Agricultural Research Reports

https://journals.pagepal.org/index.php/ARR

ISSN (Online), 3106-003X; (Print), 3106-0021

https://doi.org/10.54219/arr.02.1.2024.445

Interdisciplinary approaches to mitigate crop stress for sustainable agriculture

Burhan Khalid[1], Sadia Malik[2], Ayesha Asghar[3], Naveed Khan[4], Ameer Jan[5], Farkhanda Ashraf[6], Muhammad Umer Javed[7], Muhammad Atiq Ashraf[8], Shumaila Nawaz[8], Mahnoor[9], Talha Riaz[10]*, Rizwan Maqbool[1]

[1] Department of Agronomy, University of Agriculture Faisalabad, Faisalabad-38000, Pakistan

[2] Department of Botany, Rawalpindi Women University, Rawalpindi-46000, Pakistan

[3] School of Civil and Environmental Engineering, Harbin Institute of Technology, Shenzhen-518000, China

[4] School of Life Sciences and Engineering, Southwest University of Science and Technology, Mianyang-621000, China

[5] Department of Botany, University of Makran, Panjgur-93000, Pakistan

[6] Department of Botany, University of Gujrat, Hafiz Hayat campus, Gujrat-50700, Pakistan

[7] Department of Agricultural Engineering, Khwaja Fareed University of Engineering and Information Technology (KFUEIT), Rahim Yar Khan-64200, Pakistan

[8] College of Horticulture and Forestry Sciences, Huazhong Agricultural University, Wuhan-430000, China

[9] Department of Food Science and Human Nutrition, University of Veterinary and Animal Sciences, Lahore-54000, Pakistan

[10] College of Food Science and Technology, Huazhong Agricultural University, Wuhan-430000, China

Article Info

Keywords:
stress response, mechanism, innovations, sustainable, integrated, synergistic approach, physiological

Date:
Received: 23 January 2024
Accepted: 27 February 2024
Published: 30 June 2024

Volume: 02 (01), 2024

Abstract

Crop stress, caused by both biotic and abiotic factors, poses a major and growing threat to global food security. With the world's population growing and projected to reach 9.7 billion by 2050, demand for food production is expected to increase by 70%. Nevertheless, global food systems are increasingly threatened by crop stress events, which are both more common and more severe, as the impact of climate change continues to intensify their frequency and severity. This review examines crop stress responses through physiological, genetic, and molecular pathways. It highlights the importance of interdisciplinary strategies in tackling these challenges, drawing on knowledge from agronomy, horticulture, genetics, and environmental science to formulate innovative and sustainable solutions. The review underscores the need for precision agriculture, utilizing new technologies-including GPS, remote sensing, and IoT-to fine-tune crop management and reduce stress. It also discusses the potential role of advanced breeding methods such as marker-assisted selection (MAS) and CRISPR/Cas9 in breeding stress-resistant crop varieties. In addition, this review highlights the importance of sustainable practices like IPM, agroforestry, or efficient water use in improving crop resilience. Emerging technological innovations serve as transformative tools for stress management and enhancing transparency in agricultural supply chains, particularly through AI, machine learning, and blockchain technology.

1. Introduction

Soil health plays a crucial role in determining crop yield, yet it's increasingly vulnerable to biotic and abiotic stressors, posing a significant threat to global food security by impacting both yield quantity and quality. As the population increases and the impacts of climate change amplify stress events, sustainable solutions are required now more than

Corresponding Author: Talha Riaz Email: talhariaz2844@gmail.com

ever. Innovations in crop resilience and future food security must be interdisciplinary, integrating agronomy, horticulture, and technology to meet the challenges of the 21st century and beyond. Crop stress-arising from biological factors (e.g., pests, diseases) and abiotic factors (e.g., drought, salinity, temperature), significantly affects plant growth and productivity. These stresses can lead to considerable crop yield loss, resulting in both food scarcity and reduced nutritional quality. As climate change drives more frequent and severe stressors, such as extreme temperatures, altered precipitation, and elevated atmospheric carbon dioxide, the interaction between plants and soil is therefore an important focus of research. Drought stress by itself may reduce yields of crops by up to 50% depending on the crop and the severity of the stress. Similarly, the salinity stress affects over 20 percent of the global irrigated land, and the agricultural output is decreased (Munns & Tester, 2008). The combined effect of all these pressures may lead to a massive drop in food production as well as a threat to global food security.

One of the greatest causes of food insecurity is crop stress, especially in the third world. Biotic and abiotic stresses are most devastating; alone, abiotic stresses may lead to a 50% reduction in crop yields and cause hunger and malnutrition (FAO, 2020; Ikram *et al.,* 2025b). The cost in terms of the economy is also huge, as billions of dollars are used annually due to the loss of agricultural activities. In the case of the United States, the 2012 drought resulted in the loss of agriculture that amounted to about USD 30 billion (Lobell *et al.,* 2014). The depletion of soil health by means of cultivating soil without taking measures to improve its health causes not only the underdevelopment of crops but also the lack of nutritional value, which eventually results in hidden hunger and malnutrition (Welch & Graham, 1999).

Estimates have it that the world population will increase to 9.7 billion people by 2050, and this will necessitate the need for a 70 percent rise in food production. Crop stress should be dealt with so that the demand can be sustainable. This challenge is further compounded by the fact that the available resources in the form of arable land and water sources are being stretched such that more food will have to be produced with fewer resources. It is predicted that by the year 2025, an astonishing 1.8 billion individuals will reside in a region where they are potentially experiencing total water scarcity (FAO, 2017; Ikram *et al.,* 2018), e.g. The creation of effective solutions to such multilateral and complicated challenges is a serious scientific and practical obstacle. This international scenario of dealing with crop stress is further complicated by the facts of climate change, where changes in frequency and intensity of stress events are foreseen, and an overwhelming necessity to develop more stable agricultural systems.

