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Conventional Vs Molecular Breeding Approaches for Abiotic Stress Tolerance in Cereals

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

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Abstract

Cereal crops are fundamental to global food security, yet their productivity is severely constrained by abiotic stresses such as drought, salinity, heat, flooding, and nutrient imbalances. These stresses are further intensified by climate change, leading to significant yield losses and posing a major challenge to sustainable agriculture. Developing stress-tolerant cereal varieties is therefore a critical priority in modern plant breeding. This review examines the role of both conventional and molecular breeding approaches in enhancing abiotic stress tolerance in cereals. Conventional methods, including germplasm selection, hybridisation,

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backcrossing, and recurrent selection, have contributed to the development of several stress-tolerant varieties, although their progress is often limited by time consumption, low selection precision, and strong genotype × environment interactions. In contrast, molecular breeding techniques such as marker-assisted selection, marker-assisted backcrossing, genomic selection, transgenic approaches, and genome editing (CRISPR/Cas systems) offer greater accuracy and efficiency in targeting complex traits. The integration of conventional and molecular approaches has emerged as a promising strategy for accelerating genetic gains and improving resilience under stress-prone environments. This review highlights recent advances, comparative advantages, and limitations of these approaches, and emphasises the need for integrated, data-driven breeding strategies to develop climate-resilient cereal cultivars for sustainable agricultural production. Future breeding efforts should focus on combining phenotypic selection with genomic tools, strengthening data-driven approaches, and improving the understanding of stress-responsive mechanisms.

Keywords: Abiotic stress; cereal crops; conventional breeding; molecular breeding; marker-assisted selection; climate resilience.

1. Introduction

Cereals constitute a fundamental component of global food systems, with their productivity closely linked to food security. However, agricultural output is substantially constrained by Abiotic stress, defined as the detrimental effects of non-living environmental factors on plant physiology, growth, and yield. Globally, abiotic stressors—including drought, salinity, extreme temperatures, and nutrient imbalances—are estimated to reduce the average yields of major crops by more than 50% (Tilman et al., 2002). These stresses impair key physiological processes such as photosynthesis, promote the accumulation of Reactive oxygen species, and induce oxidative damage, processes that are mediated through the regulation and feedback regulation of stress-responsive genes (Zhou, 2025). Under severe conditions, such stresses may reduce the survival and productivity of staple crops by up to 70%, thereby posing a significant threat to global food security (Vorasoot et al., 2004; Kaur et al., 2008; Rodriguez et al., 2005; Acquaah, 2012; Boraiah et al., 2022).

The impact of abiotic stress is further exacerbated by Climate change, land degradation, and diminishing water resources, all of which are increasing both the frequency and intensity of stress events (Tester and Langridge, 2010). Climate projections indicate that crops will increasingly be exposed to multiple and interacting stress conditions in the near future (Chapman et al., 2012; Zandalinas et al., 2018). In the context of India, abiotic stresses play a pivotal role in shaping agricultural productivity, sustainability, and resilience. The country's diverse agro-climatic zones render it particularly vulnerable to challenges such as drought, erratic rainfall, extreme temperatures, and soil degradation, all of which significantly affect crop yields and threaten food security (Gajera et al., 2024; Rawat et al., 2025). Approximately 67% of agricultural land in India is rainfed and frequently exposed to drought conditions, while the remaining irrigated areas (about 33%) are increasingly affected by heat stress, with climate change expected to exacerbate yield reductions (Bisbis et al., 2018; DaMatta et al., 2019; Leichenko & Silva, 2014). Overall, abiotic stresses are responsible for nearly 50% of global crop yield losses, with drought, submergence, heat, salinity, and cold identified as the primary contributing factors (Ashraf et al., 2008, Ashraf, 2010; Kumar et al., 2017c, 2017d; Snehi et al., 2024).

Among these, drought is widely recognised as the most critical abiotic stress affecting global food security and is projected to intensify under changing climatic conditions (Ebert et al., 2019; Oshunsanya et al., 2019). Drought frequently occurs in conjunction with heatwaves, resulting in compounded effects that are more detrimental than individual stress factors alone (Zandalinas et al., 2016). Consequently, enhancing plant adaptation to drought conditions has become a major research priority, driving the development of stress-resilient crop varieties (Hashmi et al., 2023). Submergence stress, particularly prevalent in low-lying and flood-prone regions, severely impacts crops such as rice, leading to substantial yield losses. Similarly, elevated temperatures disrupt plant growth, physiological processes, and yield stability. Soil salinity affects more than 800 million hectares worldwide and is expected to expand further, particularly in Asia (Nazar et al., 2011). Cold stress also imposes significant limitations on productivity in temperate and high-altitude regions by impairing plant growth and reproductive development.

