FRONTIERS IN AGRICULTURAL RESEARCH

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AGRI ROOT
Publication House

First Published in May, 2026

ISBN: 978-81-998100-8-2

Price: 999.00 INR

Published By:

AGRI ROOT PUBLICATION HOUSE

Publisher and Distributor

57- A, First Floor, Sriram Nagar-C

Jhotwara, Jaipur, Rajasthan – 302012 (India)

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CHAPTER - 30

CLIMATE RESILIENT CROPS AND STRESS MANAGEMENT

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Introduction

The modern era of agriculture is faced with a myriad of unprecedented and intertwined challenges that are threatening the security of food globally and the sustainability of agricultural systems. The high rate of population growth has greatly led to high food, feed and fiber demand, yet the supply of natural resources like arable land, fresh water and fertile soils is decreasing. Climate change is one of the most important and widespread factors affecting agricultural productivity amongst these challenges. The global increase in temperatures, inconsistent and unforeseeable rainfall patterns, higher frequency of extreme weather events like droughts, floods and heat waves, and the slow degradation of ecosystems have all led to a very uncertain climate in crop production. Such climatic variations have not only impacted the amount of agricultural production but also its stability and quality thus presenting significant threats to food systems across the globe.

Among the most notable effects of climate change on agriculture, there is the increase of abiotic and biotic stress. Abiotic stresses such as drought, heat, cold, salinity and flooding have a direct impact on plant physiological and biochemical processes resulting in decreased plant growth, impaired photosynthesis and low yields. Examples include long periods of drought that reduce water supply, nutrient uptake, and oxidative stress in plants, and high temperatures that may destroy cell structures, decrease pollen quality, and speed up crop development, frequently leading to losses. Likewise, salinity of soil, which is compounded by ineffective irrigation methods and increasing sea levels, disrupts water uptake and ionic regulation in plants. Conversely, biotic stresses like pathogens, insect pests and weeds are also becoming increasingly severe and unpredictable with changing climatic conditions. Higher temperatures and change in humidity conditions provide good conditions in which pests and diseases multiply and spread, making crops more vulnerable and making it harder to manage pests.

To address these increased problems, the idea of climate-resilient crops has become an important aspect of agricultural research and development. Climate-resilient crops refer to crops that have the capacity to survive, adapt or recover to unfavorable environmental conditions without experiencing significant changes on their productivity. The traits that define these crops include drought tolerance, heat resistance, salinity tolerance, submergence tolerance and pest and disease resistance. Such crops should be developed to achieve food security amidst climate variability and resource shortages. In contrast to the old breeding methods, which mainly aimed at yield enhancement in optimal environments, the new crop improvement programs have resilience and adaptability as the main goals, since future agricultural systems should be able to work under stressful environments.

The production of crops that are resistant to climate is a blend of traditional breeding methods, molecular breeding, and the use of sophisticated biotechnological methods. Traditional breeding approaches, such as selection and hybridization, have been effectively employed to breed stress tolerant varieties by taking advantage of natural genetic variation. Nonetheless, these approaches tend to be time-consuming and restricted by the convolution of stress tolerance characteristics, which are usually governed by several genes. The recent developments in molecular biology and genomics have transformed the field of crop improvement by making it possible to identify and manipulate individual genes linked to stress tolerance. The use of marker-assisted selection, genomic selection, and gene pyramiding have also made the breeding process faster and more precise in incorporating the traits. In more recent times, genome editing technologies, such as CRISPR-based systems, have offered potent means of introducing targeted changes in the genomes of plants, enabling the creation of crops that are more resilient to environmental stresses.

Besides genetic enhancement, the idea of climate-resilient agriculture focuses on the combination of enhanced crop varieties with sustainable management and technological innovations. Stress management in agriculture entails optimization of agronomic activities like irrigation timing and management, nutrient management, crop diversification and soil conservation to improve the adaptive capacity of farming systems. Organic matter addition, conservation tillage, and balanced fertilization can help maintain soil health and enhance water retention, nutrient availability, and microbial activity, contributing to crop resilience. Equally, climate-smart technologies, such as precision agriculture, remote sensing, and decision-support systems, allow farmers to observe the environmental conditions and make reasonable decisions in management. These combined strategies not only reduce the negative impact of climate change but also help to use the resources sustainably and protect the environment.