The interdisciplinary solution to crop stress should combine ideas of agronomy, horticulture, genetics, and environmental science. The intersection between two aspects of creativity gives a greater chance to achieve the creation of new solutions that make crops more resilient and sustainable (Table 1). The multidisciplinary approach to crop stress will put in place complete approaches to problem-solving. As an example, agronomic engineering, combined with genetic engineering, may result in creating stress-tolerant and high-yield crops (Zhang and Sonnewald, 2017). Because crop responses to stress are mediated by numerous and diverse physiological, genetic, and molecular mechanisms that typically are involved together in complex manners (Mittler, 2006), the importance of interdisciplinary investigations remains even more exemplified.

2. The mechanism and science of crop stress response

Plants employ physiological, genetic, and molecular mechanisms to signal and respond to stress. stress response. The buildup of solutes, such as proline, manages stomata and generates antioxidants to counter the injury. Stress-responsive genes such as DREB and NAC activate defense pathways, while protective proteins help maintain cellular function (Figure 1). Gene expression is also regulated by epigenetic modifications. These mechanisms are crucial for creating stress-resistant crops and sustainable agriculture.

2.1. Physiological basis of stress responses in plants

Plants have developed intricate physiological responses to deal with stress. They include osmotic adjustment regulation. For example, plants accumulate osmolytes such as proline in response to drought stress to retain cell turgor. Therein, under salt stress conditions, plants can sequester sodium ions within vacuoles to protect cellular functions (Munns & Tester, 2008). These physiological responses are important for developing crop varieties with improved stress tolerance. Accumulation of compatible solutes has been shown to improve drought tolerance in wheat (Ashraf & Foolad, 2007). The physiological basis of stress responses

Table 1. Key physiological and genetic mechanisms of plant adaptation to abiotic stress

Mechanism	Description	References
Physiological responses	Plants adapt to stress by accumulating osmolytes like proline to maintain cell turgor during drought.	(Ashraf & Foolad, 2007)
	Stomatal regulation helps reduce water loss under drought conditions.	(Zhang and Sonnewald, 2017)
	Under salt stress, plants sequester sodium ions in vacuoles to protect cellular functions.	(Munns & Tester, 2008)
Genetic responses	Stress-responsive genes, such as DREB and NAC, activate defense pathways.	(Yamaguchi-Shinozaki & Shinozaki, 2006)
	Overexpression of the DREB1A gene has been shown to improve drought tolerance in crops like Arabidopsis.	(Li *et al.*, 2018)
	Epigenetic modifications, such as DNA methylation, regulate gene expression during stress.	(Chinnusamy & Zhu, 2009; Kozai *et al.*, 2015)

also includes stomatal conductance regulation, which allows plants to achieve reduced water consumption.

2.2. Genetic and molecular foundations

At the genetic level, responses to stress are governed by networks of genes and signal-transudative pathways. Key

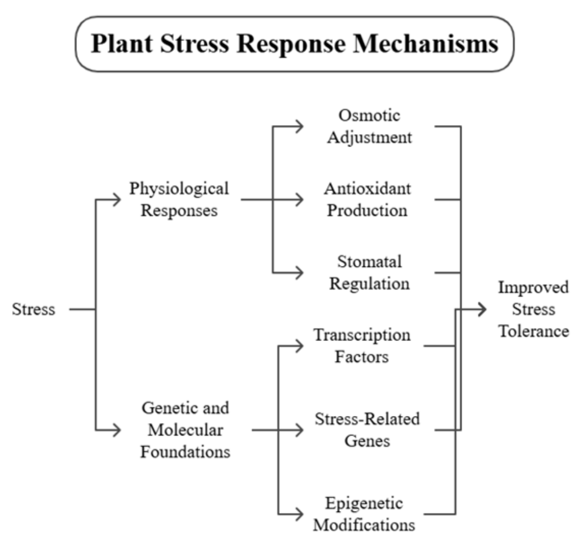

Figure 1. Mechanisms of Plant Stress Response
Integrating Physiological Adaptations, Genetic Regulation, and Molecular Foundations for Enhanced Stress Tolerance

stress-responsive transcription factors, such as DREB and NAC, play essential roles in mediating plant responses to abiotic stress (Yamaguchi-Shinozaki & Shinozaki, 2006). From molecular studies, it is known that there are many stress-related genes which encode, for example, heat shock proteins (HSPs) and late embryogenesis abundant (LEA) proteins. Recent progress in molecular biology and genomics has made it possible to identify and manipulate these genes to increase stress tolerance. Overexpression of the DREB1A gene in Arabidopsis has been shown to enhance drought tolerance and promote vegetative growth (Kasuga *et al.*, 1999). Epigenetic modifications, such as DNA methylation and histone changes, regulate gene expression during various stress responses, contribute to long-term adaptation (Chinnusamy & Zhu, 2009).

3. Integrated agronomic and horticultural insights into crop stress management

Integrated multidisciplinary approaches utilize agronomy and horticulture to curb stress on crops. “Precision agriculture” employs GPS and remote sensing to better allocate resources, while advanced breeding results in varieties that can better withstand stress. Practices that help keep soil healthy, such as crop rotation and organic farming, improve resilience. Horticultural practices such as pruning and canopy management improve light penetration and reduce disease incidence, while post-harvest handling techniques help minimize storage and transport losses. Collectively, these strategies enhance crop resilience, productivity, and sustainability.

3.1. Precision agriculture

Precision agriculture employs GPS, remote sensing, and IOT technology to scale up crop management. An example is the invention of variable rate technology (VRT) that has made it possible to apply inputs accurately, and this relieves stress and consequently improves yields. Precision agriculture allows condition monitoring of crops in real-time and enables one to make decisions in time to avoid stressful conditions. Applications like multispectral and hyperspectral imaging (Remote sensing), e.g., can also supply information regarding the health of the crops to assist with the targeted management of the causes of the stress (Mulla, 2013; Ikram *et al.,* 2024b). The technological applications of precision agriculture aim at increasing the efficiency of water use and also reducing the impact of activities of farming activities on the environment (Gebbers & Adamchuk, 2010).

3.2. Advanced breeding techniques

Modern methodology and techniques are used in pre-breeding to promote the production of stress-tolerant crops by using tools markers, and both marker-based selections (MAS) and CRISPR/Cas9 are currently widely used in breeding programs. The same applies in the case of breeding maize, which has a large capacity to withstand drought, and rice with high salt tolerance (Li *et al.,* 2018).

