Pak. J. Bot., 57(4): 1581-1585, 2025. DOI: http://dx.doi.org/10.30848/PJB2025-4(37)

ADAPTING AGRICULTURE: STRATEGIC CROP RESPONSES AND MITIGATION TO CLIMATE SHIFTS - AN UPDATED REVIEW

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Abstract

Climate change is a major environmental issue that humanity is currently confronting, influenced by both natural and human actions. As a result of substantial changes to the atmosphere's composition brought about by industrialization, overuse of land, deforestation, and the heavy reliance on fossil fuels, greenhouse gases (GHGs) emissions have increased. Changes in weather patterns, an increase in temperature, and an intensification of extreme weather events including storms, floods, and droughts have all been brought about by this phenomenon. An industry that depends heavily on climate stability, agriculture, is especially susceptible to these shifts. Crop growth, productivity, and food security are already being impacted by changes in temperature, rainfall, and water availability. These issues will only get worse as global temperatures rise, having serious consequences for both poor and developed countries. There is still a lack of thorough, integrative methods that integrate physiological, genetic, and agronomic viewpoints to create holistic adaptation strategies, despite the increasing amount of research on the effects of climate change and crop adaptation techniques. This review aims to present a thorough analysis of the effects of climate change on crop adaptations, pinpoint knowledge gaps that currently exist, and to highlight the use of novel breeding and biotechnology techniques to mitigate the current climate change. The goal is to investigate technical developments, creative farming techniques, and physiological adaptations in crops that can support agricultural output and guarantee food security in a changing environment. This review aspires to fill in the gaps by providing practical advice that farmers, researchers, and policymakers may use to implement efficient mitigation solutions locally and globally.

Key words: Climate change; Agriculture; Weather pattern; Crop adaptation; Mitigation strategies.

Introduction

Long-term variations in weather and temperature i.e., one of the most significant environmental problems facing humanity now is climate change. It may result from man-made actions or from natural causes. Anthropogenic activities that alter the composition of the atmosphere and cause climate change include industrialization, land overuse, the use of fossil fuels, and deforestation. Climate change will result in a variety of effects, including altered rainfall patterns, an increase in sea level, and the movement of climatic zones due to rising temperatures. The intensity of storms, floods, and droughts is expected to increase due to changing climate trends (Shakoor *et al*., 2011). Emissions of greenhouse gases (GHGs), which include increasing concentrations of gases like carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), are the primary cause of global climate change (Hasan *et al*., 2016). Particularly vulnerable to the effects of climate change is the agricultural industry, which depends significantly on weather patterns. Climate change presents a serious risk to this industry's output, creating both physical and financial weaknesses. A number of climate-related factors, including changing rainfall patterns, temperature rises, adjusted planting and harvesting schedules, variations in water availability, and site suitability, have a significant impact on agricultural productivity (Hasan *et al*., 2016).

The world's food security will be severely threatened by global warming, but if it stays below 1.5°C, poor countries will be less vulnerable than those in similar regions at 2°C (Betts *et al*., 2018). Climate change has a significant impact on agriculture production, making it difficult to ensure food for the world's population (Jan *et al*., 2023; Khan *et al*., 2023; Fatima & Jan, 2023; Shinwari *et al*., 2020; Qamar *et al*., 2020; Afzal *et al*., 2018). Global cereal production of wheat and maize is expected to decrease due to climate change, which is known to have a negative impact on agricultural productivity (Lobell *et al*., 2011). Plants encounter a variety of abiotic stressors due to weather conditions, including salinity, drought, heat stress, cold stress, and others (Jan *et al*., 2017). The negative impact of climate change on agriculture is given in (Table 1 & Fig. 1). Existing research frequently concentrates on discrete impacts, like variations in temperature or drought, without incorporating these elements into a comprehensive strategy that tackles the complex aspects of agricultural difficulties resulting from climate change. A thorough search was carried out utilizing databases including PubMed and Google Scholar to guarantee an exhaustive evaluation. Keywords included "climate change," "agriculture," "crop adaptation," "mitigation strategies," and "abiotic stress." The evaluation has a strong emphasis on recent publications from the previous ten years in order to include the most recent advancements in this area.

