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BREEDING APPROACH TO DEVELOP CLIMATE RESILIENT CROPS: CURRENT STATUS AND FUTURE PROSPECTS

S. Nandakumar[1]*, G.J. Abhishek[2], D.D. Deepika[2], Sonu[1] and Vikram Jeet Singh[3]

[1]Division of Genetics, ICAR-Indian Agricultural Research Institute, New Delhi, India.

[2]ICAR-National Bureau of Plant Genetic Resources, New Delhi - 110 012, India.

[3]Department of Seed Science and Technology, ANDUA&T, Ayodhya, Uttar Pradesh, India.

*Corresponding author E-mail : nandus237@gmail.com

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ABSTRACT

Breeding approaches for climate change focus on developing resilient crop varieties that can withstand the unpredictable and extreme environmental conditions associated with a changing climate. These approaches integrate advanced genomic tools, such as genomic selection and prediction, to accelerate the breeding process by identifying and incorporating genes associated with stress tolerance, including drought, heat, and salinity resistance. Additionally, exploiting genetic diversity through wide hybridization and marker-assisted selection helps in the discovery and introgression of beneficial traits from wild or distant relatives into cultivated varieties. Field testing across diverse environments, combined with an understanding of genotype-by-environment interactions, ensures the adaptability and stability of newly developed varieties. The ultimate goal is to create crop varieties that not only yield well under stress but also contribute to sustainable agriculture in the face of global climate challenges.

Key words : Climate change, Genomic selection, Drought, Salinity, Heat.

Introduction

The art and science of plant breeding dated back to thousands of years and has significantly influenced the current breeding strategies. It was started initially by selecting desirable traits through observation and manual crossing, plant breeding has evolved significantly (Acquaah, 2015). Thousands of years ago, early humans began to select unknowingly (Domestication) and progressed towards selective breeding and hybridization. The advent of biotechnology in the 20th century accelerated the breeding progress (Bradshaw, 2017). Today, plant breeding programs combine traditional breeding methods with cutting-edge technologies. Breeders utilize genomics, bioinformatics, and high-throughput phenotyping to identify and introgress beneficial traits more efficiently. As the science of plant breeding is progressing towards the cutting-edge technology, the climate change poses significant challenges to food security globally.

Breeding for climate change resilience is becoming increasingly crucial as environmental conditions continue to shift unpredictably (Borron, 2006). In this context, genomic selection (GS) has emerged as a powerful tool that can accelerate the development of crop varieties and livestock breeds with enhanced tolerance to the stresses induced by climate change (Krishnappa *et al.*, 2021). Genomic selection allows breeders to predict the genetic potential of individuals based on their DNA markers, enabling more precise and efficient selection processes. This strategy, combined with other modern breeding techniques, offers a comprehensive approach to addressing the challenges posed by climate change.

Furthermore, breeding programs focused on climate resilience must consider the interaction between genes and the environment, often referred to as genotype-by-environment (GxE) interactions. Genomic selection models can be developed to account for GxE interactions, allowing breeders to select varieties that perform well across a range of environmental conditions (Prasanna *et al.*, 2021; Archana *et al.*, 2023). This is particularly important in the context of climate change, where environmental conditions are becoming increasingly unpredictable. By incorporating GxE into genomic selection models, breeders can develop more robust varieties that are better suited to fluctuating climates and diverse agro-ecological zones. The current review explores the profound effect of the climate change on agriculture and food security, the action plan to mitigate the problem of food security using different breeding approaches.

What is climate change

Climate change refers to long-term alterations in the average weather patterns and conditions on Earth. These changes can manifest as shifts in temperature, precipitation, wind patterns and other atmospheric phenomena over extended periods, typically spanning decades or longer (Singh *et al.*, 2021; Abbass *et al.*, 2022). While climate change can result from natural processes such as volcanic eruptions or variations in solar radiation, recent changes are primarily driven by human activities. The industrial revolution marked the beginning of significant human impact on the climate, with activities like burning fossil fuels, deforestation, and industrial processes leading to an increase in greenhouse gases in the atmosphere (Shivanna, 2022).