Another key aspect of more sophisticated breeding is genomic selection, which involves the prediction of breeding values of individuals based on genome-wide markers. He added that (Heffner *et al.,* 2009). To give an example, genomic selection has been used to develop wheat varieties that demonstrate enhanced drought tolerance (Crossa *et al.,* 2010). Due to advanced breeding methods, crops that tolerate multiple stresses, such as drought and salinity, have been obtained **(Figure 2)**.

3.3. Plant nutrition and soil health management

To reduce stress, an adequate diet and healthy soil are needed. Other practices like integrated nutrient management (INM) and organic farming raise the fertility of soils and increase plant resistance. In the same manner, biofertilizers lead to an increase in nutrient availability and tolerance of crops to stress (Adesemoye *et al.,* 2009; Ikram *et al.,* 2024a). Agronomic solutions of soil health, which may include crop rotation and leguminous cover crops, improve soil structure and fertility (Lal, 2015). Some cover crops, like the leguminous cover crops, have been proven to add nitrogen to soil and lower the artificial fertilizer demands (Cherr *et al.,* 2006). Management of soil health is key to sustainable productivity in agriculture, more so in stressed environments (Kibblewhite *et al.,* 2008).

3.4. Pruning and canopy management

Pruning and canopy management are some of the strategies that help minimize stress and ensure ventilation of light. The horticultural, especially fruit crops, i.e., grapes and apples, are especially favored by these practices because they enhance the fruit quality and yield (Jackson, 2003).

Moreover, canopy management is done effectively, which enhances aeration and minimizes the prevalence of weather-related infections (Mills *et al.,* 2002). An example here is the use of vertical shoot positioning (VSP) on grapevines, which has been linked with improved light interception and minimal occurrences of disease (Smart & Robinson, 1991). Pruning and canopy control are some of the methods in which higher efficiency of water and nutrient use is possible in horticultural crops.

3.5. Postharvest handling

Lessening of postharvest losses due to physiological stress is important in the preservation of crop quality and food security. Only a few of the methods that could be employed to prolong the shelf life and maintain the quality of the product include the use of controlled atmosphere storage and management of the cold chain (Kader, 2002; Ikram *et al.,* 2024c).

Some of the post-harvest handling technologies are Modified Atmosphere Packs (MAP) that assist in physiological stress reduction and extension of shelf life and inhibitors of ethylene, which also aid in the reduction of physiological stress and shelf-life extension (Watkins, 2006). An example of this is MAP, which is known to aid in the moderation of rates of respiration and ethylene synthesis, leading to extended shelf-life of strawberries (Zhang *et al.,* 2006). The losses that occur post-harvest might be significant

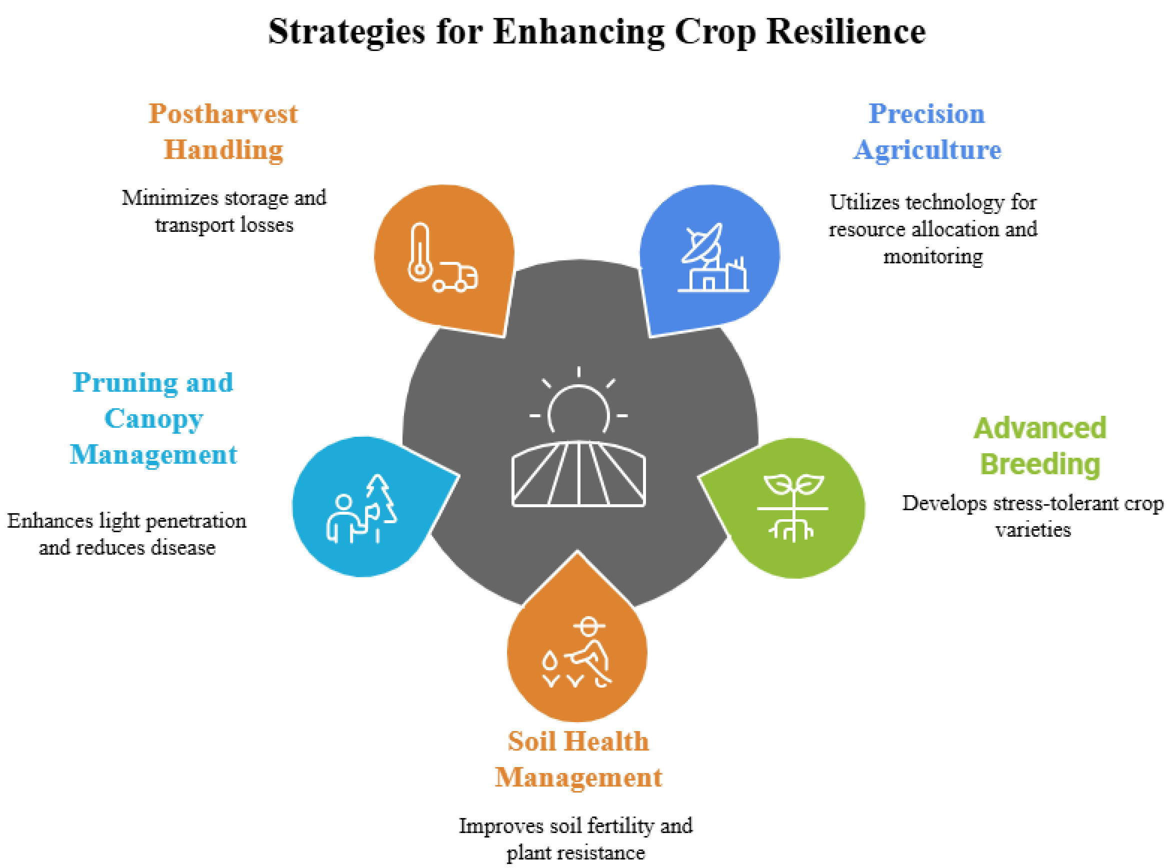

Figure 2. Key Mechanisms of Crop Stress Response
From Physiological Adaptations to Genetic and Epigenetic Regulation for Enhanced Toleranceure

in developing countries (Hodges *et al.,* 2011), and the post-harvest stress management.