Moreover, there are major socio-economic consequences associated with the development and uptake of climate-resilient crops; especially among small and marginal farmers who are the most susceptible to climate variability. These farmers are usually vulnerable to crop failures and unstable incomes due to lack of access to resources, technology and infrastructure. Proper management practices coupled with climate-resistant crop varieties can reduce the risks associated with production, stabilize production, and enhance livelihood security. Moreover, the crops are also important in ensuring food security and affordability particularly in areas where climate-sensitive farming is highly relied upon.

Although there has been an improvement in coming up with climate resistant crops, there are still a number of challenges. The multifaceted genetic nature of stress resistance, the unpredictability of the environmental situation, and the necessity to develop solutions that are specific to the location demand ongoing research and innovation. In addition, effective extension services, policy support and awareness of farmers are the key to successful adoption of resilient crop varieties. To tackle these issues, a multidisciplinary strategy that combines plant science, agronomy, ecology, and socio-economic factors is necessary.

Climate-Resilient Crops

Climate-resilient crops are plant varieties that are either genetically engineered to resist adverse environmental factors or naturally adapted to these factors that have been shown to retain their yields and quality under adverse environmental conditions. These are crops that are able to withstand the growing climatic variability, such as irregular rainfalls, rising temperatures, salinity of the soil, and extreme weather conditions such as floods and droughts. The most important characteristics of climate-resilient crops are drought tolerance, heat and cold resistance, salinity tolerance, submergence tolerance and pest and disease resistance. These traits allow plants to live and work in stressful environments that would decrease productivity in traditional crop species. Development of climate-resilient crops is done by use of traditional breeding, molecular breeding, and biotechnological methods such as genetic engineering. They are important in maintaining food security especially in areas where there is a tendency to climate stress and scarcity of resources. These crops help in stabilizing yields and minimizing the risk of crop failure, which makes them beneficial to sustainable agricultural systems and help farmers who are subjected to uncertainties caused by climate.

Crop Stresses

Abiotic Stress

Abiotic stress is the undesirable effect of the non-living environmental factors on the growth, development, and productivity of plants. One of the most important of these is drought stress, which is caused by the lack of water, impacting cellular functions, decreasing photosynthesis, and limiting nutrient uptake. The heat stress happens when the temperatures are higher than the optimal levels and enzymatic activities are disrupted and the plant tissues are damaged. Cold stresses such as chilling and freezing conditions influence the stability of membranes and metabolic processes resulting in either stunted growth or death of plants. Salinity stress is due to the presence of high levels of soluble salts in the soil which disrupts the uptake of water by the soil and leads to ionic imbalance and toxicity in the plant cells. Flooding stress, on the other hand, leads to oxygen deficiency in the root zone, impairing respiration and nutrient absorption. These abiotic stresses tend to coexist, which enhances their impacts and leads to high yield losses. The strategies to reduce abiotic stress should be developed to enhance crop resilience and agricultural sustainability.

Biotic Stress

Living organisms cause biotic stress, which has a negative impact on the health and productivity of plants. These contain a large variety of pests and pathogens which include insects, fungi, bacteria, viruses and nematodes. Insect pests inflict damage on crops by feeding on plant tissues, spreading diseases, and impairing photosynthetic ability. Fungal pathogens include rusts, blights and wilts among others which result in heavy losses of yield. Bacterial and viral infections interfere with the physiological processes of plants and can be spread quickly in favorable conditions. Nematodes, which are microscopic soil organisms, attack plant roots, impairing water and nutrient uptake. Plants have developed a number of defense strategies against biotic stress, such as protection by physical structures, defensive chemical synthesis, and immune responses. But extreme cases may bypass these mechanisms, which require the adoption of resistant crop strains and integrated pest management approaches. Biotic stress is crucial to comprehending the effective control measures and to achieve sustainable crop production.