Crops adaptation to climate change: Plants, as multicellular and sessile organisms, have developed various mechanisms to cope with environmental stress. These adaptations are necessary for their survival and ability to thrive under challenging conditions. Generally, plants utilize two primary defense strategies-avoidance and tolerance to manage environmental stressors. The adaptation to water stress, in particular, involves a complex interplay of physiological, morphological, phenological, biochemical, and molecular responses (Cabusora, 2024).

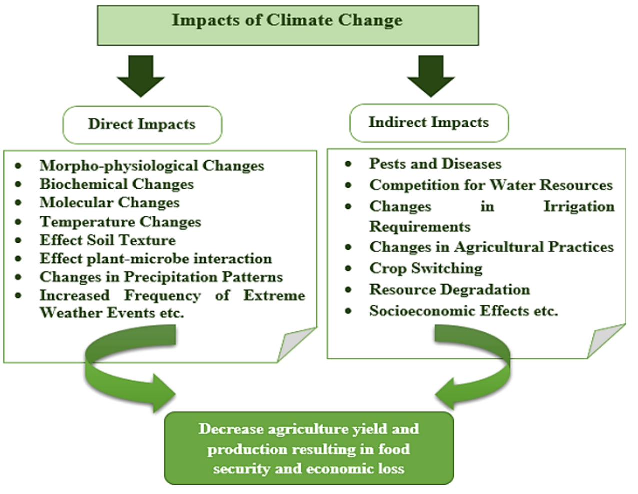

Fig. 1. A schematic overview of potential effects of climate change on the agricultural sector.

Physiological and molecular adaptation of crops to climate change: Drought and a shortage of water affect a great deal of physiological functions. Throughout their phenology, these detrimental physiological effects have varying effects on the plants, including vigor loss, decreased biomass output in terms of quantity and quality, fewer, smaller, and lower-quality fruits, as well as decreased seed production and seed characteristics (Dietz *et al*., 2021). There are numerous ways for plants to evade the consequences of a shortage of water. These include physiological changes like controlling stomatal aperture to enhance water usage efficiency without sacrificing photosynthesis, as well as structural changes like cuticle development to minimize water loss, enhanced root growth, and variance in vascular tissue. Plants have many hormone-mediated signaling pathways that control various physiological processes, accounting for all of this (Iqbal *et al*., 2022). All of these reactions are ultimately controlled by molecular regulatory mechanisms that entail the expression of genes resistant to drought, which results in signal transduction involving a wide range of metabolites of various kinds; these include proteins like abundant late embryogenesis, osmolytes compatible with drought, like proline, betaine, and glycine, and signaling molecules like $Ca^{2+,}$ abscisic acid, etc. (Yang *et al*., 2021). They investigated the impact of drought priming on winter wheat, one of the most significant crops in the world. In order to enable treated plants to react to the advent of drought stress more rapidly and effectively at the stomatal level, they discovered that pre-exposure through drought priming boosted the expression of genes involved in stomatal opening and closure.

Osmoregulation, which also governs the water contact between plants, activates the defense mechanism against antioxidant species. Osmo-protectants possess a low molecular weight, lack net charge, and exhibit hydrophilic properties. Comparing the salt-tolerant cultivars of bean plants to the salt-sensitive ones, the former had higher quantities of proline and other amino acids and lower levels of protein. Ionic homeostasis is an essential process that regulates ion flux and helps to maintain a low Na+ ion concentration while raising the K+ concentration. The various enzymes' cytosolic activities are dependent on the homeostasis (management) of intracellular Na+ and K+ ions, which also controls membrane potential and cell volume (Cabusora, 2024). Plants experience severe osmotic stress, ion toxicity, and the production of reactive oxygen species (ROS) when there is an excessive salt buildup in the root zone. In plants, ROS cause modifications to DNA sequencing as well as the disintegration of proteins. Salt stress in plants activates a variety of enzymes, including catalase and superoxide dismutase, to produce an anti-oxidative defense system (Cabusora, 2024).

