植物育种简史
Brief History of Plant Breeding

育种 5.0：人工智能驱动的设计育种革命

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摘　要　未来植物育种正朝着更加精准、高效和可持续的方向迈进。育种 5.0 代表了未来植物育种的前沿，通过引入基因组编辑、人工智能和大数据分析等创新技术和方法，实现了遗传信息集成和编辑的育种革命。这将为全球农业带来革命性的变革，提高粮食产量、改善食品质量和适应气候变化的能力。展望未来，精准农业和个性化育种将成为重要的发展方向，荧光素杂交和显微成像技术的发展将推动育种工作的进展，环境适应性和气候变化下的育种策略将帮助我们应对不断变化的环境挑战。育种 5.0 的前沿技术和方法、人类粮食安全和全球食品系统的变革，以及科学界合作和跨学科研究的重要性将决定未来植物育种的方向和发展。

关键词　植物育种 5.0; 基因组编辑; 人工智能; 大数据分析; 可持续发展

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 analytics, 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, precision 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

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.
随着全球人口的增长和气候变化等全球性挑战的出现，农业面临着前所未有的压力。为了满足不断增长的粮食需求、提高作物适应性和增强农作物的农艺性状，植物育种作为一项关键的农业技术变得愈发重要。

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).
过去几十年，植物育种取得了巨大的进展，从传统的性状表现选择到基因型选择的精确革命(育种 3.0)，再到遗传信息集成和编辑的育种革命(育种 4.0)。育种 4.0 标志着遗传信息集成和编辑技术的广泛应用，为育种工作带来了新的可能性和机遇(Wallace et al., 2018)。育种 5.0 则是利用基因组选择、高通量表型分析和数据分析等先进技术的整合，使得育种策略更加精确和高效(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.
在育种 4.0 时代，通过整合遗传和基因组信息，我们可以更精确地选择和编辑植物基因型，以实现更高效、更快速的育种目标。基因组编辑技术的出现，如 CRISPR-Cas9 系统，使得我们能够直接干预植物基因组，实现定点基因编辑和功能基因调控。

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.
随着人工智能和大数据的快速发展，为植物育种带来了前所未有的机遇。机器学习和数据分析的应用，使我们能够更好地理解和预测植物性状与基因组之间的关联，加速育种进程并优化育种策略。育种 5.0 的特点是在育种中使用先进的技术和方法，侧重于精确性、效率和探索新的育种策略及遗传潜力。

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.
展望未来，植物育种将继续面临着许多挑战，如道德和伦理问题、可持续农业和社会责任等。然而，育种 5.0 作为未来的趋势，将不断推动植物育种的创新和进展，为全球农业可持续发展做出更大贡献。

1 Innovation in Technology and Methods

1.1 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).

1 技术和方法的创新

1.1 基因组编辑和精确基因组设计

育种 5.0 将进一步发展基因组编辑技术，如 CRISPR-Cas9 系统的改进和新的基因编辑工具的引入。这些技术将允许更精确和高效的基因组改造，例如敲除(Knockout)、敲入(Knockin)、基因功能修正或替换特定 DNA 片段等(Adem et al., 2017; Alexander, 2018)。精确基因组设计将成为一种常规手段，使育种者能够在植物基因组中精确地引入或删除目标基因，从而实现对特定性状的调控和优化，创建更强的作物品种，以增强抗旱、抗病、提高产量等特性。这种技术也被用于改善作物的营养价值和适应环境的能力(Vu et al., 2021)。

1.2 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.

1.2 人工智能和大数据在育种中的应用

育种 5.0 将广泛应用人工智能和大数据分析技术。通过机器学习、深度学习和数据挖掘等方法，我们能够更好地分析和解释海量的植物遗传和表型数据。人工智能算法将帮助我们发现潜在的基因-性状关联，预测植物性状和品质，以及优化育种策略。大数据的应用也将加速育种进程，提高选择效率，并为育种决策提供科学依据。

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).

实际上，人工智能和大数据已经在育种领域展示出了巨大的潜力。例如，现代植物育种依赖于基因组和表型选择，涉及大量数据点的分析。人工智能在处理这些复杂数据集方面发挥着重要作用，尤其是在高通量表型分析、基因组选择和环境数据分析中(Khan et al., 2022)。同时，利用人工智能和大数据分析可以加速育种程序，特别是在基因型到表型的链接方面。这样的集成能够迅速识别关键基因，从而加快作物改良程序(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).

大数据分析在作物育种中提高了复杂性状预测的准确性。利用大量的基因型和表型信息可以更准确地预测作物产量和其他重要性状(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.

另外，人工智能的进步也为育种提供了新的可能性。像 ChatGPT 这样的自然语言处理模型可以用于解析和理解大量的科学文献和研究结果，从而为育种研究人员提供更广泛的知识和信息。这种智能化的工具可以辅助育种者进行决策和预测，提供更精确和全面的育种建议。

1.3 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.