With global food demand projected to rise substantially in the coming decades, there is an urgent need to enhance productivity per unit of land and water. The development of crop varieties with improved tolerance to abiotic stresses—such as drought, salinity, and heat—is therefore regarded as a resource-efficient, cost-effective, and socially acceptable strategy for ensuring sustainable agricultural production and food security (Hossain et al., 2022; Kumar and Kumar 2024). Nevertheless, breeding for abiotic stress tolerance remains challenging due to the complex genetic and physiological basis of these traits, as well as their typically low heritability (Karavolias et al., 2020; Rani Ray et al., 2025).

This review aims to examine recent advances in plant breeding approaches, encompassing both conventional and modern techniques, for enhancing abiotic stress tolerance in crop plants. It further evaluates the applications and limitations of these strategies in addressing contemporary agricultural challenges and promoting sustainable cereal production under evolving environmental conditions.

2. Major Abiotic Stresses Affecting Cereal Crops

Abiotic stresses such as drought, submergence, salinity, and temperature extremes are among the most significant constraints to plant productivity, influencing crop distribution and threatening food security. Globally, these stresses account for nearly 50% of yield losses in crops (Kumar et al., 2021; Kumar and Kumar, 2020; Ashraf et al., 2008; Ashraf, 2010). In India alone, 120.8 million hectares (36.5% of the geographical area) are affected by land degradation problems, including salinity, alkalinity, acidity, and waterlogging.

2.1 Drought Stress

Drought is considered the most critical abiotic stress affecting global food security and is expected to intensify under climate change (Ebert et al., 2019; Oshunsanya et al., 2019). Drought events are often accompanied by heatwaves, resulting in more severe crop damage compared to individual stress factors (Zandalinas et al., 2016). Severe droughts in South Asia have historically affected over half of the cropped area and millions of people, highlighting their socio-economic impact.

2.2 Heat Stress

High temperatures adversely affect plant growth, yield, and quality by causing morpho-anatomical, physiological, and biochemical disruptions. The increasing frequency of extreme heat events under climate change further threatens cereal production (Kjellstrom et al., 2016; Zampieri et al., 2017).

2.3 Salinity Stress

Soil salinity is a major constraint in arid and semi-arid regions, aggravated by declining irrigation water quality (Askari et al., 2017). More than 800 million hectares worldwide are affected by salinity, including 21.5 million hectares in Asia, and projections suggest that up to 50% of fertile land in Asia may become saline by mid-century (Nazar et al., 2011; Snehi et al., 2023).

2.4 Flooding and Waterlogging

Submergence stress, caused by heavy rainfall and flooding, particularly affects low-lying agricultural areas. Prolonged submergence restricts oxygen availability, reduces photosynthesis, and impairs root function, ultimately leading to yield loss. In rice, the incorporation of the SUB1 gene has significantly improved tolerance to flood-prone conditions.

2.5 Soil-Related Stresses (Aluminum Toxicity, Nutrient Imbalance)

Soil-related constraints such as salinity, alkalinity, acidity, and other edaphic problems contribute significantly to land degradation and reduced productivity. Quantitative trait loci associated with aluminum toxicity tolerance have been identified in rice, demonstrating the genetic basis of soil-related stress tolerance (Channapur et al., 2026a; Channapur et al., 2026b). Nutrient imbalances further exacerbate productivity losses under adverse soil conditions (Singh et al., 2022a; 2022b; Tilman et al., 2002).

3. Conventional Breeding for Abiotic Stress Tolerance

3.1 Introduction to Conventional Breeding

Conventional breeding for abiotic stress tolerance is based on assembling and recombining genetic variability to develop superior cultivars adapted to stress-prone environments. The choice of breeding method depends on the mode of reproduction of the species and the genetic control of the target traits. Breeding for abiotic stress tolerance is particularly complex because plant responses vary under similar stress conditions, and these traits are often governed by intricate genetic and physiological mechanisms (Karavolias et al., 2020). Direct selection under stressful environments and indirect selection under favourable conditions have been employed to improve tolerance.

