

Potential of Climate Resilient Crop Varieties for Sustainable Food Production and Food Security under Various Extreme Weather Conditions

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ABSTRACT

Climate change, characterized by aberrant weather conditions, poses severe threats to global agriculture and food security. This comprehensive review explores the development of climate-resilient crop varieties as a sustainable solution. Initial discussions highlight the crucial role of plant genomics and phenomics in decoding the genetic basis of climate resilience. Genomics and phenomics enable accurate mapping of traits associated with climate resilience, and coupled with advanced biotechnology, they pave the way for the precise modification of plant genomes for enhanced resilience. Translating these lab-based advancements to real-world applications presents challenges, including bridging the yield gap between optimal and field conditions and navigating socio-economic factors influencing the adoption of new varieties. Notwithstanding these hurdles, case studies such as drought-tolerant maize in Sub-Saharan Africa and salt-tolerant rice in Asia underline the significant benefits and wider adoption of these climate-resilient crops, primarily when supported by effective extension services and favourable policy environments. The review anticipates an increasing role for advanced biotechnology, including genetic engineering, genome editing, and synthetic biology in developing climate-resilient crops. Integrated breeding strategies combining traditional methods and biotechnology are envisaged, focusing on combinations of traits that enhance crop resilience under multiple stress conditions. Moreover, a shift towards systems approaches is projected, with an emphasis on optimizing interactions between genetic, environmental, and management factors. Participatory breeding and farmer-centered approaches are also gaining recognition for their potential to align crop development with the needs of farmers. Policy and regulatory evolution is identified as pivotal for managing advancements in crop improvement technologies. Regulations must balance innovation with biosafety, and policies need to promote research and development, support the seed industry, and facilitate the adoption of improved varieties.

Keywords: climate resilient plants, climate change, aberrant weather.

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INTRODUCTION

The intersection between climate change and agriculture has become an increasingly critical area of research in the last few decades. As the global population continues to grow, the demand for food also rises, with projections suggesting that food production will need to increase by 50% by 2050 to meet demand (Dhankher & Foyer, 2018). Simultaneously, the increasingly unpredictable and extreme weather conditions caused by climate change threaten agricultural productivity worldwide.

Crop plants are especially vulnerable to such environmental stressors. Drought, heat, cold, flooding, and salinity can all negatively impact crop growth, reducing yield and in extreme cases, leading to total crop failure. This directly threatens global food security, especially in regions most vulnerable to these climatic changes and with populations heavily reliant on agriculture (Rao et al., 2016). These intertwined challenges highlight the pressing need for resilient crops – plants that can withstand these environmental stressors and still produce a substantial yield. The development and cultivation of climate-resilient crop varieties have emerged as a pivotal solution to ensure food security under changing climatic conditions (Maheswari et al., 2015).

The climate resilience of a crop variety is influenced by numerous factors, including its inherent genetic traits, cultivation techniques, and external environmental conditions. Therefore, a thorough understanding of these variables is key to creating effective strategies for the development and use of climate-resilient crop varieties (Umesh et al., 2019).

Objective and Scope of the Review

This comprehensive review aims to explore the potential of climate-resilient crop varieties for sustainable food production and food security under various extreme weather conditions. The scope of the review extends to several dimensions: It will dissect the impact of climate change on agriculture, specifically focusing on the role of extreme weather conditions. The review will detail the concept

of climate-resilient crops, dissect the genetic traits contributing to such resilience, and examine the techniques involved in their development. Furthermore, it will discuss the performance of these crop varieties, their role in food security, and economic considerations surrounding their use.

Additionally, the review will take a closer look at the current policy and regulatory framework that influences the development and deployment of these crops. Finally, it will explore future directions and challenges in the field. Given the magnitude and complexity of the topics involved, this review aspires not only to provide a holistic overview of the current state of knowledge but also to identify gaps and stimulate further research in the field.

As we delve into this topic, we remember that food is not just a commodity – it's a fundamental human right. Therefore, the development and use of climate-resilient crop varieties is not just a scientific and economic endeavour. It's also a vital step towards ensuring that every individual, regardless of where they live or what conditions they face, has access to safe, nutritious, and sufficient food all year round.