4. Synergistic approaches and sustainable practices in mitigating crop stress

Synergistic approaches combine sustainable practices, which provide relief to the crops, such as integrated pest management (IPM), water, and agroforestry management. Integrated Pest Management (IPM) and agroforestry contribute to the reduction of chemical-based pest control and maximize the use of biological and cultural control methods to reduce damage to plants. Agroforestry also increases soil health and biodiversity. Sustainable agriculture is also the conservation of water using strategies like drip irrigation and the improvement of resource use (Figure 3). The practices ensure crops withstand the climatic extremities in their localities and reduce the adverse environmental impacts and making it a sustainable form of agriculture.

4.1. Integrated pest management (IPM)

Integrated Pest Management (IPM) has been described as a sustainable approach that incorporates a combination of biological, cultural, and chemical techniques with a view to managing pests. By using these techniques, such as pheromone trapping and biocontrol agents, they reduce the usage of pesticides and prevent induced stress through pests on crops (Pretty, 2008). The IPM consists of practices like crop rotation and intercropping, among others, that are useful in breaking the pest life cycle and minimizing pest populations (Altieri, 1999). As an example, coupling maize

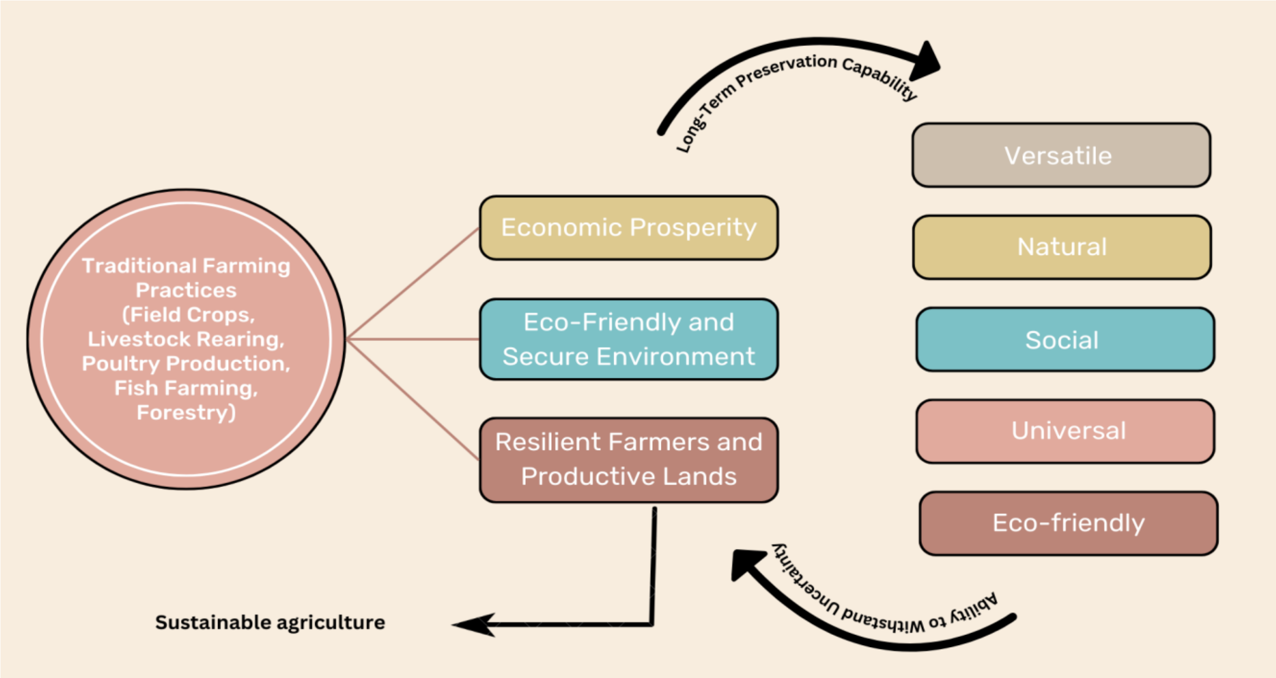

Figure 3. Traditional farming practices and their contributions to sustainable agriculture, economic prosperity, and environmental resilience

This figure illustrates the key components of traditional farming, including field crops, livestock rearing, poultry production, fish farming, and forestry. It highlights their role in fostering economic prosperity, eco-friendly environments, and resilient agricultural systems. The interconnectedness of natural, social, and universal aspects underscores their versatility and sustainability. Traditional practices are depicted as foundational to sustainable agriculture, balancing productivity with environmental stewardship

with the legumes has proven to decrease the number of stems borers, and yields become high (Khan *et al.*, 2006). It has been demonstrated that Integrated Pest Management (IPM) practices reduce the impact of pest management on the environment and enhance food production system sustainability (Pretty, 2005; Ikram *et al.*, 2025a).

4.2. Agroforestry and intercropping

Biodiversity is increased with intercropping and agroforestry practices and relieves stress on crops. These layouts offer improved microclimatic situations to the crops and assist in the improvement of soil nutrients. Legumes would be one of them as they have proved to improve nitrogen availability and drought tolerance upon intercropping with maize (Lithourgidis *et al.*, 2011). Agroforestry systems also provide extra value, such as carbon sequestration capability and as a habitat for beneficial organisms (Jose, 2009). As an example, the interrelationship of leguminous trees in use in the alley method of cropping has been shown to enhance soil fertility, not to mention the reduction of soil erosion (Nair, 1993). It has been shown that the agriculture systems can build resilience to climate change effects through Agroforestry and intercropping systems (Lin, 2011).

4.3. Water management

In reducing stress, it is important to manage the water. Drip irrigation and rainwater harvesting are some of the methods of enhancing water use efficiency and alleviating drought stresses (Pereira *et al.*, 2002). Such activities are making agriculture sustainable in terms of raising crop productivity and water productivity in arid areas (Rockström *et al.*, 2007). Water management also involves the use of technologies like soil moisture sensors and automated irrigation systems, where water is utilized optimally and stress relieved (Evans & Sadler, 2008). Indicatively, Vellidis *et al.* (2008) revealed the level of efficiency and water use advantage in cotton production using soil moisture sensors. Management of water resources is also important in the sustainability of agricultural systems, and more so in realms where water is a key limiting factor (Molden, 2007).

