing and advanced genomic and phenomic tools, along with methods like genomic selection and SB, can significantly speed up the genetic enhancement of pulses. Additionally, pulses are a cost-effective plant-based protein source for human consumption. Furthermore, given the changing global food consumption patterns due to climate change, enhancing pulses has become crucial in the current global transitional scenario. Therefore, it is imperative to explore opportunities that accelerate pulse growth for achieving sustainable global food security (Kumar *et al.*, 2021).

Ethical Implications of Genomic Selection in SB for Crop Improvement

GS in SB for crop improvement is an area of research with great promise to revolutionize modern agriculture (Parveen *et al.,* 2023). However, it also raises ethical considerations that must be addressed before implementation on a larger scale (Parveen *et al.,* 2023). These ethical concerns related to using genomic selection in SB are impacts on biodiversity, farmers' rights, and distribution of benefits and risks (Kramer and Meijboom, 2022). Rapid development and deployment of new agricultural techniques could have unintended consequences for biodiversity, as selective breeding may lead to monoculture farming practices that reduce plant diversity and harm ecosystems (Bourke *et al.,* 2021). Farmers who wish to retain control over their seed stock might find themselves at odds with companies seeking access to proprietary genetic information used during crop production processes such as speed-breeding, which could create tension between stakeholders involved in agriculture. Finally, issues surround the equitable distribution of benefits and risks associated with implementing genomic selection in speed-breeding programs worldwide for crop improvement. Future research should explore areas where the genomic selection in SB can be employed to meet global food security needs while ensuring equitable distribution of benefits across different populations (Budhlakoti *et al*., 2022).

Although genomic selection techniques like CRISPR and TALEN have potential benefits for agriculture, they also raise ethical concerns and may have negative consequences. In addition to the risk of reducing genetic diversity within crop populations, this approach could affect biodiversity, farmers' rights, and the fair sharing of benefits and risks. According to Louwaars and Jochemsen (2021), these issues relate to our broader relationship with nature. By favouring specific genetic variants over others, genomic selection might undermine biodiversity and create inequalities in access to its benefits.

The effect of new technologies on farmers' rights has become a topic of concern. According to the Stakeholder Questionnaire (2020), specific genome editing methods may result in mutagenesis or cisgenesis/intragenesis/transgenesis, affecting intellectual property rights related to plant varieties produced through these processes. In addition, seed-saving practices commonly used by farmers could become impractical due to restrictions imposed by companies holding patents over genomes created using gene editing techniques. The distribution of benefits and risks associated with SB is also a cause for concern. The European Parliament and Council Decision (EU) 2019/1904 (2020) recognizes new genomic techniques, including genome editing, as NGTs subject to personal data protection regulations, highlighting concerns about privacy regarding information shared between producers/breeders who use these approaches and consumers/end-users who purchase products derived from them.

Improving crop yields and global food security can be achieved through genomic selection. However, it is crucial to consider the ethical concerns associated with implementing it. This includes the reduction of genetic diversity in crops, possibly infringing farmers' rights, and ensuring fair distribution of advantages and disadvantages. These concerns must be acknowledged to fully utilize the benefits of this new technology while preventing any negative impacts on individuals or society.

Conclusion

The potential of genomic selection in revolutionizing crop improvement is immense. By accelerating the speed breeding process, we can meet the ever-growing demand for food production and address global issues such as climate change and population growth. Scientists have been able to identify desirable plant traits more efficiently through the use of technological advancements and genomics research. Breeders can now select plants with desired traits much faster than before, thanks to genome-wide association studies (GWAS) and QTL mapping.

By utilizing machine learning algorithms in genomic selection, the accuracy has been amplified while human error has been minimized. In addition, this has allowed breeders to use specific genetic markers to forecast yield performance, thus saving valuable time and resources that would have otherwise been used for the manual testing of plants. The incorporation of these tools has proven to be quite beneficial despite the challenges associated with data management and ethical concerns surrounding GMOs. However, with sustained research efforts to improve precision agriculture techniques, genes will continue to enhance crop production worldwide.

