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Breeding 5.0: AI-Driven Revolution in Designed Plant Breeding

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Abstract The future of plant breeding is advancing towards greater precision, efficiency, and sustainability. Breeding 5.0 represents the forefront of future plant breeding, revolutionizing the field through innovative technologies and methods such as genome editing, artificial intelligence, and big data analysis, enabling integration and editing of genetic information. This will bring revolutionary changes to global agriculture, enhancing food productivity, improving food quality, and fostering resilience to climate change. Looking ahead, precise agriculture and personalized breeding will be crucial directions for development. The development of techniques like fluorescence-based hybridization and microscopic imaging will propel breeding advancements, while strategies focusing on environmental adaptability and climate change will help address evolving environmental challenges. The frontier technologies and methods of Breeding 5.0, the transformation of global food systems for human food security, and the significance of scientific collaboration and interdisciplinary research will shape the future direction and progress of plant breeding.
Keywords Plant Breeding 5.0; Genome editing; Artificial intelligence; Big data analysis; Sustainable development

1 Introduction

With the rise in global population and the emergence of global challenges such as climate change, agriculture is facing unprecedented pressure. In order to meet the growing demand for food, enhance crop adaptability, and improve agronomic traits, Plant breeding, as a key agricultural technology, has become increasingly important.

Over the past few decades, plant breeding has made tremendous progress, evolving from traditional trait performance selection to the precision revolution of genotype selection (Breeding 3.0), and further advancing to the breeding revolution of genetic information integration and editing (Breeding 4.0). Breeding 4.0 signifies the widespread application of genetic information integration and editing technologies, bringing new possibilities and opportunities to breeding efforts (Wallace et al., 2018). Breeding 5.0, on the other hand, involves the integration of advanced technologies such as genomic selection, high-throughput phenotypic analysis, and data analysis, making breeding strategies more precise and efficient (Kuriakose et al., 2020).

In the era of Breeding 4.0, by integrating genetic and genomic information, we can precisely select and edit plant genotypes to achieve more efficient and faster breeding goals. The emergence of genome editing technologies, such as the CRISPR-Cas9 system, allows us to directly intervene in the plant genome, enabling targeted gene editing and functional gene regulation.

With the rapid development of artificial intelligence and big data, unprecedented opportunities have emerged for plant breeding. The application of machine learning and data analysis enables us to better understand and predict the associations between plant traits and the genome, accelerating the breeding process and optimizing breeding strategies. Breeding 5.0 is characterized by the use of advanced technologies and methods in breeding, focusing on precision, efficiency, and exploring new breeding strategies and genetic potentials.

Looking ahead, plant breeding will continue to face numerous challenges such as ethical and moral considerations, sustainable agriculture, and social responsibility. However, as the future trend, Breeding 5.0 will continually drive innovation and progress in plant breeding, making greater contributions to global agricultural sustainability.

2 Innovation in Technology and Methods

2.1 Genome editing and precise genome design

Breeding 5.0 will further advance genome editing technologies, such as improvements to the CRISPR-Cas9 system and the introduction of new gene-editing tools. These technologies will enable more precise and efficient genome modifications, including knockout, knockin, gene function correction, or replacement of specific DNA segments (Adem et al., 2017; Alexander, 2018). Precise genome design will become a routine method, allowing breeders to accurately introduce or delete target genes in the plant genome, thereby achieving regulation and optimization of specific traits, creating stronger crop varieties, enhancing drought resistance, disease resistance, and increasing yield. Moreover, this technology will be utilized to improve the nutritional value of crops and enhance their ability to adapt to environmental conditions (Vu et al., 2021).

2.2 Application of artificial intelligence and big data in breeding

Breeding 5.0 will extensively employ artificial intelligence and big data analysis technologies. Through methods such as machine learning, deep learning, and data mining, we can better analyze and interpret massive amounts of plant genetic and phenotypic data. Artificial intelligence algorithms will assist in discovering potential gene-trait associations, predicting plant traits and quality, and optimizing breeding strategies. The application of big data will also expedite the breeding process, enhance selection efficiency, and provide a scientific basis for breeding decisions.