Significance of Climate-resilient Crops

Climate resistant crops play a crucial role in curbing the climate change problem and promoting the sustainability of agricultural systems in the long run. Among their major advantages is the fact that they can sustain stable yields in unstable environmental conditions hence guaranteeing food security to the ever-increasing world population. The crops are especially valuable in marginal and resource-poor areas, where the traditional types of crops fail in most cases because of the stress conditions. Climate-resilient crops help reduce poverty and increase livelihoods of farmers by increasing productivity in these regions. They also lessen reliance on chemical inputs like fertilizers and pesticides by integrating natural resistance characteristics resulting in low production expenses and less environmental impact. Moreover, these crops contribute to sustainable agricultural production through enhanced resource-use efficiency and climate-resilience. With the ongoing climate change impacting the agricultural systems of many countries across the world, the design and implementation of climate resistant crops will be of paramount importance in maintaining food security and environmental sustainability.

Morphological Adaptations

Morphological adaptations are changes in the structure of plants that enables them to survive and function in the stressful environmental conditions. Among the adaptations that have been very crucial is the formation of deep and extensive root systems that help plants to tap water in the deeper layers of the soil in times of drought. Another adaptation is the reduced leaf area that reduces the loss of water to the environment by transpiration, which helps plants to save water. Other plants grow thicker cuticles or waxy layers on leaves, which serve as protective measures against water loss and environmental stress. Other typical responses are leaf rolling and adjustment of leaf orientation to minimize exposure to sunlight and minimize water loss. In some crops, the alterations like the high proportion of roots to shoot make the plant more resilient to stress. As an example, *Triticum aestivum* (wheat) varieties that have deeper root systems are more suited to drought conditions. These morphological characteristics are very important in enhancing plant survival and productivity in unfavourable environmental conditions.

Physiological Mechanisms

Physiological mechanisms are the inner processes through which plants are able to continue functioning normally in stressful situations. Stomatal regulation is one of the most important responses in which plants regulate the amount of water that is lost to the environment through opening and closing of stomata to preserve carbon dioxide uptake to sustain photosynthesis during drought. Another significant process is osmotic adjustment, in which plants store solutes like sugars and amino acids to ensure cell turgor and water balance. Plants can survive on limited water supply through efficient water-use strategies, such as enhanced transpiration efficiency. Plants also adapt, under stress conditions, to conserve energy and preserve vital functions, by changing their metabolic processes. As an example, *Oryza sativa* (rice) controls stomatal functions and decreases transpiration in response to drought stress to conserve water. These physiological changes can help plants to survive in the stressful environment and remain growing and productive even in adverse conditions.

Biochemical Responses

Biochemical responses are critical for protecting plant cells from damage caused by environmental stress. Under stress conditions, plants produce osmoprotectants such as proline and glycine betaine, which help stabilize proteins and membranes and maintain cellular osmotic balance. Antioxidant enzymes, including superoxide dismutase, catalase, and peroxidases, play a vital role in scavenging reactive oxygen species (ROS) generated during stress. These ROS can cause oxidative damage to cellular components if not properly controlled. Plants also synthesize stress-related metabolites such as phenolics and flavonoids, which contribute to stress tolerance and defense mechanisms. Additionally, changes in enzyme activity and metabolic pathways help plants adapt to stress conditions. These biochemical adjustments enhance the plant’s ability to survive and recover from stress, ensuring continued growth and productivity. By understanding these responses, researchers can develop strategies to improve stress tolerance in crops.

Molecular Mechanisms

Molecular mechanisms of stress tolerance involve the regulation of gene expression and signaling pathways that enable plants to respond to environmental stress at the cellular level. Stress conditions trigger the activation of specific genes that encode proteins involved in protective and adaptive responses. For example, heat shock proteins help maintain protein stability under high temperatures, while other stress-responsive proteins protect cellular structures. Hormonal regulation plays a key role in stress responses, with hormones such as abscisic acid (ABA), ethylene, and cytokinins coordinating physiological and biochemical processes. Signal transduction pathways enable plants to perceive stress signals and initiate appropriate responses. Advances in genomics, transcriptomics, and molecular biology have facilitated the identification of genes associated with stress tolerance, enabling the development of improved crop varieties through genetic engineering and molecular breeding. These molecular insights are essential for enhancing the resilience of crops to climate change and ensuring sustainable agricultural production.