Genomic Selection has shown promising outcomes in plant science research, including gene discovery, marker-assisted selection, and agronomical improvement at a whole-genome scale level. Scholars continuously seek new methods to enhance crop productivity using genomics-based techniques to address current and future global challenges associated with feeding the ever-growing population sustainably. Hence, investing heavily in Genomic Selection could be vital for nations' economies to thrive while ensuring adequate food supply amidst severe climate changes caused by global industrialization. This review concludes that it can provide an alternative solution to traditional plant breeding and revolutionize crop improvement.

References

Abdul Fiyaz, R, Ajay, B. C., Ramya, K.T., Kumar, J., Raman Meenakshi Sundaram and Mohan, V. 2020. Speed Breeding: Methods and Applications. *Springer EBooks.* 31–49.

Ahmar, S., Gill, R. A., Jung, K.-H., Faheem, A., Qasim, M. U., Mubeen, M. and Zhou, W. 2020. Conventional and Molecular Techniques from Simple Breeding to Speed Breeding in Crop Plants: Recent Advances and Future Outlook. *International Journal of Molecular Sciences.* 21(7).

Anand, A., Subramanian, M. and Kar, D. 2023. Breeding techniques to dispense higher genetic gains. *Frontiers in Plant Science.* 13(1076094).

Anilkumar, C., Sunitha, N. C., Harikrishna, D.N.B. and Ramesh, S. 2022. Advances in integrated genomic selection for rapid genetic gain in crop improvement: a review. *Planta.* 256(5).

Begna, T. 2022. Speed breeding to accelerate crop improvement. *Int J Agric Sc Food Technol*. 8(2): 2.

Bhat, J.A., Ali, S., Salgotra, R.K, Mir, Z.A., Dutta, S., Jadon, V., Tyagi, A., Mushtaq, M., Jain, N., Singh, P.K., Singh, G.P. and V.P.K. 2016. Genomic selection in the era of next-generation sequencing for complex traits in plant breeding. *Frontiers in Genetics. 7*.

Bohra, A., Chand Jha, U., Godwin, I.D. and Kumar Varshney, R. 2020. Genomic interventions for sustainable agriculture. *Plant Biotechnology Journal.* 18(12): 2388–2405.

Bourke, P.M., Evers, J.B., Bijma, P., Apeldoorn, van, Smulders, Marinus J.M, Kuyper, T. W., Mommer, L. and Bonnema, G. 2021. Breeding beyond monoculture: Putting the "Intercrop" into crops. *Frontiers in Plant Science. 12*.

Breseghello, F. and Coelho, A.S.G. 2013. Traditional and Modern Plant Breeding Methods with Examples in Rice (*Oryza sativa* L.). *Journal of Agricultural and Food Chemistry.* 61(35): 8277–8286.

Budhlakoti, N., Kushwaha, A.K., Rai, A., Chaturvedi, K.K., Kumar, A., Pradhan, A.K., Kumar, U., Kumar, R.R., Juliana, P., Mishra, D.C. and Kumar, S. 2022. Genomic Selection: A Tool for Accelerating the Efficiency of Molecular Breeding for Development of Climate-Resilient Crops. *Frontiers in Genetics.* 13(832153).

Chiurugwi, T., Kemp, S., Powell, W. and Hickey, L. T. 2018. Speed breeding orphan crops. *Theoretical and Applied Genetics*. 132(3) : 607–616.

Crain, J., DeHaan, L. and Poland, J. 2021. Genomic prediction enables rapid selection of high performing genets in an intermediate wheatgrass breeding program. *The Plant Genome*. 14(2).

Crossa, J., Pérez-Rodríguez, P., Cuevas, J., Montesinos-López, O., Jarquín, D., de los Campos, G., Burgueño, J., González-Camacho, J. M., Pérez-Elizalde, S., Beyene, Y., Dreisigacker, S., Singh, R., Zhang, X., Gowda, M., Roorkiwal, M., Rutkoski, J. and Varshney, R.K. 2017. Genomic Selection in Plant Breeding: Methods, Models, and Perspectives. *Trends in Plant Science.* 22(11): 961–975.