Plants can use their genetic and sensory systems to build molecular defenses against abiotic stresses. Abiotic stress can affect many different cell compartments, such as the nucleus, cytoplasm, mitochondria, endoplasmic reticulum, peroxisomes, chloroplasts, and cell wall (CW) (Praveen *et al*., 2023). This could initiate chemical processes. These stress sensors send signals to secondary messengers and downstream regulatory proteins like ROS, Ca^{2+}, and protein kinases. Abiotic stress also initiates a cascade of responses including several tiers of regulation, signal transmission, and stress perception. Plants have therefore developed defense mechanisms to alter their developmental patterns in order to survive and reproduce in hostile conditions (Zhang *et al*., 2023).

Different proteins are produced by different plant components as a result of gene expression. These proteins protect the cell from harm and turn on a wide range of genes that are vital for the abiotic resistance mechanisms in plants. Many different types of proteins are created, including those that are essential to the development of tolerance, such as chaperones and late embryogenesis abundant proteins (LEA proteins). Genes linked to stress are all focused on the stress response at the same time (Paul & Roychoudhury, 2018).

Mitigation strategies: Many different agricultural adaptation techniques have been put up to lessen the expected adverse consequences of climate change. Farmers have created customary management techniques in arid and semi-arid areas over many generations to improve soil water retention, lessen the land's susceptibility to drought, and stop soil erosion. Raised beds with linked slopes are one such tactic that improves water penetration, decreases runoff, and helps hold onto rainfall (Saikanth *et al*., 2023).

Conventional and modern genetic approaches for enhancing climate resilience: Traditional breeding, or conventional breeding, is a tried-and-true technique that involves choosing plant types with desirable qualities and crossing them to produce new ones. This method, which has long been the foundation of agriculture, is still essential for creating hardy crop types. The first step in the selection process is to identify current crop types that exhibit innate resistance to environmental stresses. These cultivars could have characteristics like pest and disease resistance, drought tolerance, or climatic adaptability. Breeders hope to incorporate these desired features onto new plant lines by crossing these hardy types with commercially valued crops (Sahar *et al*., 2021).

Table 1. Major climate change variables and its effects on agriculture.

Sr. No.	Variables	Effect on agriculture	References
1.	Global warming	The greenhouse effect leads to a rise in temperatures as greenhouse gases concentration in the atmosphere increase. By 2100, the global average temperature is projected to increase by 2°C, potentially causing substantial economic losses worldwide.	(Malhi *et al*., 2021)
2.	Precipitation fluctuations	Drought from irregular or insufficient rainfall can dry out farmlands and cause crop failures, while excessive rainfall and flooding can damage crops and soil, disrupting agriculture, especially during the monsoon season.	(Saikanth *et al*., 2023)
3.	Global change of atmospheric CO_2	The rapid rise in CO_2 levels, a major component of greenhouse gases, has led to a boost in plant productivity and growth due to enhanced photosynthesis. However, elevated temperatures also contribute to increased crop respiration, higher rates of evapotranspiration, more frequent pest infestations, changes in weed flora, and shorter crop growing seasons.	(Malhi *et al*., 2021)
4.	Temperature rise	Increased temperatures have the potential to cause heat stress in crops, resulting in lower yields and lower-quality produce.	(Saikanth *et al*., 2023)

Table 2. Impact of climate change on crop yields and potential adaptation strategies across different countries.

Sr. No.	Crops	Country	Adaptation Strategies that can be opted.	References
1.	Rice, Soybean, Maize	Northeast China	• Expanding heat-tolerant varieties, irrigation infrastructure, and alternative cropping systems.	Xu *et al*., 2024
2.	Potato, Winter wheat, Spring barley, and Faba bean	Northern Europe	• Implementing early sowing combined with enhanced irrigation or utilizing early sowing alongside increased fertilization and irrigation.	Grados *et al*., 2024
3.	Crop sp.	Sub-Saharan Africa	• Encouraging the adoption of climate-resilient agriculture, including the use of drought- and disease-resistant crop varieties, reforestation efforts, and sustainable farming techniques among traditional agricultural communities.	Okoronkwo *et al*., 2024
4.	Wheat	Northwestern Turkey Central Anatolia	• Intercropping and crop rotation. • Drought-resistant wheat and new farming methods like conservation agriculture.	(Demirdogen *et al*., 2024)