The most critical consequence of increased greenhouse gas emissions is global warming, which refers to the rise in Earth's average surface temperature. Since the late 19th century, global temperatures have increased by approximately 1.2°C (2.2°F) (Lindsey and Dahlman, 2020). This warming is largely due to the enhanced greenhouse effect, where gases like carbon dioxide (CO_2), methane (CH_3), and nitrous oxide (N_2O) trap heat in the Earth's atmosphere. The implications of global warming are vast and far-reaching, affecting ecosystems, weather patterns and human societies (Kweku *et al.*, 2018).

One of the most visible effects of climate change is the alteration of weather patterns, leading to more frequent and severe weather events. Heatwaves, droughts, heavy rainfall, hurricanes, and wildfires are becoming more common and more intense (Koetse and Rietveld, 2009). Human health and livelihoods are also directly impacted by climate change. Rising temperatures can lead to heat-related illnesses and exacerbate the spread of infectious diseases (Sarofim *et al.*, 2016). Additionally, changes in weather patterns and increased frequency of extreme weather events can threaten food and water security, particularly in regions that are already vulnerable. The economic impact of climate change is significant, affecting agriculture, fisheries, and tourism, and potentially leading to large-scale displacement and migration (McAdam, 2010).

Addressing climate change requires a dual approach of mitigation and adaptation. Mitigation involves efforts to reduce or prevent the emission of greenhouse gases by transitioning to renewable energy, improving energy efficiency, and protecting forests. Adaptation, on the other hand, involves making adjustments to social, economic, and environmental practices to reduce the vulnerability of communities to the impacts of climate change. This can include building flood defences, developing drought-resistant crops, and planning for climate-resilient infrastructure (Jagers and Duus-Otterström, 2008).

Effect of climate change on agriculture

Climate change has profound implications for agriculture and food security, affecting crop yields, livestock productivity and the overall stability of food systems. As temperatures rise, precipitation patterns shift, and extreme weather events become more frequent, the ability of agricultural systems to produce sufficient, nutritious food is increasingly under threat.

Impact on Crop yields

One of the most direct effects of climate change on agriculture is the alteration of crop yields. Higher temperatures can accelerate crop maturation, reducing the growing period and, consequently, the size of the harvest (Malhi *et al.*, 2021). Some crops, such as wheat, rice, and maize, are particularly sensitive to temperature increases during critical growth stages like flowering and grain filling, leading to reduced yields. In regions where temperatures are already near the upper limit of crop tolerance, even small increases can result in significant yield losses.

In some areas, climate change is leading to more intense and frequent droughts, which reduce soil moisture and water availability for irrigation, harming crop production. Conversely, other regions may experience increased rainfall and flooding, which can lead to waterlogged soils, delayed planting and crop damage (Lesk *et al.*, 2022). Both extremes-drought and excessive rainfall-disrupt the delicate balance required for optimal crop growth, leading to variability in food production (Du and Xiong, 2024).

Pests, diseases and weeds

As temperatures rise and precipitation patterns shift, the distribution and intensity of agricultural pests, diseases, and weeds are also changing. Warmer climates can increase the reproductive rates and geographic range of pests, leading to more frequent and severe infestations (Skendžiæ *et al.*, 2021). For instance, insects like locusts and armyworms thrive in warmer conditions and can cause devastating damage to crops. Similarly, the spread of plant diseases, such as rusts and blights, is facilitated by changes in temperature and humidity, posing additional challenges for farmers. Weeds, which compete with crops for nutrients, water, and light, are also likely to become more problematic under climate change. Warmer temperatures and elevated CO_2 levels can boost the growth of certain weed species, making them more difficult to control (Mao *et al.*, 2021). This increased weed pressure can lead to reduced crop yields and higher costs for weed management.

Food Security and Nutrition

The combined effects of reduced crop yields, livestock productivity, and increased pest and disease pressures directly impact food security. As agricultural production becomes more variable and less predictable, the availability of food can fluctuate, leading to price volatility in global markets. In regions heavily dependent on agriculture for livelihoods, such as sub-Saharan Africa and South Asia, reduced agricultural productivity can exacerbate poverty and food insecurity (Wudil *et al.*, 2022).