3.2 Germplasm Collection and Evaluation

Conventional breeding typically commences with the collection and systematic evaluation of available germplasm to generate and exploit genetic variability (Kumar et al., 2017a; 2017b). In cases where desirable traits are not present within local genetic resources, the introduction of exotic germplasm is employed to broaden the genetic base. Traditional landraces have historically served as valuable reservoirs of stress tolerance. For instance, salt-tolerant rice varieties such as Damodar (CSR-1), Dasal (CSR-2), and Getu (CSR-3) were developed through pure-line selection from indigenous cultivars of the Sundarbans delta (Meena et al., 2016). Similarly, cultivars including Jhona-349, SR-26B, and Bhura Rata 4-10 have been derived from landraces to achieve site-specific adaptation. Effective screening under stress conditions remains a critical component of conventional breeding programmes. However, grain yield is frequently utilised as the principal selection criterion, despite its relatively low heritability and pronounced Genotype–environment interaction (Reddy, 2019).

3.3 Hybridisation and Selection Methods

The pedigree method involves crossing parents with desirable traits and selecting superior genotypes across generations until stabilisation, typically by F7 or F8. Although effective, it is labour-intensive and resource-demanding. The modified bulk-pedigree method combines pedigree and bulk approaches, allowing early generation bulking and later selection, especially for less heritable traits (Souleymane et al., 2017; Fischer & Rebetzke, 2018).

Backcross breeding is used to incorporate specific stress tolerance traits into elite cultivars. Large-scale backcross programs have produced introgression lines with improved drought and other stress tolerances (Ali et al., 2006; Oladosu et al., 2014). Recurrent selection has been applied to improve complex traits such as drought tolerance and photosynthetic efficiency, leading to the development of maize varieties like ZM621 and ZM303 (Lekgari & Setimela, 2004). Heterosis breeding has led to the development of high-yielding hybrids (Das et al., 2021; Singh et al., 2019; Singh et al., 2020; Singh et al., 2021; Snehi et al., 2024).

3.4 Selection Based on Morphological and Physiological Traits

In conventional breeding, grain yield under stress has commonly been used as a selection criterion despite challenges associated with low heritability and genotype × environment interactions (Reddy, 2019). However, reliance solely on yield has limited progress, as physiological and adaptive traits directly associated with stress tolerance have been underutilised. The complexity of stress responses and environmental interactions further complicates the simultaneous improvement of multiple adaptive traits.

3.5 Achievements of Conventional Breeding in Cereals

Conventional breeding has successfully developed several stress-tolerant cereal varieties. In rice, salinity-tolerant varieties such as CSR-1, CSR-2, and CSR-3 were developed through selection from traditional cultivars (Meena et al., 2016). Deep-water-tolerant varieties, including Jaladhi-1 and Jalaprabha, were developed through selection and composite breeding. In maize, recurrent selection led to the development of improved drought-tolerant varieties such as ZM301 C1 (Lekgari & Setimela, 2004). Backcross breeding has also generated numerous introgression lines with enhanced abiotic stress tolerance (Ali et al., 2006).

3.6 Limitations of Conventional Breeding

Despite its successes, conventional breeding has achieved limited progress in developing highly stress-resilient cultivars. The approach is time-consuming and labour-intensive, particularly due to repeated backcrossing and multi-generational selection. The reliance on grain yield as a primary selection criterion, combined with strong genotype × environment interactions, affects selection precision. Additionally, limited genetic variability and the polygenic nature of abiotic stress tolerance further constrain breeding efficiency (Karavolias et al., 2020).

4. Molecular Breeding for Abiotic Stress Tolerance

4.1 Introduction to Molecular Breeding

Conventional breeding approaches, though foundational, often fall short in addressing complex traits such as abiotic stress tolerance due to time requirements, reliance on phenotypic selection, and limited genetic diversity (Sarkar et al., 2021; Neelam et al., 2020). To overcome these limitations, modern breeding integrates molecular tools such as marker-assisted selection, genomic technologies, genetic engineering, and precision breeding to enhance efficiency and accuracy in crop improvement (Sarkar et al., 2021).