Marker-assisted selection (MAS) is an advanced breeding method that enables plant breeders to efficiently develop crop varieties resilient to climate challenges. It involves identifying genetic markers that are linked to specific traits such as drought tolerance or resistance to pests and diseases, thereby expediting the breeding process (Anderson *et al*., 2020). The process begins by discovering DNA markers associated with desirable traits. For instance, a genetic marker connected to drought tolerance can be identified, allowing breeders to swiftly detect its presence in plant DNA. This approach offers a significant advantage over traditional breeding techniques by accelerating the selection process (Ali *et al*., 2023). Unlike conventional methods, which require multiple generations to select for desired traits, MAS allows for immediate identification of plants carrying the target markers, making the breeding process more efficient and precise (Anderson *et al*., 2020). MAS has been widely utilized to enhance climate resilience in crops by selecting for traits like drought tolerance in regions prone to water scarcity. This has led to the creation of drought-resistant crops capable of sustaining productivity under limited water conditions (Haroon *et al*., 2022a). Beyond drought tolerance, MAS has been applied to improve other traits such as resistance to extreme temperatures, pests, diseases, and improved nutrient efficiency. By streamlining the breeding process and facilitating the selection of key traits, MAS has become a critical tool in developing crops better suited to the challenges posed by climate change (Razzaq *et al*., 2022).

Genetic engineering pay key role in the development of crop varieties capable of withstanding climate-related stresses. This technique involves the intentional modification or introduction of specific genes into a plant's genome to enhance traits that improve climate adaptability (Razzaq *et al*., 2021). Genetic engineering plays a crucial role in overcoming climate-related challenges such as drought and pest infestations. Drought-tolerant crops, often engineered with genes that optimize water usage, can thrive in environments with limited water availability. Similarly, pest-resistant crops reduce the dependence on chemical pesticides, encouraging sustainable agricultural practices while ensuring stable yields (Haroon *et al*., 2022b).

Challenges and Future Perspective

Effective strategies for agricultural adaptation include a variety of approaches such as developing crop varieties through innovative breeding techniques, managing land use, and implementing sustainable water and soil practices.

Agronomic techniques, coupled with farmer education and knowledge dissemination, are key to enhancing resilience. On a broader scale, strategies at both regional and national levels might involve financial mechanisms, insurance, migration strategies, and integrating cultural aspects into planning. Additionally, agricultural services, meteorological information, and research and development efforts—such as creating early warning systems—can be prioritized to support local and regional adaptation efforts (Grigorieva *et al*., 2023). Advanced breeding techniques, genomics, and biotechnology, resilient crop varieties can be developed to be against environmental extremes. These approaches will significantly increase yield under current climate change conditions, hence improve agriculture sustainability (Ngongolo & Mmbando, 2024). Biotechnology can help to understand plant responses to stress at physiological, biochemical and molecular levels (Guleria *et al*., 2023). Previous studies provided data that Genetically Modified (GM) crops expressing abiotic stress tolerant genes can provide benefits against current climate change and to cover SDG 13 (climate action).

These adaptation and mitigation strategies aim to boost farmers' incomes while ensuring sustainable agricultural production. However, the unpredictable nature of climate change presents challenges in planning for these adaptations. Addressing these challenges requires climate-resilient technologies that are developed with a region-specific, interdisciplinary approach. Proper agronomic management, pest control, and the breeding of crops that can adapt to shifting climate patterns are essential. Farmers must also be trained and educated in the use of climate-smart technologies to ensure their successful application in the field (Malhi *et al*., 2021). The detail of potential climate change adaptation strategies of different crop species across different countries is given in (Table 2).

Conclusion

Ecosystems, food security, and global agriculture are all under risk from climate change. The problem of adjusting to new environmental realities faces the agriculture sector as temperatures rise and weather patterns change. A combination of conventional and novel molecular breeding and biotechnological approaches will be needed to achieve this, such as using advanced molecular breeding techniques, production of climate smart transgenic genotypes, and the use of cutting-edge genome editing methods. In order to lessen the negative consequences of climate change and make sure that agricultural productivity can keep up with the rising demands of the world's population, the success of these adaptation strategies is essential.