Climate Change and Agriculture

Impact of Climate Change on Agriculture

Climate change and its impacts on agriculture have been a significant area of research in recent years. The Intergovernmental Panel on Climate Change (IPCC) reports that climate change, characterized by increased global temperatures and shifts in rainfall patterns, has and will continue to have profound effects on agricultural systems worldwide (Yadav et al., 2019).

Rising temperatures can lead to increased evapotranspiration, intensifying the need for water in agriculture and leading to elevated water stress, especially in regions already experiencing water scarcity. Moreover, warmer temperatures can accelerate crop development, reducing the growing period and potentially lowering yields. On the other hand, certain crops, like maize and wheat, exhibit a decrease in yield with every degree rise in temperature (Selvaraju et al., 2011).

Changes in rainfall patterns, with more intense but less frequent rain, can increase the risk of both drought and flooding. Drought stress can severely inhibit crop growth, leading to substantial yield reductions, while flooding can cause damage to crops, particularly if it occurs at sensitive growth stages. In addition to these direct effects, climate change also contributes to secondary agricultural issues, such as shifts in the distribution of pests and diseases, changes in soil quality, and disruptions to pollination processes (Balasundram et al., 2023).

The Challenge of Extreme Weather Events

Extreme weather events – such as heatwaves, cold snaps, severe storms, heavy rainfall leading to flooding, and prolonged periods of drought – are becoming more frequent and severe due to climate change. These events can have a significant impact on crop productivity and pose a substantial threat to global food security (Leisner, 2020).

Extreme temperatures, both hot and cold, can cause physiological stress to plants, leading to reduced growth and productivity. Heatwaves, in particular, can cause substantial crop losses, as many crops are sensitive to high temperatures, especially during flowering and grain filling stages. Similarly, severe cold can damage crops, with frosts causing significant agricultural losses. Droughts and floods can also cause considerable crop damage. Drought conditions can lead to water stress, causing crops to wilt and eventually die, whereas flooding can lead to root oxygen deprivation and increased susceptibility to root diseases, often resulting in crop losses (Njeru, 2013).

Case Studies of Recent Climate Disruptions in Agriculture

Several recent events serve to illustrate the potentially devastating impact of extreme weather events on agriculture. In 2020, an unprecedented locust outbreak, facilitated by unusually wet weather, devastated crops across East Africa, the Arabian Peninsula, and South Asia, threatening food security in these regions (Chhogyel & Kumar, 2018).

Likewise, severe droughts in California from 2012 to 2017 led to substantial losses in agricultural yield, with direct economic impacts and wider implications for food prices and food security. The 2010 heatwave in Russia is another prominent example, causing widespread crop failures and a significant decrease in grain production (Marengo et al., 2022).

Furthermore, floods in the Midwest of the United States in 2019 delayed planting and led to substantial yield reductions. Similarly, in 2020, extreme rainfall and flooding in China caused significant damage to the agricultural sector, affecting millions of hectares of crops (Leippert et al., 2020). These case studies underline the vulnerability of our agricultural systems to extreme weather events and highlight the urgent need for the development and implementation of climate-resilient crops.

The Concept of Climate Resilient Crops

Definition and Overview

Climate-resilient crops can be broadly defined as crop varieties that possess the capacity to maintain productivity and nutritional quality despite exposure to extreme weather conditions linked to climate change. These conditions include, but are not limited to, high and low temperatures, drought, flooding, and elevated soil salinity. The resilience of these crops is typically built upon a complex combination of genetic traits, carefully selected or engineered to optimize the plant's physiological responses to environmental stressors (Altieri & Nicholls, 2017; & Neupane et al., 2022).

While some degree of natural variation for climate resilience traits exists within traditional crop cultivars and wild relatives, this variation is often insufficient to meet the scale of the challenges posed by climate change (Ghosh, 2019). As a result, researchers are increasingly looking towards advanced breeding techniques, including marker-assisted selection, genomic selection, and genetic engineering, to develop crop varieties with improved resilience.

The Importance of Climate Resilient Crops

The development of climate-resilient crops is of paramount importance in our changing world. Agriculture is the primary food source for the global population; therefore, any decline in agricultural productivity due to climate change could severely impact food security (Singh et al., 2022).

Climate-resilient crops can help mitigate these impacts by maintaining, and in some cases, increasing agricultural productivity under climate change scenarios. In addition to enhancing food security, these crops can also provide economic benefits. By improving the consistency and quality of yields, climate-resilient crops can help farmers maintain their incomes in the face of increasing climatic uncertainty (Reddy, 2015).