4.2 Molecular Markers and QTL Mapping

The use of molecular markers has enabled the identification of genomic regions associated with abiotic stress tolerance. Quantitative trait loci (QTL) mapping has successfully detected loci linked to aluminum toxicity tolerance in rice and salinity tolerance in barley and wheat (Snehi et al., 2024; Ellis et al., 1997; Wang et al., 2007). These advances facilitate the precise incorporation of stress-responsive or desired traits into breeding programs (Yathish et al., 2022).

4.3 Marker-Assisted Selection (MAS)

Marker-assisted selection enhances breeding efficiency by enabling the incorporation of desirable traits that are difficult to evaluate phenotypically, especially under strong environmental influence (Semikhodskii, 1997; Meena et al., 2016). In rice, MAS has been widely used to introgress QTLs for salinity tolerance into high-yielding mega-varieties and to pyramid multiple stress tolerance traits (Meena et al., 2016).

4.4 Marker-Assisted Backcross Breeding (MABB)

Backcrossing combined with molecular markers has improved the precision of introgressing specific stress tolerance genes into elite cultivars. Large-scale backcross programs involving multiple donors and recurrent parents have generated numerous introgression lines with enhanced abiotic stress tolerance (Ali et al., 2006; Oladosu et al., 2014).

4.5 Genomic Selection (GS)

The integration of genomic tools into breeding programs has improved the selection efficiency for complex traits. The combination of genomic selection with marker-assisted approaches enables early-stage selection of desirable traits and enhances breeding progress under stress conditions (Sarkar et al., 2021).

4.6 Transgenic Approaches

Genetic engineering allows direct manipulation of stress-responsive genes to enhance tolerance. The incorporation of the HVAI1 gene from barley into wheat improved drought tolerance (Chauhan & Khurana, 2011). Similarly, insertion of Na^+/H^+ antiporters and H^+ pyrophosphatases improved tolerance to salinity and drought stresses (Brini et al., 2007).

4.7 Genome Editing (CRISPR/Cas)

Advanced genomic tools such as CRISPR-Cas9 enable precise modification of target genes associated with abiotic stress tolerance. These tools, along with QTL mapping and genome-wide studies, have accelerated breeding progress for stress resilience (Sarkar et al., 2021).

5. Comparative Analysis: Conventional vs Molecular Breeding

5.1 Time Requirement

Conventional breeding approaches, such as pedigree selection and repeated backcrossing, require multiple generations to achieve genetic stabilisation, often up to F7 or F8, making the process time-consuming and labour-intensive. Similarly, extensive backcrossing programs demand several cycles depending on parental performance (Ali et al., 2006). In contrast, modern approaches such as marker-assisted selection and doubled haploid production through anther culture accelerate breeding cycles by enabling early and rapid identification of desirable genotypes (Senadhira et al., 2002; Sarkar et al., 2021).

5.2 Precision and Accuracy

Conventional breeding primarily relies on phenotypic selection, often using grain yield under stress as the main criterion, which is strongly influenced by genotype × environment interactions and low heritability (Maurya et al., 2017; Kumar et al., 2016; Kumar et al., 2017a; 2017b; Reddy, 2019). Molecular breeding enhances precision by targeting specific genomic regions associated with stress tolerance through QTL mapping and marker-assisted selection (Meena et al., 2016). This reduces reliance on environmental expression and improves selection accuracy (Semikhodskii, 1997).

5.3 Cost Implications

Traditional breeding methods are resource-demanding due to extensive field evaluations, labour requirements, and long breeding cycles. Molecular breeding approaches require advanced infrastructure, laboratory facilities, and technical expertise, increasing initial investment costs (Sarkar et al., 2021). However, techniques such as the modified bulk-pedigree method have been adopted to reduce resource requirements in conventional programs (Fischer et al., 2018).

5.4 Suitability for Polygenic Traits

Abiotic stress tolerance is genetically complex and often exhibits low heritability, complicating improvement through conventional selection (Karavolias et al., 2020). Grain yield-based selection alone has shown limited success due to the multifaceted nature of stress tolerance and strong environmental interactions (Kumar and Kumar, 2025; Mukri et al., 2024; Singh et al., 2024; Yathish et al., 2024; Kumar and Kumar 2024; Kumar and Kumar, 2020). Molecular approaches, including QTL mapping and genomic tools, facilitate the identification and pyramiding of multiple loci associated with complex stress-responsive traits (Ellis et al., 1997; Wang et al., 2007; Sarkar et al., 2021).