References

Ali, A., MM. Zafar, Z. Farooq, S.R. Ahmed, A. Ijaz and Z. Anwar. 2023. Breakthrough in CRISPR/Cas system: Current and future directions and challenges. *Biotechnol. J.*, 18(8): 2200642.

Anderson, R., P.E. Bayer and D. Edwards. 2020. Climate change and the need for agricultural adaptation. *Curr. Opin. Plant Biol.*, 56: 197-202.

Betts, R.A., L. Alfieri, C. Bradshaw, J. Caesar, L. Feyen and P. Friedlingstein. 2018. Changes in climate extremes, freshwater availability and vulnerability to food insecurity projected at 1.5°C and 2°C global warming with a higher-resolution global climate model. *Philosop. Trans. Royal Soc. A: Math. Phys. Eng. Sci.*, 376(2119): 20160452.

Cabusora, C.C. 2024. Developing climate-resilient crops: adaptation to abiotic stress-affected areas. *Technol. Agron.*, 4(1):e005

Demirdogen A., B. Karapinar and G. Özertan. 2024. The impact of climate change on wheat in Turkey. *Reg. Environ. Change.*, 24(1).

Dietz, K., C. Zörb and C. Geilfus. 2021. Drought and crop yield. *Plant Biol.*, 23(6): 881-893.

Fatima, A. and S.A. Jan. 2023. Approaches for sustainable production of soybean under current climate change conditions. *MOJ Biol. Med.*, 8(1): 27-31.

Grados, D, D. Kraus, E. Haas, K. Butterbach-Bahl, J.E. Olesen and D. Abalos. 2024. Common agronomic adaptation strategies to climate change may increase soil greenhouse gas emission in Northern Europe. *Agric For. Meteorol.*, 349: 109966.

Grigorieva, E., A. Livenets and E. Stelmakh. 2023. Adaptation of Agriculture to climate Change: A scoping review. *Climate.*, 11(10): 202.

Guleria, P., V. Kumar and B. Mo. 2023. Biotechnology for agricultural sustainability. *Front. Sustain. Food Sys.*, 7: 1128411.

Haroon, M, X. Wang, R. Afzal, M.M. Zafar, F. Idrees, M. Batool and M. Imran. 2022a. Novel plant breeding techniques shake hands with cereals to increase production. *Plants*, 11(8): 1052.

Haroon, M., R. Afzal, M.M. Zafar, H. Zhang and L. Li. 2022b. Ribonomics approaches to identify RBPome in plants and other eukaryotes: current progress and future prospects. *Int. J. Mol. Sci.*, 23(11): 5923.

Hasan, M.M., M.A.R. Sarker and J. Gow. 2016. Assessment of climate change impacts on aman and boro rice yields in Bangladesh. *Clim. Change Econ.*, 07(03): 1650008.

Iqbal, S, X. Wang, I. Mubeen, M. Kamran, I. Kanwal, G.A. Díaz, A. Abbas, A. Parveen, M.N. Atiq, H. Alshaya, T.K.Z. El-Abedin and S. Fahad. 2022. Phytohormones Trigger drought tolerance in crop Plants: outlook and Future Perspectives. *Front. Plant Sci*., 12.

Jan, S.A., N. Bibi, Z.K. Shinwari, M.A. Rabbani, S. Ullah, A. Qadir and N. Khan. 2017. Impact of salt, drought, heat and frost stresses on morpho-biochemical and physiological properties of *Brassica* species: An updated review. *J. Pure. Appl. Agri*., 2(1): 1-10.

Jan, S.A., Z.K. Shinwari, N. Habib, Abdullah, S. Ali, M.SS Afridi and M. Khan. 2023. Impact of Climate Change on Marine Biodiversity: Current Challenges and Future Perspectives. *Proc. Pak. Acad. Sci (B) Life Env. Sci.*, 60(1): 29-47.

Khan, A., F. Bibi, S.A. Jan and Z.K. Shinwari. 2023. Role of Dof Transcription Factors under Abiotic Stresses. *Proc. Pak. Acad. Sci (B) Life Env. Sci.*, 60 (03): 367-376.