5. Role of technological and system innovations in stress management

Remote sensing, artificial intelligence (AI), and blockchain are additional technologies that are being used in modern agriculture to manage crops better based on their stresses. That is, in-time data via remote sensing and GIS visualization are implemented, as well as AI is used to make specific interventions and requirements to control stress events and better decision-making in agricultural practices (Table 2). Blockchain improves the transparency of the supply chain, which reduces post-harvest wastage. Use of the technologies enhances operational efficiency and leads to resiliency and sustainability of agricultural systems.

5.1. Remote sensing and GIS

Crop health and its states of stress can be determined in real-time using remote sensing and geographic information systems (GIS). Such strategies may enable effective interventions and reduce the loss due to stress. Technology remote sensing, like multispectral and hyperspectral imaging, provides data on the spatial distribution of crops, whereas stress factors should be improved (Mulla, 2013). An example is that hyperspectral imaging has been used to identify the onset of drought stress in maize (Zhang *et al.*, 2012). It was observed that remote sensing and GIS technologies improve the level of agricultural management at lower costs and reduce the intensity of environmental impacts (Mulla, 2013).

5.2. Artificial intelligence and machine learning

AI and machine learning algorithms can forecast stress-related events and manage them in the most efficient way when trained on large data (Figure 4). Intelligent Artificial Intelligence will be able to forecast the outbreak of pests and advise adequate measures to take (Kamilaris & Prenafeta-Bold, 2018). The machine learning algorithms are also capable of evaluating remote sensing data and others to provide real-time recommendations in the context of stress management (Liakos *et al.*, 2018). An example can be the use of machine learning algorithms, which have proven their ability to improve the accuracy of yield prediction of wheat (Khaki & Wang, 2019). Machine learning (and AI) has shown itself to be immensely promising in enhancing crop stress and optimizing sustainable agriculture (Liakos *et al.*, 2018).

Table 2. Innovative agricultural practices and technologies for enhancing crop resilience, resource efficiency, and sustainability

Innovation/Practice	Description	References
Precision agriculture	Uses GPS, remote sensing, and IoT to monitor crops in real-time and optimize resource use.	(Mulla, 2013)
Advanced breeding	Techniques like CRISPR/Cas9 and marker-assisted selection (MAS) create stress-resistant crops.	(Li *et al.*, 2018)
Integrated pest management (IPM)	Combines biological, cultural, and chemical methods to reduce pest-related stress.	(Pretty, 2008; Khan *et al.*, 2006)
Agroforestry	Integrating trees with crops improves soil health and creates better microclimates.	(Jose, 2009; Lithourgidis *et al.*, 2011)
Water management	Practices like drip irrigation and rainwater harvesting improve water efficiency.	(Pereira *et al.*, 2002; Rockström *et al.*, 2007)
AI and machine learning	Predicts stress events and optimize farming practices using large datasets.	(Kamilaris & Prenafeta-Boldú, 2018; Khaki & Wang, 2019)
Blockchain technology	Enhance transparency in supply chains, reducing post-harvest losses.	(Kamilaris *et al.*, 2019)

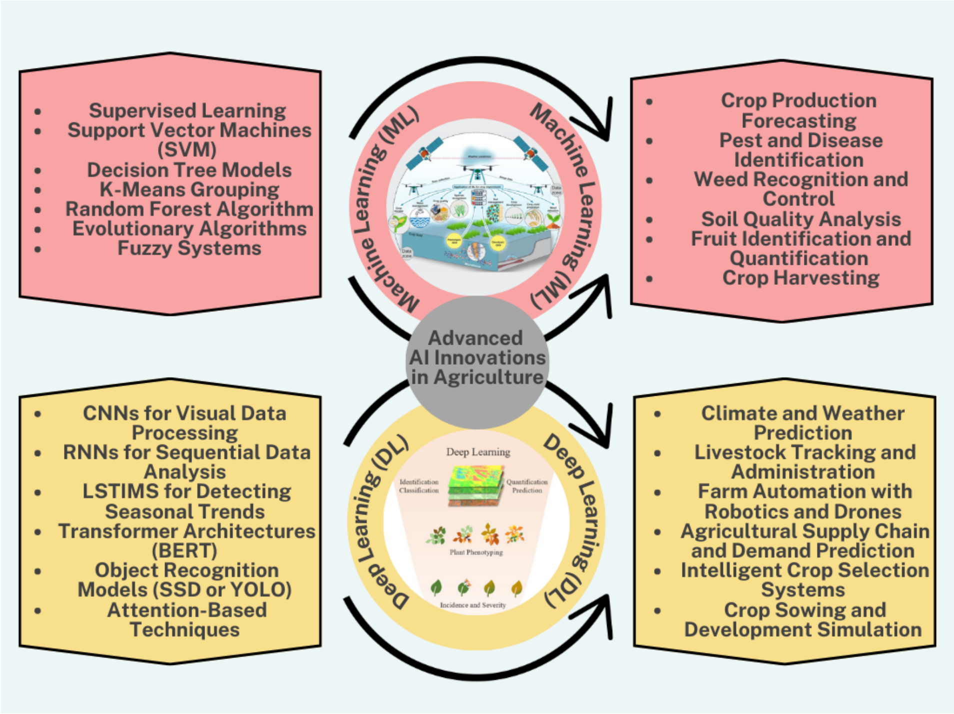

Figure 4. Advanced AI innovations in agriculture

Applications of supervised learning, deep learning, and AI-driven techniques. This figure outlines the integration of cutting-edge AI technologies such as Support Vector Machines (SVMs), Convolutional Neural Networks (CNNs), and Transformer architectures into agricultural practices. It highlights key applications, including crop production forecasting, pest/disease identification, soil analysis, and farm automation using robotics and drones. The diagram also emphasizes AI's role in climate prediction, livestock tracking, and optimizing supply chains. By leveraging supervised learning, deep learning models (e.g., LSTMs, YOLO), and attention-based techniques, these innovations enhance precision, efficiency, and sustainability in modern agriculture.