Moreover, climate-resilient crops can play a crucial role in climate change adaptation strategies. For regions already experiencing or expected to face severe climate change impacts, the cultivation of climate-resilient crop varieties can serve as an important component of broader efforts to adapt agricultural systems to new climatic realities.

Role of Crop Resilience in Sustainable Agriculture

Beyond their importance for food security and climate change adaptation, climate-resilient crops are also crucial for the transition towards more sustainable agricultural systems. Conventional agricultural practices, characterized by high inputs and monoculture cropping, have contributed to significant environmental degradation, including soil erosion, water pollution, and loss of biodiversity (Kandegama et al., 2022).

Climate-resilient crops can contribute to sustainable agriculture in several ways. By improving crop productivity under low-input conditions, these crops can help reduce the reliance on synthetic fertilizers and pesticides, thereby mitigating environmental harm. In addition, climate-resilient crops can be an essential part of diversified cropping systems, serving to enhance both biodiversity and resilience to environmental stressors (Jat et al., 2022).

Furthermore, the development of climate-resilient crops aligns with several of the United Nations' Sustainable Development Goals (SDGs), including zero hunger (SDG 2), responsible consumption and production (SDG 12), and action to combat climate change and its impacts (SDG 13). Thus, the advancement of climate-resilient crop research can significantly contribute to the broader sustainable development agenda (Lipper et al., 2014).

In summary, developing and implementing climate-resilient crops are vital to meeting the dual challenges of climate change and sustainability in agriculture. Through scientific innovation, policy support, and farmer adoption, these crops can help ensure the future of food security and agricultural livelihoods on a rapidly changing planet.

Genetic Traits for Climate Resilience**Drought Resistance**

Drought resistance is a crucial trait for crops in many regions of the world, particularly those experiencing arid or semi-arid conditions. Drought-resistant crops employ various physiological mechanisms to cope with water scarcity, such as deeper root systems to access water at greater soil depths, smaller leaf surface area to reduce water loss through transpiration, and modifications in stomatal conductance to manage water usage efficiently (O'Brien et al., 2021).

At the genetic level, drought resistance is a complex trait regulated by numerous genes. For example, the DREB1A/CBF3 gene in *Arabidopsis* has been associated with improved drought tolerance when overexpressed in transgenic plants. Similarly, the DEEPER ROOTING 1 (DRO1) gene in rice is known to alter root system architecture, enabling plants to reach deeper water sources during drought conditions (Lipper et al., 2014).

Heat Tolerance

Heat tolerance is another critical trait, particularly given the expected rise in global temperatures due to climate change. Heat-tolerant crops can survive and maintain

productivity during periods of high temperature. Key adaptive mechanisms include the synthesis of heat-shock proteins that protect against cellular damage, modifications in membrane lipid composition to maintain membrane stability, and changes in flowering time to avoid peak temperatures (O'Brien et al., 2021).

Several genes associated with heat tolerance have been identified. The HSFA1a gene in tomato, for instance, regulates a network of other genes related to heat stress response, and its overexpression has been shown to enhance heat tolerance. Likewise, the Heat Shock Transcription Factor A2 (HSFA2) gene in wheat is associated with heat tolerance (Mekonnen et al., 2022).

Cold Hardiness

Cold hardiness, or the ability of a plant to survive freezing temperatures, is an essential trait for crops grown in regions with cold winters or cool growing seasons. Cold hardiness involves mechanisms such as the synthesis of antifreeze proteins, accumulation of solutes like sugars and amino acids to lower the freezing point of cellular water, and changes in membrane lipid composition to maintain fluidity at low temperatures (Umesha et al., 2018).

Several genes have been linked to cold tolerance. For example, the CBF (C-repeat Binding Factor) gene family in Arabidopsis is known to regulate the expression of many cold-responsive genes. In rice, the COLD1 gene has been found to enhance cold tolerance during the germination and young seedling stages (Gupta et al., 2017).

Salinity Tolerance

Salinity tolerance is critical for crops grown in areas with high soil salinity, often caused by irrigation with saline water. Salinity-tolerant crops can manage high soil salinity through mechanisms such as the exclusion of sodium ions from uptake, sequestration of sodium ions into vacuoles to prevent toxic accumulation, and synthesis of compatible solutes to maintain osmotic balance (Gonzalez, 2011).