1.3 多组学整合和系统生物学方法的应用

育种 5.0 将进一步推动多组学整合和系统生物学方法在育种中的应用(Kuriakose et al., 2020)。整合不同层次的遗传、表观遗传、转录组、代谢组等多组学数据，可以全面解析植物性状和基因组之间的关系。系统生物学方法，如网络分析、代谢通路建模等，将帮助我们深入理解植物的生物过程和互作网络，为育种目标的实现提供新的策略和思路。

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).
多组学方法对于阐明作物的生长、衰老、产量及其对生物和非生物压力的响应起着重要作用。这些方法已在小麦、大豆、番茄等重要作物中得到应用，通过功能基因组学与其他组学的整合，强调了作物基因组与表型之间的关系(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).
系统生物学结合多组学数据集，可以增强我们对作物改良的分子调控网络的理解。采用“表型到基因型”和“基因型到表型”的概念，可以促进作物育种改良，在环境压力下的应用尤为重要(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.
毫无疑问，在技术和方法的创新下，育种 5.0 将进一步提高育种效率、精确性和可持续性。通过基因组编辑和精确基因组设计，植物的遗传改良将变得更加精确和可控。人工智能和大数据的应用将加速育种进程和优化育种策略。多组学整合和系统生物学方法的应用将加深对植物性状和基因组的理解，为育种目标的实现提供更全面的支持。

2 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.

2 新兴领域和应用

育种 5.0 将积极探索新兴领域和应用，以应对精准农业和个性化育种的需求，利用荧光素杂交和显微成像技术深化对植物生物学的认识，以及加强环境适应性和气候变化下的育种策略，以推动农业的可持续发展和粮食安全。这些新兴领域和应用的发展将进一步推动植物育种的创新和进步。

2.1 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.

2.1 精准农业和个性化育种

育种 5.0 将与精准农业相结合，实现更个性化的育种策略。精准农业利用传感器技术、遥感和地理信息系统等手段，使用摄像头和移动机器人等技术，能够在实际的农田中分析作物的生长状态，监测如生长阶段等表型特征。这为精准管理和育种试验提供了关键信息(Weyler et al., 2021)结合育种 5.0 的技术和方法，我

们能够基于农田的实际情况和需求，精确地选择和培育适应特定环境的农作物品种。这种个性化的育种方法将使农业生产更加可持续，提高产量和质量，并减少资源浪费和环境影响。

2.2 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.

2.2 荧光素杂交和显微成像技术的发展

荧光原位杂交技术和显微成像技术在植物育种中的应用已经取得显著进展，这些技术不仅在基因定位和表达分析方面发挥着重要作用，也在理解植物生长发育的分子机制中起到了关键作用。在育种 5.0 时代，荧光素杂交和显微成像技术在育种中的应用将得到进一步的发展。

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).

荧光素杂交技术可以帮助研究人员直观地观察和分析植物的基因表达和蛋白质互作，从而深入理解植物的生物学过程。例如，使用荧光原位杂交技术，结合免疫荧光技术，可以在玉米的联会复合体上定位特定的蛋白质和 DNA 序列。这项技术被广泛应用于植物减数分裂期染色体的研究，对理解基因重组过程至关重要(Stack et al., 2020)。利用 FISH 和显微成像技术，可以在单细胞水平上精确测量基因表达。这对于理解空间或时间依赖性过程对植物生长发育的影响具有重要意义(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).

结合显微成像技术的进步，我们能够以高分辨率和实时的方式观察植物细胞和组织的结构和功能。例如，FISH 技术结合高通量和超分辨率显微镜被用于绘制和空间定义不同基因组区域之间的接触频率。这些方法显著促进了对人类基因组在细胞核中打包方式的理解(Mao et al., 2020)。新开发的显微成像方法，如扩展显微术(ExM)，使得在传统荧光显微镜上实现核糖核酸(RNA)的纳米级成像成为可能，从而在细胞或亚细胞水平上提供基因表达的复杂模式信息(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.

这些技术的应用将为育种提供更多的信息和工具，帮助我们更好地理解和操控植物的性状和适应性。

2.3 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.

2.3 环境适应性和气候变化下的育种策略

育种 5.0 将致力于开发适应不断变化的环境和气候条件的农作物品种。随着全球气候变化的加剧，农作物面临着更频繁的极端气候事件和逆境压力。因此，育种者将加强对环境适应性和气候稳定性的育种策略。

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).
植物的基因型对环境变化有不同的响应。研究表明，在不同环境下，基因型与环境(GxE)之间的互动对作物品种的表型响应有显著影响，这对作物育种者来说至关重要(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).
表观遗传学变化在植物适应环境压力中起着关键作用。这些变化可以帮助植物“记住”过去的压力事件，从而更有效地应对未来的挑战(Ashapkin et al., 2020; Miryeganeh, 2021)。这种“植物应激记忆”对于提高作物的适应性和产量潜力具有重要意义(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).
通过“环境预测”方法(基于广义加性模型, 大规模环境协变量数据)来量化气候驱动因素对作物产量的影响，并为不同生产场景预测最优环境条件，这对发展适应特定区域气候的作物品种至关重要(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).
在不同环境下对作物进行多环境试验(METs)是评估作物生产力和适应性的重要手段。通过这种方式，可以识别出在不同气候条件下表现稳定的高产作物品种(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.
总之，在应对气候变化的挑战中，植物育种的关键策略包括理解和利用基因型与环境之间的相互作用，应用环境预测方法，利用表观遗传学变化以及进行多环境试验，以提高作物的环境适应性和产量稳定性。

3 Future Prospects and Challenges

3.1 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.