5.3. Blockchain for supply chain transparency

The architecture of blockchain is used to make better management of the post-harvest stress, the transparency of the supply chain, and quality assurance. This kind of technology will assist in the tracking of the origin and handling of agricultural products and assist in the post-harvest loss reduction (Kamilaris *et al.*, 2019). Blockchain will allow a clear and irreversible picture of the transactions to be seen, and this will improve trust and responsibility in the agricultural supply chains (Tian, 2016). As an example, blockchain technology has been demonstrated to be useful in such activities with increased traceability and decreased fraud in coffee supply chains. The supply chain in agriculture can be streamlined with the help of blockchain-based solutions, particularly in situations of low-income countries where post-harvest losses are a common occurrence (Kamilaris *et al.*, 2019).

6. Emerging trends and interdisciplinary approaches towards sustainable and resilient food systems

New developments like climate-smart agriculture, Urban farming, and vertical farming are emerging to be seen as the potential that can help build sustainable food systems. We can create resilience by working in an interdisciplinary way by developing a combination of agronomy, horticulture, and technology. There are research policies and farmer education policies that support adoption. All these developments and plans lead to food systems that are resilient and can adapt and respond to the impacts of climate change and comprehensive food security in the globalized world.

6.1. Climate-smart agriculture

Climate-smart agriculture (CSA) includes practices that foster resilience, emission reduction, and productivity. Agroecology, conservation agriculture, and other CSA practices are key for addressing crop stress under changing climate conditions (Lipper *et al.,* 2014). CSA also includes introducing climate-resilient crop varieties and practices (agroforestry) to build climate resilience (Lin, 2011). For example, drought-tolerant maize varieties have been developed to enhance resilience (Cairns *et al.,* 2013). Adoption of CSA practices has been associated with increased resilience of farming systems to climate change and reduced environmental impacts of agriculture (Lipper *et al.,* 2014).

6.2. Urban agriculture and vertical farming

Urban agriculture and vertical farming are some of the new ways of solving crop stress. These are the ways that entail controlled conditions **(Figure 5)**, which are meant to increase cultivation provisions and reduce the outside stressors (Despommier, 2010). Urban agriculture also encompasses strategies like rooftop gardening, community gardens, etc, which enhance city food security and resiliency of the cities (Orsini *et al.,* 2013). As an example, vertical farming systems proved to be more profitable regarding the amount of water used and decreased pesticide dependence (Kozai *et al.* 2015). Introduction The world is increasingly becoming urbanized, and the population is expanding, leading to massive degradation of agricultural land (Despommier, 2010).

6.3. Policy and institutional support

An effective policy and institutional support are essential to scale up the practice of stress management. To facilitate sustainability practices, governments and institutions should be responsible for investing in research, development, and the training of farmers (Pretty *et al.,* 2011). Other constructs of policy support are the formation of sustainable regulations

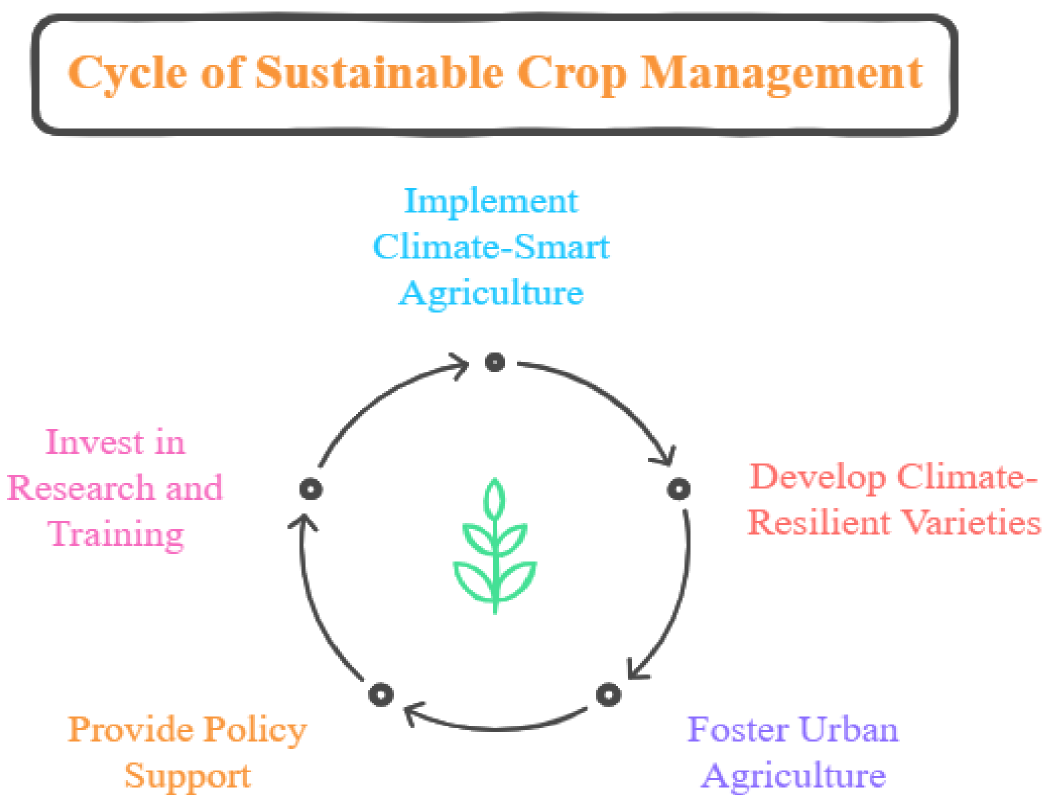

Figure 5. Unveiling Plant Stress Adaptation: Physiological, Molecular, and Genetic Pathways to Enhanced Tolerance

and incentives for agricultural and stress management practices (Tilman *et al.,* 2002). Sustainable agricultural activities have been given incentives by subsidizing them, thus facilitating increased levels of adoption and reduced impact on the environment (Pretty, 2008). Putting emphasis on policy, it is vital to develop efficient policies and provide them with sufficient institutional backing so that more sustainable procedures and strengthening agricultural regimes can be acquired (Pretty *et al.,* 2011).