Table 1: Types of Stress and Plant Responses

Stress Type	Cause	Plant Response	Example Crop
Drought	Water deficiency	Deep roots, stomatal closure	*Zea mays*
Heat	High temperature	Heat shock proteins	*Triticum aestivum*
Salinity	High salt levels	Ion regulation, osmolytes	*Oryza sativa*
Flooding	Waterlogging	Aerenchyma formation	*Oryza sativa*
Biotic	Pathogens, pests	Defense proteins	*Solanum lycopersicum*

Conventional Breeding

Conventional breeding remains one of the most widely used and effective strategies for developing climate-resilient crops. This approach involves the selection of naturally occurring stress-tolerant genotypes from diverse germplasm pools and their use in breeding programs to develop improved varieties. Plant breeders identify desirable traits such as drought tolerance, heat resistance, and pest resistance through field evaluation and phenotypic screening under stress conditions. Hybridization is then carried out between selected parent lines to combine beneficial traits, followed by successive generations of selection to stabilize these characteristics. Mutation breeding is another important technique, where genetic variations are induced using physical or chemical mutagens to create new traits that may enhance stress tolerance. Although conventional breeding is time-consuming, it is highly reliable and widely accepted. For example, improved varieties of *Sorghum bicolor* have been developed with enhanced drought tolerance, making them suitable for arid and semi-arid regions. This approach continues to play a crucial role in developing resilient crop varieties.

Marker-Assisted Selection (MAS)

Marker-assisted selection (MAS) is an advanced breeding technique that integrates molecular biology with traditional breeding methods to accelerate the development of climate-resilient crops. In this approach, molecular markers linked to specific stress-tolerant traits are used to identify and select desirable genotypes at an early stage of plant development. This reduces the need for extensive field trials and speeds up the breeding process. MAS enables the precise transfer of genes associated with traits such as drought tolerance, salinity resistance, and disease resistance into elite crop varieties. By using DNA markers, breeders can track the inheritance of these traits across generations, ensuring accuracy and efficiency in selection. This method is particularly useful for complex traits controlled by multiple genes. Compared to conventional breeding, MAS significantly reduces time, cost, and uncertainty, making it a powerful tool in modern crop improvement programs. It has been widely applied in crops such as rice, wheat, and maize to enhance stress tolerance and productivity.

Genetic Engineering

Genetic engineering involves the direct manipulation of an organism's genetic material to introduce specific traits that enhance stress tolerance and productivity. This approach allows scientists to transfer genes from unrelated species into crop plants, overcoming the limitations of traditional breeding. For instance, genes responsible for insect resistance, drought tolerance, or salinity tolerance can be inserted into crops to improve their resilience under adverse conditions. One well-known example is the development of Bt crops using genes from *Bacillus thuringiensis*, which provide resistance against insect pests and reduce the need for chemical pesticides. Genetic engineering also enables the modification of metabolic pathways to enhance stress tolerance and nutrient use efficiency. Although this technology offers significant advantages in terms of precision and speed, it is subject to regulatory frameworks and public acceptance issues. Nevertheless, genetic engineering remains a powerful tool for developing climate-resilient crops capable of meeting future agricultural challenges.

Genome Editing (CRISPR/Cas Technology)

Genome editing technologies, particularly CRISPR/Cas systems, have revolutionized crop improvement by enabling precise and targeted modification of plant genomes. Unlike traditional genetic engineering, which introduces foreign genes, CRISPR allows for the editing of existing genes within the plant, making it more acceptable and efficient. This technology works by using a guide RNA to direct the Cas enzyme to a specific DNA sequence, where it introduces changes such as gene insertion, deletion, or modification. CRISPR has been widely used to develop crops with improved tolerance to drought, heat, salinity, and diseases. For example, genes controlling stress responses can be edited to enhance water-use efficiency or improve heat tolerance in crops. The precision, speed, and cost-effectiveness of CRISPR make it a promising tool for developing next-generation climate-resilient crops. As research advances, genome editing is expected to play a central role in sustainable agriculture and food security.