Dreisigacker, S., Pérez-Rodríguez, P., Crespo-Herrera, L., Bentley, A.R. and Crossa, J. 2023. Results from rapid-cycle recurrent genomic selection in spring bread wheat. *G3 Genes | Genomes | Genetics.* 13(4).

Ghosh, S., Watson, A., Gonzalez-Navarro, O.E., Ramirez-Gonzalez, R.H., Yanes, L., Mendoza-Suárez, M., Simmonds, J., Wells, R., Rayner, T. and Green, P. 2018. Speed breeding in growth chambers and glasshouses for crop breeding and model plant research. *Nature Protocols.* 13: 12.

Greenlee, V. 2022. *Genomic selection eased for more plant, animal breeders*. Cornell Chronicle.

Habier, D., Fernando, R.L. and Dekkers, J.C.M. 2007. The Impact of Genetic Relationship Information on Genome-Assisted Breeding Values. *Genetics*. 177(4): 2389–2397.

He, T. and Li, C. 2020. Harness the power of genomic selection and the potential of germplasm in crop breeding for global food security in the era with rapid climate change. *The Crop Journal.* 8(5): 688–700.

Hickey, L. T., N. Hafeez, A., Robinson, H., Jackson, S. A., Leal-Bertioli, S.C.M., Tester, M., Gao, C., Godwin, I.D., Hayes, B.J. and Wulff, B.B.H. 2019. Breeding crops to feed 10 billion. *Nature Biotechnology.* 37(7): 744–754.

Hickey, L., Germán, S., Pereyra, S., Diaz, J., Ziems, L., Fowler, R., Platz, G.J., Franckowiak, J. and Dieters, M. 2017. Speed breeding for multiple disease resistance in barley. *Euphytica*. 213.

IRRI, 2022, September 19. *SpeedBreed: A crop breeding center built for speed*. International Rice Research Institute. https://www.irri.org/news-and-events/news/speedbreed-crop-breeding-center-built-speed

Jasmitha, M. and Sandhyarani, M. 2021. *Speed Breeding: innovative approach for present era of crop breeding*. Just Agriculture.1-12

Jighly, A., Lin, Z., Pembleton, L.W., Noel, Spangenberg, G.C., Hayes, B.J. and Daetwyler, H.D. 2019. Boosting genetic gain in allogamous crops via speed breeding and genomic selection. *Frontiers in Plant Science*. 10(1364).

Juliana, P., Singh, R.P., Poland, J., Mondal, S., Crossa, J., Montesinos López, O.A., Dreisigacker, S., Pérez Rodríguez, P., Huerta Espino, J., Crespo Herrera, L. and Govindan, V. 2018. Prospects and Challenges of Applied Genomic Selection-A New Paradigm in Breeding for Grain Yield in Bread Wheat. *The Plant Genome.* 11(3): 180017.

Kramer, K. and Meijboom, F.L.B. 2022. The Ethics of Innovations in Genomic Selection: on How to Broaden the Scope of Discussion. *Journal of Agricultural and Environmental Ethics.* 35(2).

Krishnappa, G., Savadi, S., Tyagi, B.S., Singh, S.K., Mamrutha, H.M., Kumar, S., Mishra, C.N., Khan, H., Gangadhara, K., Uday, G., Singh, G. and Singh, G. P. 2021. Integrated genomic selection for rapid improvement of crops. *Genomics*. 113(3): 1070–1086.

Leng, P., Lübberstedt, T. and Xu, M. 2017. Genomics-assisted breeding - A revolutionary strategy for crop improvement. *Journal of Integrative Agriculture.* 16(12) : 2674–2685.

Lorenz, A.J., Chao, S., Asoro, F.G., Heffner, E.L., Hayashi, T., Iwata, H., Smith, K.P., Sorrells, M.E. and Jannink, J.L. 2011, January 1. *Chapter Two - Genomic Selection in Plant Breeding: Knowledge and Prospects* (D.L. Sparks, Ed.). Science Direct; Academic Press.

Louwaars, N. and Jochemsen, H. 2021. An Ethical and Societal Analysis for Biotechnological Methods in Plant Breeding. *Agronomy.* 11(6): 1183.