Lobell, D.B., W. Schlenker and J. Costa-Roberts. 2011. Climate trends and global crop production since 1980. *Sci*., 333(6042): 616-620.

Malhi, G.S., M. Kaur and P. Kaushik. 2021. Impact of climate change on agriculture and its mitigation Strategies: A review. *Sustain.*, 13(3): 1318.

Ngongolo, K. and G.S. Mmbando. 2024. Harnessing biotechnology and breeding strategies for climate-resilient agriculture: pathways to sustainable global food security. *Disc. Sustain.*, 5(1): 431.

Okoronkwo, D.J., R.I. Ozioko, R.U. Ugwoke, U.V. Nwagbo, C. Nwobodo, C.H. Ugwu and E.C. Mbah. 2024. Climate smart agriculture? Adaptation strategies of traditional agriculture to climate change in sub-Saharan Africa. *Front. Clim.*, 6: 1272320.

Paul, S. and A. Roychoudhury. 2018. Transgenic plants for improved salinity and drought tolerance. In: Springer eBooks., 141-181.

Praveen, A., S. Dubey, S. Singh and V.K. Sharma. 2023. Abiotic stress tolerance in plants: a fascinating action of defense mechanisms. *3 Biotech.*, 13(3): 102.

Qamar, H, M. Ilyas, S.A. Jan, H.S.B. Mustafa, A.A. rshad, Z.K. Shinwari and T. Mehmood. 2020. Recent Trends in Molecular Breeding and Biotechnology for the Genetic Improvement of Brassica species against Drought Stress. *Fresen. Environ. Bull.*, 29 (1): 19-25.

Razzaq, A., M.M. Zafar, A. Ali, A. Hafeez, F. Sharif, X. Guan. and Y. Yuan. 2022. The pivotal role of major chromosomes of sub-genomes A and D in fiber quality traits of cotton. *Front. Genet.*, 12: 642595.

Razzaq, A., M.M. Zafar, P. Li, G. Qun, X. Deng, A. Ali A. and Y. Yuan Y. 2021. Transformation and overexpression of primary cell wall synthesis-related zinc finger gene Gh_A07G1537 to improve fiber length in cotton. *Front. Plant Sci.*, 12: 777794.

Sahar, A., M.M. Zafar, A. Razzaq, A. Manan, M. Haroon, S. Sajid, A. Rehman, H. Mo, M. Ashraf, M. Ren, A. Shakeel and Y. Yuan. 2021. Genetic variability for yield and fiber related traits in genetically modified cotton. *J. Cotton Res.*, 4(1):19.

Saikanth, D.R.K., S. Kumar, M. Rani, A. Sharma, S. Srivastava, D. Vyas and S. Kumar. 2023. A comprehensive review on climate change adaptation strategies and challenges in agriculture. *Int. J. Environ. Clim. Change.*, 13(11): 10-19.

Shakoor, U., A. Saboor, I. Ali and A.Q. Mohsin. 2011. Impact of climate change on agriculture: empirical evidence from arid region. *Pak. J. Agri. Sci.*, 48(4): 327-333.

Shinwari, Z.K., S.A. Jan, K. Nakashima and K. Yamaguchi-Shinozaki. 2020. Genetic engineering approaches to understanding drought tolerance in plants. *Plant Biotechnol. Rep.*, 14(2): 151-162.

Xu, Q., H. Liang, Z. Wei, Y. Zhang, X. Lu, F. Li and Y. Dai. 2024. Assessing climate change impacts on crop yields and exploring adaptation strategies in Northeast China. *Earth's Future.*, 12(4): e2023EF004063.

Yang, X., M. Lu, Y. Wang, Y. Wang, Z. Liu and S. Chen. 2021. Response mechanism of plants to drought stress. *Hort.*, 7(3): 50.

Zhang, Y., J. Xu, R. Li, Y. Ge, Y. Li and R. Li. 2023. Plants' response to abiotic stress: Mechanisms and strategies. *Int. J. Mol. Sci*., 24(13): 10915.

(Received for publication 22 July 2024)