Climate change also affects the nutritional quality of food (Fanzo *et al.*, 2018). For example, elevated CO_2 levels can reduce the concentrations of essential nutrients, such as protein, iron and zinc, in staple crops like wheat and rice. This decline in nutrient content poses a significant risk to global nutrition, particularly in regions where populations rely heavily on these staples for their daily dietary needs (Grosso *et al.*, 2020).

Regional Disparities

The impact of climate change on agriculture and food security is not uniform; it varies significantly across regions (Rezvi *et al.*, 2023). In general, tropical and subtropical regions, where many developing countries are located, are expected to experience the most severe impacts (Welch *et al.*, 2010). These regions are more vulnerable due to their reliance on rain-fed agriculture, limited adaptive capacity and existing challenges such as poverty and undernutrition. In contrast, some temperate regions might experience temporary benefits, such as longer growing seasons and the potential to cultivate new crops, but these gains are likely to be offset by increased weather variability and the eventual negative effects of more severe climate change.

Breeding strategies to breed for climate change

Breeding strategies to address the challenges posed by climate change are increasingly essential as global agricultural systems face unprecedented environmental shifts. Climate change affects crop yields, livestock productivity, and food security, making it imperative to develop resilient agricultural varieties that can thrive under adverse conditions (Muluneh, 2021). Breeding strategies for climate resilience must integrate traditional methods with modern technologies to accelerate the development of crops and livestock capable of withstanding the stresses of a changing climate (Bakala *et al.*, 2020) (Fig. 1).

Harnessing Genetic Diversity

Maintaining and utilizing genetic diversity within breeding populations is crucial for developing climate-resilient varieties. Genetic diversity provides a reservoir of adaptive traits that can be selected to cope with the unpredictable and variable conditions associated with climate change (Cortés and López-Hernández, 2021; Kallugudi *et al.*, 2022). Breeding programs must focus on preserving a wide range of genetic resources, including landraces, wild relatives, and underutilized species, which may harbor valuable traits for climate adaptation (Singh *et al.*, 2021). Incorporating genomic tools, such as genome-wide association studies (GWAS), can help identify and harness this diversity, ensuring that breeding efforts are well-equipped to address future environmental challenges (Galluzzi *et al.*, 2020).

Climate-Smart Crop and Livestock Breeding

Developing climate-smart crop and livestock varieties is a holistic approach that integrates multiple strategies to address the specific challenges posed by climate change. This includes breeding for traits such as water-use efficiency, heat tolerance, pest and disease resistance, and nutrient-use efficiency. Climate-smart breeding also involves the use of advanced breeding techniques, such as CRISPR and other gene-editing technologies, to introduce or enhance these traits. By focusing on a combination of traits that collectively improve resilience, climate-smart breeding aims to produce varieties that can sustain productivity in a changing climate (Matteoli *et al.*, 2020).

Speed Breeding and Rapid generation advancement

Speed breeding, or rapid generation advancement (RGA), is another key strategy for developing climate-resilient varieties. By optimizing growing conditions, such as light, temperature, and photoperiod, breeders can shorten the breeding cycle and accelerate the development of new varieties. When combined with

