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GENOMICS-DRIVEN CROP IMPROVEMENT UNDER CLIMATE STRESS

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Molecular breeding, also known as marker-assisted selection (MAS), is a genomics-driven approach that utilizes DNA markers tightly linked to phenotypic traits to enhance the efficiency and precision of plant breeding programs. This technique enables the indirect selection of desirable traits such as drought tolerance, heat and disease resistance at the seedling stage, thereby significantly reducing the time and resources required compared to conventional breeding methods. The success of molecular breeding largely depends on the identification and characterization of reliable genetic markers, including random amplified polymorphic DNA (RAPD), intersimple sequence repeats (ISSRs) and amplified fragment length polymorphism (AFLP). These markers serve as powerful tools for detecting genetic variation, mapping quantitative trait loci (QTLs), and tracking the inheritance of complex traits under climate stress conditions. By integrating high-throughput genotyping and genomic information, MAS facilitates the rapid development of climate-resilient crop varieties capable of withstanding multiple abiotic and biotic stresses, ultimately contributing to sustainable agricultural productivity. (Cooper *et al.*, 2014)

As the climate shifts, agricultural systems face increased vulnerability to pests, diseases and environmental stresses such as drought and heat, posing significant challenges to global food security. Traditional breeding methods, which rely heavily on phenotypic selection across multiple generations are often too slow to keep pace with these rapidly evolving threats. In contrast, DNA marker-based approaches significantly improve the speed and precision of plant improvement programs by enabling early and accurate selection of desirable traits. These modern strategies involve the use of DNA markers as substitutes for phenotypic selection to accelerate the development and release of improved germplasm. The major approaches include

marker-assisted selection (MAS), marker-assisted backcrossing (MABC), marker-assisted recurrent selection (MARS) and genome-wide selection (GWS). Such methods rely on identifying DNA markers that are strongly associated with the expression of target traits, including those governed by quantitative trait loci (QTLs). The integration of these techniques into breeding pipelines has been widely adopted in both private and public sector programs. Advances such as the availability of diverse molecular markers, high-throughput genotyping platforms, reduced costs of assays and access to whole-genome sequences such as maize (Murthy *et al.*, 2026) have greatly enhanced the efficiency and accessibility of these approaches. Collectively, these innovations enable the precise and efficient incorporation of important traits into crop varieties, supporting the development of climate-resilient agriculture.

In this context, molecular breeding approaches particularly genomic selection offers a powerful alternative by combining precision, speed and the ability to handle complex traits controlled by multiple genes. Genomic selection, a rapidly emerging method for crop improvement, uses genome-wide marker profile data to predict the breeding value of individuals in segregating populations, enabling the early identification and selection of superior genotypes. This approach accelerates the development of resilient crop varieties that are better adapted to changing climatic conditions and capable of withstanding multiple biotic and abiotic stresses (Wang *et al.*, 2018).

The statistical methods used in MAS, when linked to dynamic system modeling, provide a realistic procedure of defining an ideotype as a combination of genetic markers (Ragi *et al.*, 2026). Molecular breeding has made spectacular progress in a wide range of applications, such as genetic transformation, genetic diversity assessment, large-scale transcriptome and proteome studies, identification of candidate genes for trait improvement and whole genome sequencing.

Understanding Disease Resistance at the Genetic Level

Molecular breeding enables researchers to identify and target genes responsible for disease resistance. These genes can be integrated into crop varieties using advanced techniques like marker-assisted selection (MAS) and genome editing. By mapping disease resistance loci in the genome, breeders can select plants with the desired traits more efficiently. For example, genes that confer resistance to diseases like blight, rust, or fusarium wilt can be rapidly identified and incorporated into commercial crop varieties.

Climate Resilience: Drought, Heat and Flood Tolerance

Climate change is expected to bring more extreme weather events, including droughts, floods and heatwaves. Molecular breeding can help develop varieties that are better adapted to these conditions. For instance, genes associated with drought tolerance (such as those that improve root growth or water use efficiency) can be identified and introduced into crops. Similarly, heat tolerance can be enhanced by incorporating genes that help plants cope with higher temperatures, such as those involved in protein stability or antioxidant defense.

Speeding Up the Development of Resilient Varieties

Traditional breeding methods require multiple generations to achieve desirable traits. Molecular breeding, on the other hand, accelerates the process by using tools like genetic markers to identify plants with specific desirable traits early in the breeding process. This means new varieties with enhanced disease resistance or better climate resilience can be developed more quickly.

Genome Editing: CRISPR and Beyond

Advanced genome editing tools like CRISPR-Cas9 enable precise modifications to the DNA of crops. With CRISPR, specific genes can be edited to enhance disease resistance or improve tolerance to stress. For example, researchers have used CRISPR to develop rice varieties that are resistant to bacterial blight or wheat varieties that are more resistant to fungal diseases. This level of precision allows breeders to make small, targeted changes rather than introducing entire new genes from other species, reducing potential risks of unintended consequences.

Broadening Genetic Diversity

Climate change and evolving pests or diseases can lead to new threats for which existing crop varieties may not be resistant. Molecular breeding can tap into a broader genetic pool, including wild relatives and landraces, to introduce new resistance traits. These varieties may possess genes that confer resistance to emerging diseases or better adaptability to changing climates. Molecular tools can help identify these genes and bring them into commercial breeding programs, ensuring a wider genetic base for resistance.

Integrated Pest Management (IPM) and Crop Rotation

Molecular breeding doesn't just focus on direct disease resistance, it can also improve crops in ways that make them more compatible with sustainable practices like integrated pest management (IPM) and crop rotation. For example, breeding for traits like enhanced natural pest resistance (through plant-produced chemicals) can help reduce reliance on chemical pesticides, while also promoting ecological balance.

Climate-Specific Traits

Molecular breeding can help tailor varieties to specific climatic regions and microclimates. For instance, crops can be bred to thrive in areas with erratic rainfall, saline soils, or high-altitude conditions. These traits can be fine-tuned by identifying specific genetic pathways that allow plants to tolerate unique environmental stressors.

Reducing Environmental Impact

By developing crops that are more resilient molecular breeding can also reduce the need for chemicals and other interventions that have negative environmental impacts. Disease-resistant crops reduce the need for pesticide use, and drought-tolerant crops reduce water consumption, both of which contribute to more sustainable farming practices.

Example of Molecular Breeding in Action

An example of molecular breeding's success in developing disease-resistant varieties is the development of banana varieties resistant to Panama disease (a fungal infection) using genetic engineering and marker-assisted breeding. In drought-prone regions, crops like maize and sorghum have been improved for water-use efficiency through molecular breeding, helping farmers adapt to climate-induced water scarcity.

Challenges and Considerations

While molecular breeding holds great potential, it also faces some challenges. There is a need for comprehensive understanding of the complex interactions between genes, environmental factors, and diseases. Moreover, the regulatory approval process for genetically modified organisms (GMOs) can be time-consuming and complex, potentially slowing down the release of new varieties.

Conclusion

Genomics-driven crop improvement and molecular breeding provide powerful tools to address climate change and emerging plant diseases. By enabling faster and more precise selection of desirable traits, these approaches overcome the limitations of conventional breeding and accelerate the development of stress-tolerant, disease-resistant crops. The integration of genomic technologies and advanced breeding strategies will play a crucial role in ensuring sustainable agriculture and global food security under changing environmental conditions.

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