3 未来展望和挑战

3.1 育种 5.0 的前沿技术和方法

育种 5.0 将涌现出更多前沿的技术和方法，推动育种工作向更高水平发展。基因组编辑、合成生物学、人工智能、高通量表型测定等新技术将为育种带来新的突破(Chen et al., 2022)。基因组编辑技术的发展将使我们能够更精准地修改植物基因组，实现更快速、更精确的育种目标(Juma et al., 2021)。合成生物学的应用将使我们能够设计和构建全新的基因组，开启全新的育种可能性(Kim et al., 2020)。人工智能和大数据的应用将使育种过程更加高效、智能化，提供更准确的预测和决策支持(Wang et al., 2022)。在植物育种 5.0

时代，基因组编辑技术、机器学习和高通量表型鉴定技术将成为推动植物育种革新的关键工具。这些前沿技术的应用将有助于提高作物产量、质量和抗逆性能，从而实现更高效、更精确和更快速的育种目标。

3.2 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).

3.2 人类粮食安全和全球食品系统的变革

育种 5.0 面临着人类粮食安全和全球食品系统的重大挑战和变革。随着全球人口的不断增长和食品需求的不断增加，我们面临着如何在有限的资源下提高粮食产量、改善食品质量和多样性的问题。在植物育种 5.0 时代，将利用高级统计方法和基因编辑技术来控制重要农作物基因的等位基因变异，以快速生产出优良品种。这要求整合技术和大数据的力量，识别在不同环境中表现最优的基因型，并实现精准农业和智能农业的发展。同时，还需要关注农业生产对环境的影响，推动农业生产向更加可持续的方向发展。同时，育种 5.0 也将积极参与全球食品系统的变革，促进可持续农业和食品生产方式的发展，减少食品浪费和资源消耗，保障人类粮食安全，实现可持续发展的目标。例如，农业生产对水资源的依赖和环境退化问题，这要求食品系统进行根本性的改革，以实现可持续发展目标(Souza et al., 2021)。

3.3 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.

3.3 科学界合作和跨学科研究的重要性

育种 5.0 的实现需要科学界的广泛合作和跨学科的研究。在面对复杂的育种挑战和伦理问题时，科学家们需要共同努力，共享知识和资源，加强合作研究。育种 5.0 需要整合来自植物学、遗传学、生物信息学、工程学等多个学科的知识和技术，以更全面、更系统的方式解决育种难题(Dutta et al., 2022)。此外，与农民、政策制定者、非政府组织和社会机构的合作也是育种 5.0 的关键。只有通过广泛的合作和跨学科研究，我们才能更好地应对未来育种的挑战，实现粮食安全和可持续农业的目标。

4 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.

4 结语

育种 5.0 作为未来植物育种的前沿，具有巨大的预测和潜力。通过引入前沿的技术和方法，如基因组编辑、人工智能和大数据分析，以及多组学整合等，育种 5.0 将实现更精准、高效、可持续的育种目标。这将为

全球农业带来革命性的变革，提高粮食产量、改善食品质量和适应气候变化的能力。育种 5.0 的预测潜力使我们对未来植物育种充满信心，相信它将为解决全球农业挑战做出重要贡献。

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.
植物育种在解决全球农业挑战中发挥着关键作用。通过育种工作，我们能够培育出更高产、更营养、更抗逆的作物品种，以应对不断增长的食品需求和环境变化带来的压力。植物育种的进步不仅关乎农业的发展，也关系到全球粮食安全、环境保护和社会经济可持续发展的大局。育种 5.0 作为植物育种的未来方向，将通过创新的技术和方法，为全球农业挑战提供解决方案，推动农业向更可持续、高效和环保的方向发展。

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.
综上所述，育种 5.0 展望了未来植物育种的发展方向和挑战，通过引入前沿技术和方法，加强合作研究和跨学科合作，我们有信心应对未来农业挑战，实现全球粮食安全和可持续农业的目标。植物育种将继续发挥关键作用，推动农业的创新和发展，为人类社会带来更加繁荣和可持续的未来。

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.
然而，育种 5.0 的实现仍然需要大量的研究和创新，包括对基因组和基因功能的深入了解，以及对遗传改良技术的不断改进。同时，我们也需要认真对待育种 4.0 和 5.0 所带来的伦理、法律和社会问题，确保育种技术的安全和可持续性。尽管育种 5.0 的实现还面临诸多挑战，但它代表了育种领域的未来发展方向，为我们探索更加智能、高效和可持续的农业生产提供了无限可能。

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