Several genes have been associated with salinity tolerance. In Arabidopsis, the salt

overly sensitive 1 (SOS1) gene codes for a sodium/proton antiporter that helps remove sodium ions from cells, contributing to salinity tolerance. In rice, the salt tolerant 1 (ST1) gene is involved in regulating the plant's response to salt stress and is associated with improved salinity tolerance (Panda & Palita, 2021).

In summary, many genetic traits can contribute to climate resilience in crops. Advances in genomics and molecular biology techniques are aiding the identification and utilization of these traits, paving the way for the development of crop varieties with improved resilience to climate change.

Breeding Strategies for Climate Resilient Crops

Traditional Breeding

Traditional breeding methods have long been used to improve crop performance under various environmental stressors. These methods involve selecting plants with desirable traits, cross-breeding them, and selecting the best-performing progeny over several generations. Despite being time-consuming and labor-intensive, traditional breeding has been successful in developing crop varieties with improved climate resilience. For instance, drought-tolerant and heat-tolerant varieties of several major crops have been developed through traditional breeding (Srivastav et al., 2021).

However, traditional breeding has limitations, particularly when dealing with complex traits like climate resilience, which are often controlled by multiple genes. Additionally, the genetic diversity available within cultivated varieties may be insufficient to achieve the desired level of resilience.

Marker-Assisted Selection

Marker-Assisted Selection (MAS) is a modern breeding strategy that uses molecular markers linked to desirable traits to guide breeding decisions. This approach has several advantages over traditional breeding, including the ability to detect desirable traits at early developmental stages or even in the absence of the environmental stressor, thereby speeding up the breeding process (Chakraborty & Newton, 2011).

MAS has been successfully used to improve climate resilience in various crops. For instance, markers linked to drought tolerance in wheat and rice, heat tolerance in wheat and maize, and cold tolerance in rice have been used to develop climate-resilient crop varieties.

Genomic Selection

Genomic Selection (GS) is a more recent development in breeding technology, which uses genome-wide markers to predict the performance of individuals in a breeding population. This strategy is particularly useful for complex traits like climate resilience, as it takes into account the cumulative effect of multiple genes (Durodola, 2019).

GS has shown promise in breeding climate-resilient crops. For example, GS has been used to improve drought tolerance in maize, heat tolerance in wheat, and cold tolerance in barley.

Genetic Engineering

Genetic Engineering (GE) involves the direct manipulation of an organism's genes using biotechnology. In the context of breeding climate-resilient crops, GE can be used to introduce specific genes associated with climate resilience from other varieties or even other species. This strategy allows for the introduction of novel traits that may not be available within the cultivated gene pool (Zong et al., 2022).

Several climate-resilient crops have been developed using genetic engineering. For instance, genetically engineered varieties of cotton, maize, and soybean with improved drought tolerance have been developed and commercially deployed.

CRISPR-Cas9 and New Breeding Techniques

New breeding techniques, such as genome editing using CRISPR-Cas9, offer exciting possibilities for the development of climate-resilient crops. These techniques allow for precise modifications of an organism's genetic material, potentially enabling the targeted improvement of climate resilience traits (Behnassi et al., 2014).

Several proof-of-concept studies have demonstrated the potential of these techniques. For example, the use of CRISPR-Cas9 to

modify the genes involved in stomatal closure in rice led to improved water-use efficiency and drought tolerance (Liliane & Charles, 2020).

In conclusion, a range of breeding strategies, from traditional breeding to modern molecular techniques, are being employed to develop climate-resilient crops. While each strategy has its strengths and limitations, their combined use can accelerate the development of crop varieties capable of withstanding the challenges posed by climate change.

Role of Biotechnology in Enhancing Crop Resilience

Genetic Engineering for Abiotic Stress Resistance

Genetic engineering (GE) has immense potential to contribute to the development of climate-resilient crops by enabling the targeted modification of genetic traits associated with stress resistance. As previously mentioned, several crops have already been engineered to enhance their tolerance to drought, heat, cold, and salinity, and ongoing research promises to further extend these capabilities (Xiong & Tarnavsky, 2020).