Lynch, M. and Walsh, B. 1998. *Genetics and Analysis of Quantitative Traits* (Vol. 1). Sinauer Sunderland, MA.

MacNeil, M. 2021, March 30. *Study: genomic selection approach paves way for faster plant breeding*. CALS.

Osama, R., Ashraf, N., Yasser, A., Abdel Fatah, S., Masry, N. and Abdel Raouf, A. 2020. *Greenhouse plant growth supervision with the LED lights using machine learning*. 169–173.

Parveen, R., Kumar, M., Swapnil, null, Singh, D., Shahani, M., Imam, Z. and Sahoo, J.P. 2023. Understanding the genomic selection for crop improvement: current progress and future prospects. *Molecular Genetics and Genomics: MGG*.

Pereira, J., Mouazen, A.M., Foo, M. and Ahmed, H. 2021. A framework of artificial light management for optimal plant development for smart greenhouse application. *PLOS ONE.* 16(12): e0261281.

Queensland, U. 2018. *DIY crop speed breeding system to boost drought research*. Phys.org. https://phys.org/news/2018-11-diy-crop-boost-drought.html

Rahman, M.M., Field, D.L., Ahmed, S.M., Hasan, M.T., Basher, M.K. and Alameh, K. 2021. LED Illumination for High-Quality High-Yield Crop Growth in Protected Cropping Environments. *Plants*. 10(11): 2470.

Rai, K. K. 2022. Integrating speed breeding with artificial intelligence for developing climate-smart crops. *Molecular Biology Reports*. 49(12).

Raza, A., Razzaq, A., Mehmood, S.S., Zou, X., Zhang, X., Lv, Y. and Xu, J. 2019. Impact of Climate Change on Crops Adaptation and Strategies to Tackle Its Outcome: A Review. *Plants.* 8(2).

Rehman, N., Inam, S., Shahid, M., Ali, G. and Khan, M. 2020. *Speed Cloning Leading to Speed Breeding through Genome Editing*.

Riga, R. (2019 March 14). New brand of fast food under the microscope after scientists speed up crop production. *ABC News*.

Samantara, K., Bohra, A., Mohapatra, S.R., Prihatini, R., Asibe, F., Singh, L., Reyes, V.P., Tiwari, A., Maurya, A.K., Croser, J.S., Wani, S.H., Siddique, K.H.M. and Varshney, R.K. 2022. Breeding More Crops in Less Time: A Perspective on Speed Breeding. *Biology*. 11(2): 275.

Sandhu, K.S., Shiv, A., Kaur, G., Meena, M.R., Raja, A.K., Vengavasi, K., Mall, A. K., Kumar, S., Singh, P. K., Singh, J., Hemaprabha, G., Pathak, A.D., Krishnappa, G. and Kumar, S. 2022. Integrated Approach in Genomic Selection to Accelerate Genetic Gain in Sugarcane. *Plants.* 11(16): 2139.

Shanmugavel, P., Ramasamy, G., Vellingiri, G., Marimuthu, R. and Thiyagarajan, K. 2022. Speed Breeding: A Propitious Technique for Accelerated Crop Improvement. In *www.intechopen.com*. Intech Open.

Sharma, S., Kumar, A., Priyanka Dhakte, Gaurav Raturi, Gautam Vishwakarma, Barbadikar, K.M., Das, B.K., Shivaraj, S.M., Humira Sonah, and Deshmukh, R. 2022. Speed Breeding Opportunities and Challenges for Crop Improvement. *Journal of Plant Growth Regulation*. 42(1): 46–59.

Shivakumar, M., Nataraj, V., Kumawat, G., Rajesh, V., Chandra, S., Gupta, S. and Bhatia, V. 2018. Speed breeding for Indian Agriculture: a rapid method for development of new crop varieties. *Curr Sci.* 115: 7.

Sood, R. 2022. Era of Genomic Selection in Plant Breeding. *Just Agriculturel.* 2(8).

Soussi, M., Chaibi, M. T., Buchholz, M. and Saghrouni, Z. 2022. Comprehensive Review on Climate Control and Cooling Systems in Greenhouses under Hot and Arid Conditions. *Agronomy*. 12(3): 626.