5.5 Sustainability and Farmer Acceptance

Developing crop varieties with inherent tolerance to salinity, drought, and heat through breeding is recognised as a resource-efficient, cost-effective, and socially acceptable strategy to ensure agricultural sustainability and food security (Karavolias et al., 2020). Integrating conventional and modern breeding approaches offers a balanced pathway toward developing resilient cereal varieties adapted to stress-prone environments (Sarkar et al., 2021).

6. Integration of Conventional and Molecular Approaches

Conventional and molecular breeding approaches play complementary roles in improving abiotic stress tolerance in cereals. Classical methods such as hybridisation, backcrossing, and recurrent selection provide the foundation for assembling and recombining genetic variability, whereas molecular tools enhance the precision and efficiency of trait incorporation (Ali et al., 2006; Sarkar et al., 2021). The integration of marker-assisted selection with conventional backcross breeding has enabled the effective introgression of stress-tolerance traits into elite cultivars (Meena et al., 2016; Oladosu et al., 2014).

Integrated breeding strategies combine phenotypic selection under stress environments with genomic tools such as QTL mapping and marker-assisted selection to improve the identification and pyramiding of desirable traits

(Semikhodskii, 1997). The use of doubled haploid technology further accelerates the stabilisation of stress-tolerant lines within conventional breeding frameworks (Senadhira et al., 2002). Such integration enhances selection efficiency while maintaining adaptability under diverse environmental conditions.

The future of climate-resilient cereal breeding depends on combining traditional knowledge with advanced genomic technologies to address the increasing frequency and severity of abiotic stresses under climate change (Chapman et al., 2012; Zandalinas et al., 2018). Developing stress-resilient varieties through integrated approaches is recognised as a resource-efficient and sustainable strategy to ensure long-term agricultural productivity and food security (Karavolias et al., 2020; Sarkar et al., 2021).

7. Challenges and Future Prospects

Abiotic stress tolerance breeding faces increasing challenges due to the rising frequency and intensity of stress events driven by climate change (Tester and Langridge, 2010). Future climate scenarios indicate that crops will be exposed to more severe and combined stress conditions, complicating selection and varietal development (Chapman et al., 2012; Zandalinas et al., 2018). Drought events accompanied by heatwaves further intensify crop damage, highlighting the complexity of stress interactions under changing environments (Zandalinas et al., 2016).

Genotype × environment (G × E) interactions remain a major constraint in breeding for abiotic stress tolerance, as they obscure the genetic basis of tolerance and limit the consistent performance of cultivars across environments (Karavolias et al., 2020). The reliance on grain yield as a primary selection criterion, coupled with low heritability of stress tolerance traits, further reduces breeding efficiency. These complexities make it difficult to simultaneously improve multiple adaptive traits under variable field conditions.

Future prospects in stress-resilient cereal breeding rely on the continued integration of genomic tools, precision breeding, and advanced selection strategies to improve efficiency and adaptability (Sarkar et al., 2021). The incorporation of quantitative trait loci mapping and molecular-assisted approaches has already enhanced trait identification and pyramiding (Semikhodskii, 1997). Strengthening data-driven breeding frameworks will be essential to address the complex challenges posed by climate change and ensure sustainable agricultural productivity (Sarkar et al., 2021).

8. Conclusion

Abiotic stresses such as drought, salinity, heat, and flooding continue to pose significant challenges to cereal production and global food security, particularly under changing climatic conditions. Conventional breeding approaches have played a crucial role in developing stress-tolerant cultivars by utilising existing genetic variability; however, their progress is often limited by time constraints, low selection precision, and strong genotype × environment interactions.

Molecular breeding techniques, including marker-assisted selection, genomic selection, transgenic approaches, and genome editing, have significantly enhanced the efficiency and accuracy of breeding programs by enabling targeted improvement of complex traits. Despite their advantages, these approaches require advanced infrastructure, technical expertise, and higher initial investment.

The integration of conventional and molecular breeding strategies offers a promising pathway for accelerating genetic gains and developing climate-resilient cereal cultivars. Future breeding efforts should focus on combining phenotypic selection with genomic tools, strengthening data-driven approaches, and improving the understanding of stress-responsive mechanisms. Such integrated strategies will be essential for ensuring sustainable crop productivity and long-term food security under increasingly variable environmental conditions.

Disclaimer (Artificial Intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

Competing Interests

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

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