Beyond merely improving stress tolerance, genetic engineering can also be used to enhance other traits that contribute to climate resilience indirectly. For instance, improving water-use efficiency can help crops maintain productivity under drought conditions while modifying photosynthetic pathways can improve crop performance under high temperatures.

Genome Editing Technologies

Genome editing technologies, such as CRISPR-Cas9, offer a new level of precision and flexibility in crop improvement. Unlike traditional genetic engineering, which typically involves the insertion of foreign genes, genome editing enables the precise modification of an organism's own genes. This not only opens up new possibilities for trait improvement but may also help address some of the regulatory and public acceptance issues associated with genetically modified organisms (GMOs) (Khalid Abdullah et al., 2021).

CRISPR-Cas9 has already been used to improve climate resilience in several crops. For example, the DRO1 gene in rice, which controls root architecture and confers drought resistance, has been successfully edited using CRISPR-Cas9. Similarly, genes related to salt tolerance in wheat and heat tolerance in tomatoes have been modified using this technology.

'Omics' Technologies

'Omics' technologies, such as genomics, transcriptomics, proteomics, and metabolomics, provide comprehensive data on genes, transcripts, proteins, and metabolites, respectively. These technologies can be used to unravel crops' complex physiological and genetic responses to abiotic stresses, providing valuable insights for breeding and genetic engineering efforts (abu Haraira et al., 2022).

For example, transcriptomic studies have identified genes that are upregulated in response to drought in maize, wheat heat, and rice salinity. These genes can serve as potential targets for breeding or genetic engineering to enhance climate resilience.

Synthetic Biology

Synthetic biology, which involves designing and constructing new biological parts, devices, and systems, represents a frontier in crop improvement. This approach could enable the engineering of complex traits that are beyond the reach of traditional breeding and genetic engineering (Khalid et al. et al., 2021).

One promising application of synthetic biology in enhancing crop resilience is the engineering of photosynthesis. Several research groups are working on redesigning the photosynthetic machinery of crops to improve their efficiency and tolerance to environmental stresses, with promising preliminary results.

Biotechnology and Biosafety Regulations

While biotechnology offers great promise for enhancing crop resilience, its application must be balanced against biosafety considerations. Each country has its own regulatory framework for the testing and release of genetically modified crops, which must be

adhered to ensure the safe and responsible use of this technology (Khalid Tahir et al., 2021).

In conclusion, biotechnology has a vital role to play in enhancing crop resilience to climate change. While the path to realizing this potential is fraught with technical and regulatory challenges, the food security and sustainability rewards make it a worthwhile pursuit.

Translational Research for Field Application

From Lab to Field: Challenges and Solutions

Translating findings from the lab to the field is a critical step in the development of climate-resilient crops. However, this translation is often fraught with challenges. Lab conditions can be significantly different from field conditions, with many more variables in play. Moreover, the genetic modifications that prove successful in a controlled environment may not have the same effect when the crop is exposed to the multitude of stresses present in the field (Khalid et al., 2022).

To overcome these challenges, research must be complemented by comprehensive field trials. These trials should ideally span multiple locations and growing seasons to account for the variability in environmental conditions. Furthermore, using precision agriculture techniques, such as satellite imaging and remote sensing, can help monitor crop performance and environmental conditions with a high level of detail, aiding the interpretation of field trial results.

Bridging the Yield Gap

The 'yield gap' – the difference between the potential yield under optimal conditions and the actual yield under field conditions – is a crucial concept in crop improvement. Many factors contribute to the yield gap, including both biotic and abiotic stresses. Climate change is expected to exacerbate the yield gap in many regions due to the increased occurrence and intensity of abiotic stresses (Babar et al., 2023).

Climate-resilient crop varieties can help bridge the yield gap by improving crop performance under stress conditions. However, it's essential

to recognize that crop genetics is just one piece of the puzzle. Optimizing farming practices, including irrigation, fertilization, and pest management, is also critical for realizing the potential of these varieties.

Socio-economic Factors in Adoption of Climate-Resilient Varieties

The successful development and deployment of climate-resilient crops depend not only on scientific and technological factors but also on socio-economic ones. Farmers' willingness and ability to adopt new crop varieties are influenced by many factors, including their knowledge and perceptions of the new varieties, the availability and cost of seeds, and the compatibility of the new varieties with their farming systems (Hassan et al., 2021).