In fact, artificial intelligence and big data have already demonstrated significant potential in the field of breeding. For instance, modern plant breeding relies on genomic and phenotypic selection, involving the analysis of large datasets. Artificial intelligence plays a crucial role in handling these complex datasets, particularly in high-throughput phenotypic analysis, genomic selection, and environmental data analysis (Khan et al., 2022). Additionally, leveraging artificial intelligence and big data analysis can expedite breeding programs, especially in linking genotype to phenotype. Such integration can rapidly identify key genes, thereby accelerating crop improvement processes (Harfouche et al., 2019).

Big data analysis has enhanced the accuracy of predicting complex traits in crop breeding. Using a large amount of genotype and phenotype information can more accurately predict crop yield and other important traits (Singh and Prasad, 2021).

Furthermore, advancements in artificial intelligence have opened up new possibilities for breeding. Natural language processing models, such as ChatGPT, can be utilized to parse and comprehend vast amounts of scientific literature and research findings, providing breeders with broader knowledge and information. These intelligent tools can assist breeders in decision-making and predictions, offering more accurate and comprehensive breeding recommendations.

2.3 Application of multi-omics integration and systems biology approaches

Breeding 5.0 will further advance the application of multi-omics integration and systems biology approaches in breeding (Kuriakose et al., 2020). Integrating various levels of omics data, such as genetics, epigenetics, transcriptomics, metabolomics, etc., can comprehensively unravel the relationships between plant traits and the genome. Systems biology approaches, such as network analysis and metabolic pathway modeling, will aid in a deeper understanding of plant biological processes and interaction networks, offering new strategies and insights for achieving breeding goals.

Multi-omics approaches play a crucial role in elucidating the growth, aging, yield, and responses to biotic and abiotic stresses of crops. These methods have been applied in important crops such as wheat, soybeans, tomatoes, emphasizing the relationship between crop genomes and phenotypes through the integration of functional genomics with other omics data (Yang et al., 2021).

By combining systems biology with multi-omics datasets, our understanding of the molecular regulatory networks for crop improvement can be enhanced. The concepts of “phenotype to genotype” and “genotype to phenotype” can facilitate crop breeding improvements, especially under environmental stress conditions (Jamil et al., 2020).

Undoubtedly, with innovations in technology and methods, Breeding 5.0 will further enhance breeding efficiency, precision, and sustainability. Through genome editing and precise genome design, genetic improvements in plants will become more accurate and controllable. The application of artificial intelligence and big data will expedite the breeding process and optimize breeding strategies. The use of multi-omics integration and systems biology approaches will deepen our understanding of plant traits and genomes, providing more comprehensive support for achieving breeding objectives.

3 Emerging Fields and Applications

Breeding 5.0 will actively explore emerging fields and applications to meet the demands of precise agriculture and personalized breeding. It will utilize technologies such as fluorescence-based hybridization and microscopic imaging to deepen our understanding of plant biology. Additionally, there will be a focus on enhancing environmental adaptability and developing breeding strategies to address climate change, thereby promoting sustainable agriculture and food security. The development of these emerging fields and applications will further drive innovation and progress in plant breeding.

3.1 Precise agriculture and personalized breeding

Breeding 5.0 will integrate with precise agriculture to achieve more personalized breeding strategies. Precise agriculture utilizes technologies such as sensor technology, remote sensing, and geographic information systems, along with tools like cameras and mobile robots, to analyze the growth status of crops in real farmland settings. This provides crucial information for precise management and breeding experiments (Weyler et al., 2021). By combining the technologies and methods of Breeding 5.0, we can accurately select and cultivate crop varieties tailored to specific environmental conditions and agricultural needs. This personalized breeding approach will make agricultural production more sustainable, improve yields and quality, and reduce resource waste and environmental impact.