7. Conclusion and future perspective

A major conclusion of this review is the need for interdisciplinary approaches in the management of crop stress. Integrating multidisciplinary knowledge from agronomy, horticulture, and emerging technologies is essential for ensuring food stability and sovereignty. Therefore, to formulate holistic approaches to the complex nature of crop stress, we need knowledge from multiple disciplines. Future research should clarify the interactive effects of multiple stressors and design integrative management strategies to improve the ecosystem-based solution.

Advances in genomics, biotechnology, and digital agriculture offer promising avenues for enhancing crop resilience. In addition, future research should address innovations and knowledge transfer that enhance climate and other stressor change resilience. Tackling crop stress will require a collaborative effort among researchers, policymakers, and farmers. Together, we can create sustainable and resilient food systems that face the challenges of a growing population and a changing climate. Interdisciplinary approaches to development and their translation to practice are vital for global food security and sustainable development goals.

8. Author's contributions

Burhan Khalid and Sadia Malik proposed the general idea and were responsible for writing the review. Ayesha Asghar and Naveed Khan contributed to the review's conception and design. Ameer Jan, Farkhanda Ashraf, Muhammad Umer Javed, Shumaila Nawaz, and Mahnoor reviewed all manuscript drafts and provided extensive editing. Muhammad Atiq Ashraf, Rizwan Maqbool, and Talha Riaz helped draw the figures. All authors have read and approved the final version of this manuscript.

9. Funding

The authors did not receive any funding for this work.

10. Declaration of interest

The authors declare no potential conflict of interest regarding the publication of this work.

11. SDG Goals

This study aligns with multiple Sustainable Development Goals (SDGs). It contributes to SDG 2 (Zero Hunger) by enhancing crop resilience and ensuring stable food production under abiotic and biotic stress conditions. By promoting sustainable agricultural practices, including integrated pest management, agroforestry, and efficient water use, it addresses SDG 12 (Responsible Consumption and Production). Interdisciplinary approaches to stress mitigation facilitate adaptation to climate-induced challenges, supporting SDG 13 (Climate Action). Moreover, the integration of precision agriculture, artificial intelligence, and biotechnological innovations advances SDG 9 (Industry, Innovation, and Infrastructure) by fostering technological solutions for sustainable and resilient agricultural systems.

References

Adesemoye, A. O., Torbert, H. A., & Kloepper, J. W. (2009). Plant growth-promoting rhizobacteria allow reduced application rates of chemical fertilizers. *Microbial Ecology, 58*(4), 921-929.

Altieri, M. A. (1999). The ecological role of biodiversity in agroecosystems. *Agriculture, Ecosystems & Environment, 74*(1-3), 19-31.

Ashraf, M., & Foolad, M. R. (2007). Roles of glycine betaine and proline in improving plant abiotic stress resistance. *Environmental and Experimental Botany, 59*(2), 206-216.

Cairns, J. E., Hellin, J., Sonder, K., Araus, J. L., MacRobert, J. F., Thierfelder, C., & Prasanna, B. M. (2013). Adapting maize production to climate change in sub-Saharan Africa. *Food Security, 5*(3), 345-360.

Cherr, C. M., Scholberg, J. M. S., & McSorley, R. (2006). Green manure approaches to crop production: A synthesis. *Agronomy Journal, 98*(2), 302-319.

Chinnusamy, V., & Zhu, J.-K. (2009). Epigenetic regulation of stress responses in plants. *Current Opinion in Plant Biology, 12*(2), 133-139.

Crossa, J., de los Campos, G., Pérez, P., Gianola, D., Burgueño, J., & Araus, J. L. (2010). Prediction of genetic values of quantitative traits in plant breeding using pedigree and molecular markers. *Genetics, 186*(2), 713-724.

Despommier, D. (2010). *The vertical farm: Feeding the world in the 21st century*. Macmillan.

Evans, R. G., & Sadler, E. J. (2008). Methods and technologies to improve efficiency of water use. *Water Resources Research, 44*(7), Article W00E04.

FAO. (2017). *The future of food and agriculture: Trends and challenges*. FAO.

FAO. (2020). *The state of food security and nutrition in the world*. FAO.

Foley, J. A., et al. (2011). Solutions for a cultivated planet. *Nature, 478*(7369), 337-342.

Godfray, H. C. J., et al. (2010). Food security: The challenge of feeding 9 billion people. *Science, 327*(5967), 812-818.

Heffner, E. L., Sorrells, M. E., & Jannink, J.-L. (2009). Genomic selection for crop improvement. *Crop Science, 49*(1), 1-12.

Ikram, M., Batool, M., Ullah, M., Khalid, B., El-Badri, A. M., Mohamed, I. A., & Rehman, H. U. (2025a). Molecular alchemy: Converting stress into resilience via secondary metabolites and calcium signaling in rice. *Rice, 18*(1), 32.

Ikram, M., Mehran, M., Minhas, A., ur Rehman, H., Bakash, M. Z. M., Khan, M. W., & Rasheed, H. (2025b). C:N ratio and its importance in developing effective bioenergy crops. In *Forage crops in the bioenergy revolution: From fields to fuel* (pp. 259-276). Springer Nature.

Ikram, M., Mehran, M., ur Rehman, H., Ullah, S., Bakhsh, M. Z. M., Tahira, M., & El-Sabagh, A. (2024a). Mechanistic review of melatonin metabolism and signaling pathways in plants: Biosynthesis, regulation, and roles under abiotic stress. *Plant Stress*, Article 100685.

Ikram, M., Minhas, A., Al-Huqail, A. A., Ghoneim, A. M., Mahmood, S., Mahmoud, E., & Ali, W. (2024b). Promoting tomato resilience: Effects of ascorbic acid and sulfur-treated biochar in saline and non-saline cultivation environments. *BMC Plant Biology, 24*(1), Article 1053.