Therefore, extension services play a vital role in promoting the adoption of climate-resilient crops. These services can provide farmers with the necessary knowledge and resources to use new crop varieties effectively. Policies that support the seed industry and reduce the financial risks associated with adopting new varieties can further facilitate their adoption.

Policy and Regulatory Considerations

Developing and deploying climate-resilient crops also require an enabling policy and regulatory environment. This includes policies that promote research and development in crop improvement, regulations that ensure the biosafety of genetically modified crops, and intellectual property rights that protect breeders' rights while ensuring farmers' access to improved seeds (Mudasir et al., 2021).

Furthermore, international collaboration is vital for addressing the global challenge of climate change. Sharing of germplasm, data, and technologies can accelerate the development of climate-resilient crops. However, this requires harmonization of regulations across countries, which can be a significant challenge.

In conclusion, translating research on climate-resilient crops for field application involves addressing numerous scientific, socio-economic, and regulatory challenges. While this is no easy task, the stakes – food security and sustainability in the face of climate change – couldn't be higher.

Case Studies: Success Stories and Lessons Learned

Drought-Tolerant Maize in Sub-Saharan Africa

One of the most successful examples of climate-resilient crops is developing and deploying drought-tolerant maize varieties in Sub-Saharan Africa. Developed through a collaborative effort involving the International Maize and Wheat Improvement Center (CIMMYT), national agricultural research systems, and seed companies, these varieties have shown significant yield advantages under drought conditions and are currently grown by millions of smallholder farmers across the region (Bhutta et al., 2023).

This success story underscores the importance of international collaboration and public-private partnerships in crop improvement. It also highlights the vital role of local seed industries and extension services in disseminating improved varieties to farmers.

Salt-Tolerant Rice in Coastal Regions of Asia

In coastal regions of Asia, where rice cultivation is often affected by salinity, the development of salt-tolerant rice varieties has helped improve food security and livelihoods. These varieties, developed through traditional breeding and marker-assisted selection, have shown remarkable resilience to high salinity levels (Shahani et al., 2021).

The success of these varieties has been facilitated by policies supporting the seed industry and extension services, which have enabled farmers' widespread adoption of these varieties. However, the persistence of salinity issues in these regions also emphasizes the need for integrated approaches to crop improvement that consider the crop itself, the farming system, and the broader agroecosystem.

Genetically Engineered Drought-Tolerant Soybean in the USA

In the USA, the first genetically engineered drought-tolerant crop – a soybean variety known as Drought Gard – was commercially

deployed in 2013. Developed by Monsanto (now part of Bayer), Drought Gard has demonstrated improved yield stability under drought conditions (Alam et al., 2021).

A supportive regulatory environment has facilitated the development and deployment of Drought Gard for genetically modified crops in the USA. However, the experience with Drought Gard also highlights some of the challenges associated with genetically engineered crops, including regulatory hurdles, public acceptance issues, and the need for stewardship practices to manage potential environmental impacts (Khalid et al. et al., 2021).

Heat-Tolerant Wheat in South Asia

In South Asia, where wheat production is increasingly threatened by heat stress, the development of heat-tolerant wheat varieties has provided a crucial lifeline for farmers. These varieties, developed through traditional breeding and marker-assisted selection, have been widely adopted in heat-prone areas, helping to maintain wheat productivity in the face of rising temperatures (Shafiq et al.).

The success of these varieties demonstrates the power of breeding for climate resilience. However, it also highlights the ongoing need for research to keep pace with the evolving challenges of climate change.

In conclusion, these case studies highlight both the successes and challenges in developing and deploying climate-resilient crops. They underscore the importance of scientific research, international collaboration, supportive policies, and local seed industries and extension services in this endeavour.

Future Perspectives and Emerging Trends in the Development of Climate-Resilient Crops

Increasing Role of Advanced Biotechnology

As genetic engineering, genome editing, and 'omics' technologies continue to advance, their role in the development of climate-resilient crops is expected to increase. These technologies allow for more precise and targeted modification of plant genomes than traditional breeding methods, enabling the

introduction of complex traits that improve crop resilience (Manan et al., 2022).