3.2 Advancements in fluorescence-based hybridization and microscopic imaging technologies

Fluorescence in situ hybridization (FISH) technology and microscopic imaging technologies have made significant progress in their application in plant breeding. These technologies play a vital role not only in gene localization and expression analysis but also in understanding the molecular mechanisms of plant growth and development. In the era of Breeding 5.0, the application of fluorescence-based hybridization and microscopic imaging technologies in breeding will see further development.

Fluorescence-based hybridization technology helps researchers visually observe and analyze gene expression and protein interactions in plants, providing in-depth insights into plant biological processes. For instance, by using FISH technology combined with immunofluorescence technique, specific proteins and DNA sequences can be located on the maize synaptonemal complex. This technology is widely applied in the study of plant meiotic chromosome, crucial for understanding the gene recombination process (Stack et al., 2020). FISH and microscopic imaging technologies are employed to precisely measure gene expression at the single-cell level, significantly contributing to the understanding of the impact of spatial or temporal-dependent processes on plant growth and development (Lucic et al., 2021).

With advancements in microscopic imaging technology, we can observe the structure and functionality of plant cells and tissues in high resolution and real-time. For example, FISH technology combined with high-throughput and super-resolution microscopy has been used to map and spatially define the contact frequency between different genomic regions. These methods greatly contribute to the understanding of the packaging of the human genome in the cell nucleus (Mao et al., 2020). Newly developed microscopic imaging methods, such as Expansion Microscopy (ExM), make it possible to achieve nanoscale imaging of ribonucleic acid (RNA) on traditional fluorescence microscopes, providing complex pattern information of gene expression at the cellular or subcellular level (Wen et al., 2021).

The application of these technologies will provide breeding with more information and tools, assisting us in better understanding and manipulating plant traits and adaptability.

3.3 Environmental adaptability and breeding strategies under climate change

Breeding 5.0 will focus on developing crop varieties that adapt to continuously changing environmental and climatic conditions. With the intensification of global climate change, crops face more frequent extreme weather events and stress. Therefore, breeders will strengthen breeding strategies for environmental adaptability and climate stability.

The genotype of plants responds differently to environmental changes. Studies indicate that genotype-environment (GxE) interactions significantly impact the phenotypic response of crop varieties under different environmental conditions, which is crucial for crop breeders (Teressa et al., 2021).

Epigenetic changes play a critical role in helping plants adapt to environmental stress. These changes can assist plants in “remembering” past stress events, allowing them to more effectively cope with future challenges (Ashapkin et al., 2020; Miryeganeh, 2021). This “plant stress memory” is essential for enhancing crop adaptability and yield potential (Sharma et al., 2022; Kashyap et al., 2023).

Quantifying the impact of climate-driving factors on crop yield and predicting optimal environmental conditions for different production scenarios through “environmental prediction” methods (based on generalized additive models and large-scale environmental covariate data) is crucial for developing crop varieties adapted to specific regional climates (Heinemann et al., 2022).

Conducting multi-environment trials (METs) on crops under different environmental conditions is a crucial means of assessing crop productivity and adaptability. This approach helps identify high-yielding crop varieties that perform stably under different climatic conditions (Lee et al., 2023).

In conclusion, key strategies in plant breeding for addressing the challenges of climate change include understanding and leveraging the interactions between genotype and environment, applying environmental prediction methods, utilizing epigenetic changes, and conducting multi-environment trials to enhance crop adaptability and yield stability.

4 Future Prospects and Challenges

4.1 Frontier technologies and methods in Breeding 5.0

Breeding 5.0 will witness the emergence of more cutting-edge technologies and methods, propelling breeding efforts to higher levels. New technologies such as genome editing, synthetic biology, artificial intelligence, and high-throughput phenotyping will bring about breakthroughs in breeding (Chen et al., 2022). The development of genome editing technologies will enable more precise modification of plant genomes, achieving faster and more accurate breeding goals (Juma et al., 2021). The application of synthetic biology will allow the design and construction of entirely new genomes, unlocking novel breeding possibilities (Kim et al., 2020). The application of artificial intelligence and big data will make the breeding process more efficient and intelligent, providing more accurate predictions and decision support (Wang et al., 2022). In the era of Plant Breeding 5.0, genome editing technologies, machine learning, and high-throughput phenotyping identification technologies will become crucial tools driving innovation in plant breeding. The application of these cutting-edge technologies will contribute to improving crop yield, quality, and stress resistance, achieving more efficient, precise, and faster breeding goals.

