THE AGRI PUBLICATION
THE FUTURE OF AGRICULTURE
Grow With Every Page
e-Magazine for Agricultural Articles
Volume 01 | Issue 06 | November 2026
Available online at https://agripublication.com/
UDYAM REGISTERED NUMBER UDYAM-MP-06-0043239
©Agri Publication ISSN (Online): 3139-6127
Scan to Visit Our Website
Article ID: AP-V01-I06-07

CLIMATE-RESILIENT MAIZE BREEDING: INTEGRATING MOLECULAR BREEDING, GENOMICS AND GENOME EDITING FOR ABIOTIC STRESS TOLERANCE

Published Online: 02 Nov 2026

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ABSTRACT

Climate change is posing serious challenges to global maize production through increasing temperatures, irregular rainfall, prolonged drought and soil salinity. These abiotic stresses adversely affect crop growth, reproductive development and grain productivity, creating a need for improved climate-resilient maize varieties. Conventional breeding has contributed significantly to maize improvement; however, the complex genetic nature of stress tolerance requires more advanced and precise approaches. Recent developments in molecular breeding, genomics and genome editing have created new opportunities to accelerate the development of stress-tolerant maize. Marker-assisted selection, genomic selection and CRISPR-Cas-based genome editing can help identify, select and modify important genes associated with drought, heat and salinity tolerance. Integrating these technologies with conventional breeding and advanced phenotyping can improve selection efficiency and genetic gain. This article highlights the importance of modern breeding technologies and their potential role in developing climate-resilient maize varieties for sustainable agricultural production and future food security.

Keywords: Climate-Resilient Maize, Molecular Breeding, Genome Editing

INTRODUCTION

Maize (*Zea mays L.*) is one of the most important cereal crops worldwide and plays a vital role in human nutrition, livestock feeding and industrial processing. It is cultivated under diverse agro-climatic conditions and contributes substantially to global agricultural economies. However, climate change has emerged as a major threat to maize productivity, particularly in regions experiencing frequent droughts, high temperatures and unpredictable rainfall patterns. The increasing occurrence of extreme weather events has made it necessary to develop maize varieties that

ISSN (Online): 3139-6127

can maintain stable productivity under changing environmental conditions. Abiotic stresses such as drought, heat and salinity affect maize plants at different growth stages. Water scarcity during flowering can interfere with silk emergence and pollen viability, resulting in poor fertilisation and reduced grain formation. Similarly, high temperatures can disturb photosynthesis, accelerate plant development and reduce grain-filling duration. Soil salinity affects water and nutrient absorption, ultimately restricting plant growth and development. These stresses often occur simultaneously, further increasing the difficulty of maintaining consistent maize production. Traditional breeding methods have played an important role in developing high-yielding and adaptable maize varieties. Nevertheless, the development of varieties with tolerance to multiple environmental stresses is often time-consuming because these traits are influenced by several genes and environmental factors. Modern biotechnological approaches, particularly molecular breeding, genomics and genome editing, provide opportunities to overcome these limitations. Their integration with conventional breeding can accelerate genetic improvement and contribute to the development of climate-resilient maize for sustainable agriculture.

CLIMATE CHANGE AND ITS IMPACT ON MAIZE PRODUCTION

Among the major environmental challenges, drought is considered one of the most damaging stresses affecting maize cultivation. Water deficiency reduces leaf expansion, stomatal conductance, photosynthetic activity and nutrient uptake. The reproductive stage is particularly sensitive, as water stress can increase the interval between pollen shedding and silk emergence, commonly known as the anthesis-silking interval. An extended interval reduces successful pollination and ultimately results in poor kernel development. Heat stress is another important constraint, particularly during flowering and grain filling. Elevated temperatures can reduce pollen viability, disturb fertilisation and affect the development of maize kernels. High temperatures also increase respiration and accelerate crop maturity, resulting in reduced grain weight. Similarly, salinity stress causes osmotic imbalance, ion toxicity and nutrient disturbances, negatively affecting seedling establishment and plant development. The combined occurrence of drought and heat stress presents an even greater challenge because the effects of these stresses may intensify one another. Therefore, future maize improvement programmes must focus not only on tolerance to individual stresses but also on the ability of plants to maintain growth, reproductive success and grain yield under multiple environmental constraints.

MOLECULAR BREEDING: IMPROVING SELECTION EFFICIENCY

Molecular breeding has emerged as an important approach for improving the efficiency and accuracy of crop improvement programmes. Unlike conventional selection, which primarily depends on observable plant characteristics, molecular breeding uses DNA markers to identify desirable genetic variations associated with important traits. Marker-assisted selection (MAS) is particularly useful for selecting plants carrying favourable genes or quantitative trait loci (QTLs) associated with drought, heat and salinity tolerance. For example, molecular markers linked to drought-related traits can help breeders select maize plants with improved root development, water-use efficiency and reproductive stability. Marker-assisted backcrossing can also facilitate the transfer of desirable stress-tolerance genes into popular high-yielding varieties while retaining their favourable agronomic characteristics Several studies have demonstrated the importance of identifying suitable genetic donors for improving maize tolerance to environmental stresses. Cairns et al. (2013) highlighted the potential of maize genetic resources for identifying tolerance to drought, heat and their combined effects. Such research provides valuable information for selecting parental lines and developing improved breeding populations. However, abiotic stress tolerance is generally controlled by multiple genes, making selection based on a single molecular marker insufficient in many situations. Therefore, combining marker-assisted selection with field evaluation and physiological screening is essential for developing varieties with stable performance across different environments.