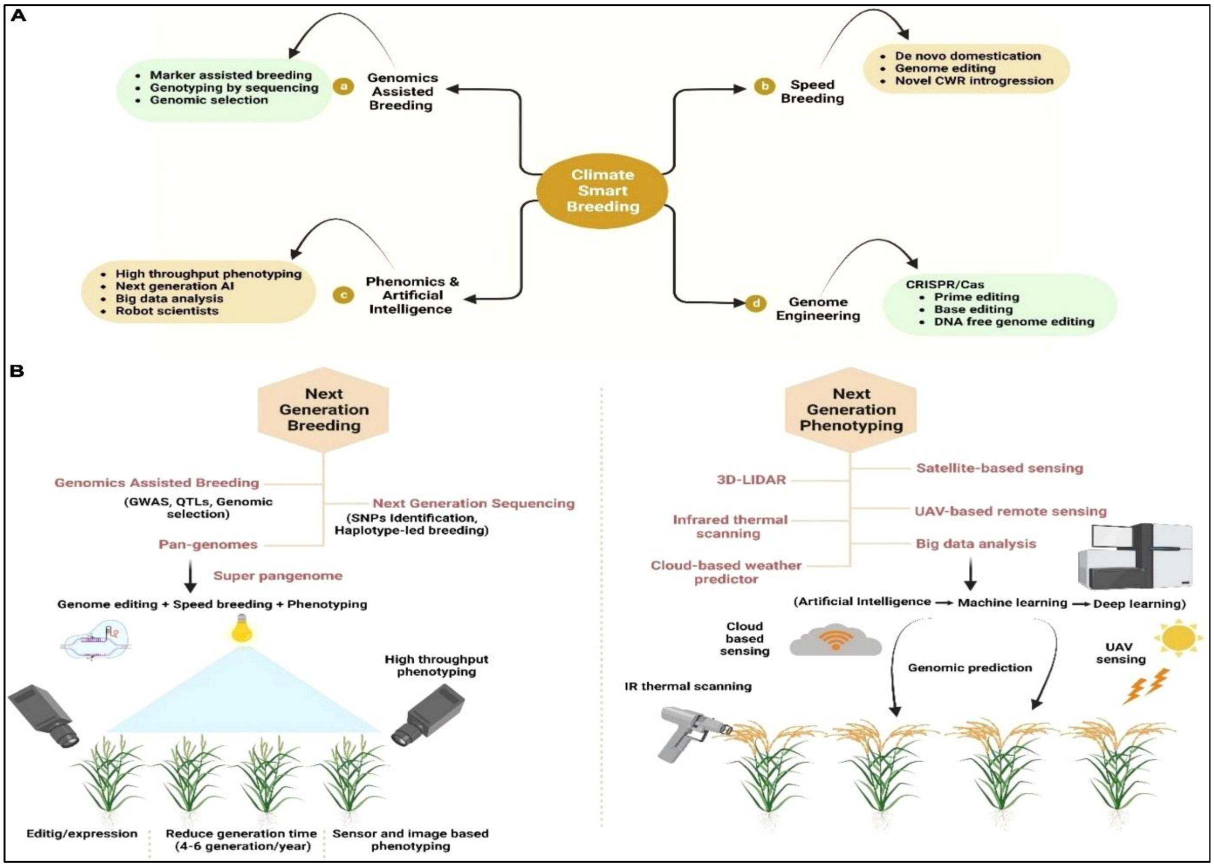

Fig. 1 : Modern breeding for crop improvement under climate change scenario. (A) Climate-smart breeding is the combination of (a) genomics assisted breeding, (b) speed breeding, (c) phenomics and artificial intelligence (AI), and (d) genome editing. (B) Next generation breeding and phenotyping tools including breeding with genomics, next-generation sequencing (NGS) and Pan genomics while phenotyping includes 3D LIDAR, satellite-based sensing, UAV-based remote sensing, cloud-based sensing, and Infrared thermal prediction. All these breeding techniques and tools help in the sustainable production of crops as well as the selecting the high yield crops.

genomic selection, speed breeding allows for the rapid production and testing of climate-resilient crops and livestock, ensuring that new varieties are ready for deployment in a shorter time frame. This approach is particularly important in the face of climate change, where the speed of adaptation can be critical for maintaining food security (Lal *et al*., 2024).

Genomic Selection and Marker-assisted breeding

One of the most promising strategies for breeding climate-resilient varieties is genomic selection (GS). This approach uses genome-wide DNA markers to predict the performance of breeding candidates, allowing for more accurate and efficient selection of traits related to climate resilience, such as drought tolerance, heat resistance and disease resistance. GS accelerates the breeding process by enabling early selection, reducing the time required to develop new varieties. When combined with marker-assisted selection (MAS), which focuses on specific genomic regions associated with critical traits, GS can significantly enhance the precision and effectiveness of breeding programs aimed at climate adaptation (Sinha *et al*., 2023).