Stewart-Brown, B.B., Song, Q., Vaughn, J.N. and Li, Z. 2019. Genomic Selection for Yield and Seed Composition Traits Within an Applied Soybean Breeding Program. *G3 Genes|Genomes|Genetics.* 9(7): 2253–2265.

Strandén, I., Kantanen, J., Russo, I.R.M., Orozco-ter Wengel, P. and Bruford, M.W. 2019. Genomic selection strategies for breeding adaptation and production in dairy cattle under climate change. *Heredity.* 123(3): 307–317.

Swami, P., Deswal, K., Rana, V., Yadav, D. and Munjal, R.

2023). *Chapter 3 - Speed breeding-A powerful tool to breed more crops in less time accelerating crop research* (Mohd. K. Khan, A. Pandey, M. Hamurcu, O. P. Gupta, & S. Gezgin, Eds.). Science Direct; Academic Press.

The European Parliament and Council Decision (EU) 2019/1904. (2020, February 10). *Stakeholder questionnaire on new genomic techniques to contribute to a Commission study requested by the Council*. Europa.eu.

Tong, H. and Nikoloski, Z. 2021. Machine learning approaches for crop improvement: Leveraging phenotypic and genotypic big data. *Journal of Plant Physiology*, 257(153354): 153354.

Varshney, R.K., Bohra, A., Roorkiwal, M., Barmukh, R., Cowling, W. A., Chitikineni, A., Lam, H.M., Hickey, L.T., Croser, J.S., Bayer, P.E., Edwards, D., Crossa, J., Weckwerth, W., Millar, H., Kumar, A., Bevan, M.W. and Siddique, K.H.M. 2021. Fast-forward breeding for a food-secure world. *Trends in Genetics.* 37(12): 1124–1136. https://doi.org/10.1016/j.tig.2021.08.002

Wang, X., Xu, Y., Hu, Z. and Xu, C. 2018. Genomic selection methods for crop improvement: Current status and prospects. *The Crop Journal.* 6(4): 330–340.

Wanga, M.A., Shimelis, H., Mashilo, J. and Laing, M.D. 2021. Opportunities and challenges of speed breeding: A review. *Plant Breeding.* 140(2): 185–194.

Wartha, C. and Lorenz, A. 2021. Implementation of genomic selection in public-sector plant breeding programs: Current status and opportunities Implementation of genomic selection in public- sector plant breeding programs: Current status and opportunities ARTICLE. *Crop Breeding and Applied Biotechnology.* 21.

Watson, A., Ghosh, S., Williams, M. J., Cuddy, W. S., Simmonds, J., Rey, M.-D., Asyraf Md Hatta, M., Hinchliffe, A., Steed, A., Reynolds, D., Adamski, N. M., Breakspear, A., Korolev, A., Rayner, T., Dixon, L. E., Riaz, A., Martin, W., Ryan, M., Edwards, D., and Batley, J. 2018. Speed breeding is a powerful tool to accelerate crop research and breeding. *Nature Plants.* 4(1): 23–29.

Watson, A., Hickey, L. T., Christopher, J., Rutkoski, J., Poland, J. and Hayes, B.J. 2019. Multivariate Genomic Selection and Potential of Rapid Indirect Selection with Speed Breeding in Spring Wheat. *Crop Science.* 59(5): 1945–1959.

Wolter, F., Schindele, P. and Puchta, H. 2019. Plant breeding at the speed of light: the power of CRISPR/Cas to generate directed genetic diversity at multiple sites. *BMC Plant Biology.* 19(1).

Xu, Y., Liu, X., Fu, J., Wang, H., Wang, J., Huang, C., Prasanna, B.M., Olsen, M.S., Wang, G. and Zhang, A. 2020. Enhancing Genetic Gain through Genomic Selection: From Livestock to Plants. *Plant Communications.* 1(1): 100005.

Xu, Y., Luo, H., Zhang, H., Yung, W.-S., Li, M.-W., Lam, H.M. and Huang, C. 2023. Feeding the world using speed breeding technology. *Trends in Plant Science*. 28(3): 372–373.