ISSN (Online): 3139-6127

GENOMICS: UNDERSTANDING THE GENETIC BASIS OF STRESS TOLERANCE

The development of advanced genomic technologies has significantly improved our understanding of the genetic mechanisms responsible for stress tolerance in maize. Genome sequencing, transcriptomics, gene-expression analysis and bioinformatics enable researchers to identify candidate genes and molecular pathways involved in plant responses to environmental stresses. Genomic selection (GS) is an important development in modern plant breeding. It uses genome-wide molecular markers to estimate the genetic potential of breeding lines for complex traits. Unlike conventional marker-assisted selection, which generally focuses on specific genomic regions, genomic selection considers information from across the entire genome. This makes it particularly useful for traits such as drought tolerance, heat resilience, grain yield and overall stress adaptation, which are controlled by numerous genes. Genomic information can also help identify genetic variations associated with important physiological characteristics, including root architecture, stomatal regulation, osmotic adjustment and photosynthetic efficiency. These traits contribute to the ability of maize plants to maintain growth under adverse environmental conditions. The integration of genomic selection with high-throughput phenotyping can further improve breeding efficiency. Advanced imaging systems, remote sensing technologies and automated field-monitoring platforms can provide large amounts of information about plant growth, canopy temperature, water status and stress responses. Combining these observations with genomic data allows breeders to identify superior genotypes more efficiently and accelerate the development of climate-adapted maize varieties.

GENOME EDITING: PRECISION TOOLS FOR FUTURE MAIZE IMPROVEMENT

Genome editing represents a major advancement in modern crop improvement. Among the available technologies, CRISPR-Cas systems have gained considerable attention because of their ability to make targeted modifications in specific regions of the plant genome. This technology offers opportunities to improve important agronomic traits by modifying genes associated with plant growth, development and environmental stress responses. In maize, genome editing can potentially be used to modify genes involved in stomatal regulation, root development, stress-responsive signalling, antioxidant activity and osmotic adjustment. For example, targeted modification of genes regulating stomatal behaviour may improve water-use efficiency by reducing excessive water loss during drought conditions. Similarly, modifications in genes associated with root architecture may enhance water absorption from deeper soil layers. Genome editing also provides opportunities to improve heat and salinity tolerance by modifying specific genetic pathways involved in stress perception and cellular protection. Unlike conventional breeding, which involves the transfer of genetic material through successive generations, targeted genome editing can introduce specific genetic changes more directly. Nevertheless, the success of this technology depends on identifying appropriate target genes and ensuring that modifications do not negatively affect other important characteristics, particularly grain yield and quality. Although genome editing has considerable potential, its wider application requires careful evaluation of genetic stability, environmental performance, biosafety and regulatory requirements. Combining genome editing with conventional and molecular breeding programmes can provide a more effective approach to developing improved maize varieties.

INTEGRATION OF MODERN TECHNOLOGIES FOR CLIMATE-RESILIENT MAIZE

The future of maize improvement depends on the effective integration of conventional breeding, molecular markers, genomics and genome editing. Each technology offers different advantages and can contribute to different stages of the breeding process. Molecular breeding helps identify and transfer favourable genes, while genomic selection improves the prediction of complex traits controlled by multiple genes. Genome editing provides opportunities for targeted genetic modification, whereas advanced phenotyping helps evaluate plant responses under different environmental conditions. Their combined application can improve the speed, precision and efficiency of maize breeding programmes. Artificial intelligence and machine learning are also emerging as useful tools for analysing large genomic and phenotypic datasets. These technologies can help identify relationships between genetic

ISSN (Online): 3139-6127

characteristics, environmental conditions and crop performance. Remote sensing, drone-based monitoring and digital field observations can further support the identification of stress-tolerant plants under natural field conditions. An integrated breeding approach should also consider regional climatic conditions and farmers' requirements. Varieties developed for drought-prone regions may require different characteristics from those intended for areas affected by heat or soil salinity. Therefore, multi-location field evaluation is essential to ensure that improved maize varieties perform consistently under diverse agro-climatic conditions.

FUTURE PROSPECTS AND CHALLENGES

Despite remarkable progress in molecular breeding and biotechnology, several challenges remain in developing climate-resilient maize. Abiotic stress tolerance is a complex trait influenced by genetic factors, environmental conditions and interactions between different stress responses. Identifying reliable genetic markers and maintaining desirable agronomic characteristics during breeding remain important considerations. Another major challenge is translating laboratory-based discoveries into improved field performance. A genotype showing strong stress tolerance under controlled conditions may not necessarily perform well under natural field environments. Therefore, extensive field testing under different climatic conditions is necessary before recommending improved varieties for commercial cultivation. Future research should focus on developing maize varieties with combined tolerance to drought, heat and salinity while maintaining high grain yield, nutritional quality and resistance to major diseases. Greater emphasis should also be placed on exploiting genetic diversity from traditional landraces, wild relatives and existing germplasm collections. Collaboration among plant breeders, molecular biologists, geneticists, biotechnologists and agricultural researchers will be essential for translating advanced scientific discoveries into practical breeding solutions. Farmer participation and location-specific varietal evaluation should also be encouraged to ensure that improved technologies meet the needs of agricultural production systems.

CONCLUSION

Climate-resilient maize breeding is becoming increasingly important for sustaining crop productivity under changing climatic conditions. The integration of molecular breeding, genomics and genome editing offers promising opportunities to accelerate the development of maize varieties with improved tolerance to drought, heat and salinity. While conventional breeding remains the foundation of crop improvement, modern biotechnological approaches can enhance selection efficiency, genetic precision and the speed of varietal development. Combining these technologies with advanced phenotyping, artificial intelligence and multi-location field evaluation will further strengthen maize improvement programmes. Developing high-yielding, stress-tolerant and environmentally adaptable maize varieties will be essential for ensuring future food security and supporting sustainable agricultural development.

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