Participatory and Farmer-Led Breeding

Engaging farmers in the breeding process through participatory and farmer-led breeding programs is another effective strategy for addressing climate change. Farmers possess valuable knowledge of local environmental conditions and can provide insights into the traits that are most needed for climate resilience. By involving farmers in the selection and testing of new varieties, breeding programs can ensure that the developed crops and livestock are well-suited to the specific challenges faced by different regions. This approach also promotes the adoption of climate-resilient varieties by ensuring that they meet the practical needs of the farming community (Noru *et al*., 2024).

Integration of Traditional and Modern Breeding techniques

Finally, integrating traditional breeding methods with modern technologies is key to developing climate-resilient varieties. While modern techniques like genomic selection, gene editing and speed breeding offer significant advantages, traditional methods such as cross-breeding, backcrossing and selection for local adaptation remain valuable. The integration of these approaches allows for a more comprehensive and adaptable breeding strategy, combining the strengths of both old and new methods to address the multifaceted challenges of climate change (Koshariya, 2022).

Targeted traits for climate resilient breeding

Targeted traits for climate-resilient breeding focus on enhancing the ability of crops and livestock to withstand the stresses associated with climate change, such as extreme temperatures, irregular rainfall patterns, and the increased prevalence of pests and diseases. These traits are critical for maintaining agricultural productivity and ensuring food security in a changing environment. Below are some of the key targeted traits for climate-resilient breeding:

Drought tolerance

Breeding for improved water-use efficiency ensures that plants can maintain productivity with less water, making them more resilient to drought conditions. Traits such as deeper root systems, stomatal control, and osmotic adjustment are essential for enhancing drought tolerance. Deep, extensive root systems allow crops to access water from deeper soil layers, improving their ability to survive prolonged dry periods. Selecting for root traits that enhance water uptake is crucial for drought resilience (Ilyas *et al*., 2022).

Heat tolerance

Breeding for heat tolerance involves selecting plants that can maintain normal physiological functions at higher temperatures. This includes traits such as heat shock protein production, which helps protect cellular functions under thermal stress (Wahid *et al*., 2007). A more open or upright canopy structure can reduce heat stress by allowing better air circulation and reducing the canopy temperature. Leaf angle, orientation, and leaf area index are traits that contribute to heat tolerance and enhances the yield (Nandakumar *et al*., 2024).

Flood tolerance

In flood-prone areas, selecting for traits that allow crops to survive and recover from prolonged submergence is critical. For example, the *Sub1* gene in rice confers submergence tolerance, enabling the plant to survive underwater for extended periods (Oladosu *et al*., 2020). Breeding for tolerance to waterlogged conditions involves selecting for traits that enable roots to function in low-oxygen environments, such as aerenchyma formation and anaerobic respiration capacity.

Salinity tolerance

Breeding for salinity tolerance includes selecting for the ability to maintain ionic balance under high salt conditions (Sonu *et al*., 2024). Traits that prevent excessive sodium uptake and ensure proper potassium levels are crucial for plant health in saline soils. The ability to maintain cellular turgor pressure through osmotic adjustment is important for plants growing in saline environments. This trait helps maintain growth and productivity despite the osmotic stress caused by high salt concentrations.

Pest and Disease Resistance

As climate change alters the distribution and intensity of pests and diseases, breeding for broad-spectrum resistance becomes increasingly important. This involves selecting for traits that confer resistance to multiple pathogens and pests (Bradshaw and Bradshaw, 2016). Traits that enhance a plant's ability to resist or tolerate insect attacks, such as the production of secondary metabolites or physical barriers (*e.g.*, thick cuticles), are vital for reducing crop losses and maintaining productivity.

Resilience to Variable Climate conditions

Breeding for phenotypic plasticity allows plants to adjust their growth and development in response to varying environmental conditions. Stability, or the ability to perform consistently across different environments, is also a key trait for climate resilience. In regions where growing seasons may become shorter due to climate change, early maturing varieties that can complete their life cycle before adverse conditions set in are important for ensuring harvests (Gratani, 2014).