Ikram, M., Rauf, A., Rao, M. J., Maqsood, M. F. K., Bakhsh, M. Z. M., Ullah, M., & Tahira, M. (2024c). CRISPR-Cas9-based molecular breeding in crop plants: A review. *Molecular Biology Reports, 51*(1), 227.

Ikram, M., Shoaib, M., Tariq, H., Jahanzaib, S., Rasool, M. B. B., Ahmad, S., & Riaz, Z. (2018). Allelopathic effect of *Eucalyptus* extract on seedling germination and establishment of wheat and chickpea. *International Journal of Research in Biomedicine, 3*(11), 24-31.

Jackson, D. I., & Lombard, P. B. (1993). Environmental and management practices affecting grape composition and wine quality: A review. *American Journal of Enology and Viticulture, 44*(4), 409-430.

Jose, S. (2009). Agroforestry for ecosystem services and environmental benefits. *Agroforestry Systems, 76*(1), 1-10.

Kader, A. A. (2002). *Postharvest technology of horticultural crops*. University of California Press.

Kamilaris, A., & Prenafeta-Boldú, F. X. (2018). Deep learning in agriculture: A survey. *Computers and Electronics in Agriculture, 147*, 70-90.

Kamilaris, A., Kartakoullis, A., & Prenafeta-Boldú, F. X. (2019). A review on the practice of big data analysis in agriculture. *Computers and Electronics in Agriculture, 143*, 23-37.

Kasuga, M., Liu, Q., Miura, S., Yamaguchi-Shinozaki, K., & Shinozaki, K. (1999). Improving plant drought, salt and freezing tolerance by gene transfer of a single stress-inducible transcription factor. *Nature Biotechnology, 17*(3), 287-291.

Khaki, S., & Wang, L. (2019). Crop yield prediction using deep neural networks. *Frontiers in Plant Science, 10*, 621.

Khan, Z. R., Pickett, J. A., Wadhams, L. J., & Muyekho, F. (2006). Habitat management strategies for the control of cereal stemborers and *Striga* in maize in Kenya. *International Journal of Tropical Insect Science, 26*(3), 157-164.

Lal, R. (2015). Restoring soil quality to mitigate soil degradation. *Sustainability, 7*(5), 5875-5895.

Li, Z., Liu, H., & Zhang, Y. (2018). CRISPR/Cas9-mediated genome editing in plants: A review. *Molecular Plant, 11*(5), 535-547.

Liakos, K. G., Busato, P., Moshou, D., Pearson, S., & Bochtis, D. (2018). Machine learning in agriculture: A review. *Sensors, 18*(8), 2674.

Lin, B. B. (2011). Resilience in agriculture through crop diversification: Adaptive management for environmental change. *BioScience, 61*(3), 183-193.

Lipper, L., Thornton, P., Campbell, B. M., Baedeker, T., Braimoh, A., Bwalya, M., ... Torquebiau, E. F. (2014). Climate-smart agriculture for food security. *Nature Climate Change, 4*(12), 1068-1072.

Lithourgidis, A. S., Dordas, C. A., Damalas, C. A., & Vlachostergios, D. N. (2011). Annual intercrops: An alternative pathway for sustainable agriculture. *Australian Journal of Crop Science, 5*(4), 396-410.

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

Mills, P. F., & Wood, D. (2002). The effects of canopy management on grapevine performance. *Australian Journal of Grape and Wine Research, 8*(2), 70-76.

Molden, D. (2007). *Water for food, water for life: A comprehensive assessment of water management in agriculture*. Earthscan.

Mulla, D. J. (2013). Twenty-five years of remote sensing in precision agriculture: Key advances and remaining knowledge gaps. *Biosystems Engineering, 114*(4), 358-371.

Munns, R., & Tester, M. (2008). Mechanisms of salinity tolerance. *Annual Review of Plant Biology, 59*, 651-681.

Nair, P. K. R. (1993). *An introduction to agroforestry*. Springer.

Pereira, L. S., et al. (2002). Irrigation management under water scarcity. *Agricultural Water Management, 57*(3), 175-206.

Pretty, J. (2008). Agricultural sustainability: Concepts, principles and evidence. *Philosophical Transactions of the Royal Society B: Biological Sciences, 363*(1491), 447-465.

Pretty, J., & Bharucha, Z. P. (2014). Sustainable intensification in agricultural systems. *Annals of Botany, 114*(8), 1571-1596.

Rockström, J., Lannerstad, M., & Falkenmark, M. (2007). Assessing the water challenge of a new green revolution in developing countries. *Proceedings of the National Academy of Sciences, 104*(15), 6253-6260.

Smart, R. E., & Robinson, M. (1991). *Sunlight into wine: A handbook for winegrape canopy management*. Winetitles.

Tian, F. (2016). An agri-food supply chain traceability system for China based on RFID and blockchain technology. In *2016 13th International Conference on Service Systems and Service Management (ICSSSM)* (pp. 1-6). IEEE.

Tilman, D., Balzer, C., Hill, J., & Befort, B. L. (2011). Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences, 108*(50), 20260-20264.

Vellidis, G., Tucker, M., Perry, C., Kvien, C., & Bednarz, C. (2008). A real-time wireless smart sensor array for scheduling irrigation. *Computers and Electronics in Agriculture, 61*(1), 44-50.

Watkins, C. B. (2006). The use of 1-methylcyclopropene (1-MCP) on fruits and vegetables. *Biotechnology Advances, 24*(4), 389-409.

Yamaguchi-Shinozaki, K., & Shinozaki, K. (2006). Transcriptional regulatory networks in cellular responses and tolerance to dehydration and cold stresses. *Annual Review of Plant Biology, 57*, 781-803.

Zhang, C., & Kovacs, J. M. (2012). The application of small unmanned aerial systems for precision agriculture: A review. *Precision Agriculture, 13*(6), 693-712.

Zhang, H., & Sonnewald, U. (2017). Differences and commonalities of plant responses to single and combined stresses. *The Plant Journal, 90*(5), 839-855.

Zhang, M., Zhan, Z., & Wang, S. (2006). Effects of modified atmosphere packaging on quality and shelf life of strawberries. *Journal of Food Engineering, 72*(3), 256-261.