4.2 Transformation of human food security and global food systems

Breeding 5.0 faces significant challenges and transformations in human food security and the global food system. With the continuous growth of the global population and increasing food demand, there is a challenge of how to enhance food production, improve food quality and diversity within limited resources. In the era of Plant Breeding

5.0, advanced statistical methods and gene editing technologies will be utilized to control allelic variations of crucial crop genes, enabling the rapid production of superior varieties. This requires harnessing the power of technology and big data to identify genotypes that perform optimally in different environments and to achieve the development of precise and smart agriculture. Attention should also be given to the environmental impact of agricultural production, promoting the shift of agricultural production towards sustainability. Additionally, Breeding 5.0 will actively engage in the transformation of the global food system, promoting the development of sustainable agriculture and food production methods, reducing food waste and resource consumption, ensuring human food security, and achieving sustainable development goals. For example, addressing issues related to water resource dependence and environmental degradation in agricultural production requires fundamental reforms in the food system to achieve sustainable development goals (Souza et al., 2021).

4.3 Importance of scientific collaboration and interdisciplinary research

The realization of Breeding 5.0 requires widespread collaboration in the scientific community and interdisciplinary research. Faced with complex breeding challenges and ethical issues, scientists need to collaborate, share knowledge and resources, and strengthen cooperative research efforts. Breeding 5.0 necessitates the integration of knowledge and technologies from multiple disciplines such as botany, genetics, bioinformatics, and engineering to address breeding challenges in a more comprehensive and systematic manner (Dutta et al., 2022). Additionally, collaboration with farmers, policymakers, non-governmental organizations, and societal institutions is crucial for Breeding 5.0. Only through extensive collaboration and interdisciplinary research can we better address the challenges of future breeding, achieving food security and sustainable agriculture goals.

5 Conclusion

Breeding 5.0, as the frontier of future plant breeding, holds tremendous promise and potential. By introducing cutting-edge technologies and methods such as genome editing, artificial intelligence, big data analysis, and multi-omics integration, Breeding 5.0 will achieve more precise, efficient, and sustainable breeding goals. This will bring about revolutionary changes in global agriculture, enhancing food production, improving food quality, and bolstering resilience to climate change. The predicted potential of Breeding 5.0 instills confidence in the future of plant breeding, believing it will make significant contributions to addressing global agricultural challenges.

Plant breeding plays a crucial role in addressing global agricultural challenges. Through breeding efforts, we can cultivate crops that are higher yielding, more nutritious, and more resistant to adversity, meeting the growing demands for food and adapting to environmental pressures. Progress in plant breeding is not only essential for agricultural development but also critical for global food security, environmental conservation, and the sustainable socio-economic development at large. As the future direction of plant breeding, Breeding 5.0 will provide solutions to global agricultural challenges through innovative technologies and methods, propelling agriculture towards sustainability, efficiency, and environmental responsibility.

In summary, Breeding 5.0 envisions the future development and challenges of plant breeding. By introducing cutting-edge technologies and methods, strengthening collaborative research and interdisciplinary collaboration, we are confident in addressing future agricultural challenges and achieving the goals of global food security and sustainable agriculture. Plant breeding will continue to play a crucial role in promoting innovation and development in agriculture, bringing a more prosperous and sustainable future to human society.

However, the realization of Breeding 5.0 still requires extensive research and innovation, including a deep understanding of the genome and gene functions, as well as continuous improvement in genetic improvement technologies. Additionally, we must address the ethical, legal, and societal issues arising from Breeding 4.0 and 5.0, ensuring the safety and sustainability of breeding technologies. Despite facing numerous challenges, the implementation of Breeding 5.0 represents the future development direction in breeding, offering endless possibilities for exploring a more intelligent, efficient, and sustainable agricultural production.

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