Grain Quality and Yield stability

Ensuring that crop yields remain stable under fluctuating environmental conditions is a primary goal. This involves selecting for traits that allow crops to buffer against environmental stress, such as stable flowering times and stress-responsive gene expression (Altieri *et al*., 2015). Maintaining or improving grain quality under stress conditions is important for both marketability and nutritional value (Wang and Frei, 2011). Traits that protect against quality degradation during periods of heat or drought are key targets.

Current status

Advancements in Genomic Technologies

Marker-assisted selection (MAS) continues to be used for specific traits. For instance, the use of MAS has enabled the development of rice varieties with improved resistance to the bacterial blight disease, such as IR64-1, which carries resistance genes identified through MAS (Quang *et al*., 2004). CRISPR/Cas9 technology has revolutionized gene editing, allowing for precise modifications to improve climate resilience. In rice, CRISPR/Cas9 has been used to enhance heat tolerance by targeting genes involved in heat stress response. For example, a study by Zhang *et al*. (2021) successfully used CRISPR to create rice lines with improved heat tolerance, which are more likely to maintain yields under high temperatures.

Development of Climate-Resilient varieties

Significant progress has been made in developing drought-tolerant varieties. The drought-tolerant maize variety DroughtGuard™, developed by Monsanto, demonstrates the effectiveness of breeding for water-use efficiency. This variety maintains yield stability under drought conditions, showing a 10-20% yield advantage over conventional varieties (Nuccio *et al*., 2018). The development of the heat-tolerant wheat variety 'Sunshine' in Australia exemplifies success in breeding for high-temperature resilience. This variety has been shown to perform well under heat stress conditions, improving yield stability (Hasan *et al*., 2019).

In rice, the development of varieties with the Sub1 gene, such as the rice variety Swarna-Sub1, showcases progress in flood tolerance. The Sub1 gene allows rice to survive prolonged submergence, and Swarna-Sub1 has been adopted in flood-prone regions of South Asia (Singh *et al*., 2011). Salinity tolerance has been addressed in crops like rice with the development of varieties such as FL478, which is resistant to high salinity levels. This variety has been effective in saline-affected areas, helping maintain productivity (Singh *et al*., 2010).

Integration of Climate-Smart Agriculture

Development of the "climate-smart" barley variety, which improves nutrient-use efficiency and reduces methane emissions, is a key achievement. This variety contributes to more sustainable and resilient barley production (Haider *et al*., 2023). Incorporating agroecological principles, such as promoting biodiversity, is exemplified by the use of intercropping systems. For instance, the use of legume-cereal intercrops can enhance soil health and resilience. Studies show that these systems can improve nutrient availability and crop performance under variable climatic conditions (Okumu *et al*., 2023).

Challenges and Limitations

While progress is evident, adapting varieties to specific local conditions remains a challenge. For example, while drought-tolerant varieties are available, their performance may vary significantly across different regions. Ongoing research and field testing are necessary to ensure local adaptation (Kawecki and Ebert, 2004). Similarly, the cost of developing and implementing new technologies can be high. For example, gene-edited crops may face regulatory and financial barriers that limit their widespread adoption, particularly in developing countries (Rock *et al*., 2023).

Future Directions

Future directions include the development of more advanced genomic tools, such as high-throughput phenotyping and multi-omics approaches. These tools will provide deeper insights into plant responses to climate stressors and improve breeding precision (Yang *et al*., 2020). Focus on multidimensional traits, such as, breeding for multiple climate-resilient traits simultaneously will be essential. For example, developing varieties that combine drought tolerance, heat resistance and disease resistance will help ensure comprehensive resilience (Saad *et al*., 2022). Incorporating climate models into breeding programs will enhance the ability to predict future conditions and develop varieties that are well-suited to future climates (Conroy *et al*., 2011).

Conclusion

The current status of breeding for climate change reveals significant progress through the use of genomic technologies, climate-smart practices, and international collaborations. The successful developments include drought-tolerant maize, heat-resistant wheat and flood-tolerant rice varieties. However, challenges related to local adaptation, economic constraints, and regulatory issues remain. Ongoing research and innovative approaches will be crucial for advancing climate-resilient breeding and ensuring agricultural sustainability in a changing climate.

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