Additionally, the development and application of synthetic biology in agriculture are expected to surge. For instance, efforts are ongoing to engineer C4 photosynthesis into C3 crops (like rice and wheat) to enhance their productivity under high temperatures and low water conditions. Moreover, entirely new traits could be engineered into crops using synthetic biology, opening up unprecedented possibilities for crop improvement (Zafar et al., 2021).

Integrated Breeding Strategies

In the future, breeding for climate resilience is likely to become more integrated, combining traditional breeding methods with advanced biotechnology. These integrated breeding strategies can harness the strengths of both approaches: the wide genetic diversity accessible through traditional breeding and the precision and speed of biotechnology (Razzaq et al., 2020).

Furthermore, breeding is expected to target not just single traits but combinations of traits that enhance crop resilience under multiple stress conditions. This requires a deep understanding of the genetic and physiological interactions between different traits, which can be facilitated by 'omics' technologies and systems biology approaches.

Systems Approaches to Crop Improvement

Crop improvement is increasingly being viewed from a systems perspective, considering not just the crop itself but also its interactions with the environment and other components of the agricultural system. This shift is driven by the recognition that crop performance under field conditions is determined by a complex interplay of genetic, environmental, and management factors (Khalid et al. et al., 2021).

Therefore, the development of climate-resilient crops needs to be complemented by innovations in farming practices and technologies that optimize these interactions. For instance, precision agriculture technologies, such as remote sensing and machine learning, can help monitor and

manage field conditions in real-time, enhancing crop performance under stress conditions.

Participatory Breeding and Farmer-Centered Approaches

Participatory breeding, which involves farmers in the breeding process, is expected to gain prominence in the future. This approach can ensure that the development of climate-resilient crops is aligned with farmers' needs and preferences, increasing the likelihood of their adoption.

Moreover, farmer-centered approaches that empower farmers to innovate and adapt to changing conditions are being recognized as crucial for building climate resilience. These approaches can leverage local knowledge and resources, fostering crop and farming system resilience.

Policy and Regulatory Evolution

As crop improvement technologies advance, policies and regulations will need to evolve to keep pace. This includes biosafety regulations for genetically modified and genome-edited crops, which must balance the need for innovation with the need to protect the environment and human health.

Moreover, policies that promote research and development, support the seed industry, and facilitate the adoption of improved varieties by farmers will continue to be crucial for developing and deploying climate-resilient crops.

In conclusion, the future of climate-resilient crop development is likely to be characterized by rapid technological advancements, integrated and systems approaches, and evolving policies and regulations. Amid these changes, the goal remains the same: to ensure food security and sustainability in the face of climate change.

CONCLUSION

Climate change poses a profound challenge to global food security and agricultural sustainability. However, the development of climate-resilient crop varieties offers a promising solution. As we have discussed, this endeavour involves not just scientific and

technological innovation but also a broad array of socio-economic and policy factors.

Firstly, the development of climate-resilient crops hinges on the understanding of the genetic basis of climate resilience, which can be facilitated by genomics and phenomics technologies. Furthermore, genetic engineering and genome editing technologies allow for the precise and targeted modification of plant genomes to enhance climate resilience.

However, translating research findings from the lab to the field involves numerous challenges, including bridging the yield gap and managing socio-economic factors that influence farmers' adoption of new varieties. Success stories such as drought-tolerant maize in Sub-Saharan Africa and salt-tolerant rice in Asia underscore the potential of climate-resilient crops and provide valuable lessons for future efforts.

Looking ahead, the role of advanced biotechnology in the development of climate-resilient crops is likely to increase. At the same time, crop improvement is expected to become more integrated and systems-oriented, involving not just the crop itself but also its interactions with the environment and other components of the agricultural system. Furthermore, participatory breeding and farmer-centered approaches can help align the development of climate-resilient crops with the needs and preferences of farmers.

Policy and regulatory evolution will be crucial to support these advancements, including biosafety regulations for genetically modified and genome-edited crops, policies that promote research and development, and mechanisms to facilitate the adoption of improved varieties by farmers.

In conclusion, the development of climate-resilient crops is a complex and multifaceted endeavour. Nevertheless, with continued research, collaboration, and policy support, we can harness the power of plant science to ensure food security and sustainability in the face of climate change.

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Author Contribution

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Khalid and Amjad	<i>Emrg. Trnd. Clim. Chng.</i> (2023) 2(2), 30-43	ISSN: 2583 – 4770
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