Omics Approaches

Omics approaches provide comprehensive insights into the biological processes underlying stress tolerance in plants by analyzing different levels of biological organization. Genomics focuses on the structure and function of the entire genome, helping identify genes associated with stress tolerance. Proteomics studies the proteins expressed under stress conditions, revealing how plants respond at the functional level. Metabolomics analyzes the chemical compounds produced in plants, providing insights into metabolic changes during stress. Phenomics involves large-scale measurement of plant traits to understand their response to environmental conditions. By integrating data from these approaches, researchers can gain a holistic understanding of plant stress responses and identify key targets for crop improvement. These advanced technologies enable the development of more resilient crop varieties through informed breeding and genetic engineering strategies. Omics approaches are essential for accelerating innovation in climate-resilient agriculture.

Agronomic Practices

Agronomic practices play a crucial role in managing stress and enhancing crop resilience in agricultural systems. Techniques such as crop rotation help break pest and disease cycles while improving soil fertility and structure. Intercropping involves growing multiple crops together, which can enhance resource use efficiency and reduce the impact of environmental stress. Conservation tillage practices minimize soil disturbance, preserving soil moisture and organic matter, which are essential for plant growth under stress conditions. These practices not only improve crop productivity but also contribute to long-term sustainability by maintaining soil health and reducing environmental degradation. By adopting appropriate agronomic strategies, farmers can mitigate the effects of climate variability and enhance the resilience of their cropping systems.

Water Management

Effective water management is critical for reducing the impact of drought and ensuring optimal crop growth. Techniques such as drip irrigation deliver water directly to the root zone, minimizing losses due to evaporation and improving water-use efficiency. Rainwater harvesting systems capture and store rainfall for use during dry periods, providing a reliable water source. Efficient irrigation scheduling based on crop requirements and soil moisture levels ensures that water is used judiciously, preventing both water stress and wastage. These practices are particularly important in regions facing water scarcity and irregular rainfall patterns. By optimizing water use, farmers can improve crop productivity and resilience while conserving valuable water resources.

Soil Health Management

Soil health management is a fundamental aspect of building climate-resilient agricultural systems. Healthy soils provide essential nutrients, support root growth, and improve water retention, all of which contribute to plant resilience under stress conditions. The addition of organic matter, such as compost and farmyard manure, enhances soil structure and fertility. Biofertilizers introduce beneficial microorganisms that improve nutrient availability and promote plant growth. Cover cropping protects the soil from erosion, improves organic matter content, and enhances soil biodiversity. These practices collectively improve soil quality and create a favorable environment for plant growth. By maintaining healthy soils, farmers can enhance the resilience of crops to environmental stress and ensure sustainable agricultural production.

Use of Biostimulants and Plant Growth Regulators

Biostimulants and plant growth regulators play an important role in enhancing plant tolerance to environmental stress. Biostimulants, such as seaweed extracts, humic substances, and microbial formulations, improve nutrient uptake, root development, and stress resistance. Plant growth regulators, including hormones like auxins, gibberellins, and cytokinins, influence plant growth and development processes. These substances help plants adapt to stress by regulating physiological and biochemical processes, such as water balance, photosynthesis, and nutrient metabolism. The use of biostimulants and growth regulators can significantly improve crop performance under adverse conditions, making them valuable tools in climate-resilient agriculture.

Integrated Pest Management (IPM)

Integrated Pest Management (IPM) is a sustainable approach to managing pests and diseases while minimizing environmental impact. IPM combines multiple strategies, including biological control, the use of resistant crop varieties, cultural practices, and limited use of chemical pesticides. Biological control involves the use of natural predators and beneficial organisms to control pest populations. Resistant varieties are developed to withstand pest attacks, reducing the need for chemical interventions. Cultural practices, such as crop rotation and sanitation, help prevent pest outbreaks. By integrating these methods, IPM reduces reliance on chemical pesticides, lowers production costs, and promotes environmental sustainability. This approach is essential for managing biotic stress and ensuring the long-term resilience of agricultural systems.

Drought-Resistant Crops

Drought-resistant crops play a vital role in sustaining agricultural productivity in water-scarce regions, where rainfall is erratic and irrigation resources are limited. Crops such as *Sorghum bicolor*, *Pennisetum glaucum* (pearl millet), and *Cicer arietinum* (chickpea) are well-adapted to dry environments due to their efficient water-use mechanisms and deep root systems.

These crops possess physiological traits such as reduced transpiration rates, osmotic adjustment, and the ability to maintain cellular functions under low moisture conditions. Morphologically, their roots can penetrate deeper soil layers to access residual moisture, ensuring survival during prolonged drought periods. Additionally, these crops have shorter life cycles, enabling them to complete their growth before severe water stress occurs. Their resilience makes them suitable for cultivation in arid and semi-arid regions, contributing to food security and farmer livelihoods. Moreover, these crops often require fewer inputs and are more sustainable under low-resource conditions, making them essential components of climate-resilient agricultural systems.

Heat-Tolerant Crops

Heat-tolerant crops are essential for maintaining productivity in regions experiencing rising temperatures and frequent heatwaves. Crops such as *Triticum aestivum* (heat-tolerant wheat varieties) and *Zea mays* (heat-resilient maize hybrids) have been developed to withstand high-temperature stress during critical growth stages such as flowering and grain filling. These crops possess physiological adaptations such as heat-stable enzymes, efficient photosynthetic mechanisms, and improved membrane stability, which allow them to function effectively under elevated temperatures. Heat-tolerant varieties also exhibit traits like early maturity, enabling them to escape extreme heat conditions. Breeding programs have focused on selecting genotypes with improved thermal tolerance and yield stability. The adoption of such crops is particularly important in tropical and subtropical regions, where temperature extremes can significantly reduce crop yields. By maintaining productivity under heat stress, these crops contribute to food security and agricultural sustainability in a warming climate.

Salinity-Tolerant Crops

Salty-tolerant crops play a very important role in agriculture in areas where soil salinity restricts crop production. The crops like *Oryza sativa* (salt-tolerant rice varieties) and Hordeum vulgare (barley) have developed systems to survive high salinity levels in the soil. These processes involve selective absorption of ions, the rejection of harmful ions like sodium and the compartmentalization of salts in plant tissues to avoid harm to the vital cellular functions. Salinity-tolerant crops are also able to maintain osmotic balance by accumulating compatible solutes to absorb water even in salty conditions. These adaptations enable plants to live and yield in soils which would otherwise be unproductive. It is especially significant to develop and cultivate salinity-tolerant crops in coastal locations and areas with salinization caused by irrigation. With the use of such crops, farmers are able to rehabilitate the degraded lands and increase agricultural productivity and this leads to sustainable land management and food security.

Flood-Tolerant Crops

Flood-tolerant crops are meant to withstand and grow in waterlogged or submerged conditions, which are becoming more frequent owing to high rainfall events and inadequate drainage systems. There has been an impressive capability of submergence-tolerant rice varieties including Sub1 gene to survive during extended flooding. These varieties are able to endure total submergence over a few days by reducing their metabolic rates and retaining energy until the floods have subsided. When they are brought back to normal conditions, they grow and develop with minimal loss of yield. Physiological adaptations to flood tolerance include effective oxygen use and cellular integrity in low oxygen environments. Flood-tolerant crops are also adopted which is also advantageous in flood-prone areas where traditional varieties fail. These crops make the crops more resilient to climatic variations and secure constant food production in susceptible regions.

Marginal Land Climate-Resilient Crops

The use of climate-resilient crops that can be grown in marginal lands is crucial in enhancing productivity in regions that have low fertility of soils, water scarcity, and adverse environmental factors. Crops such as quinoa, pulses, and millets (also known as nutri-cereals) are very versatile and do not need a lot of inputs to grow. These crops are characterized by their drought, heat and poor soil resistance, and are therefore suitable to grow in degraded and resource-limited areas. These crops are also nutrient-rich in addition to their adaptability, which helps in enhancing food and nutritional security. Their high potential in growing in harsh environments gives farmers sure yields and returns even in unfavourable situations. Such crops are increasingly being promoted as a part of sustainable agricultural practices and climate adaptation measures. These crops help to make agricultural production and resilience more productive and effective by using marginal lands.

Conclusion

Climate change poses a major threat to world agriculture including the productivity of crops, availability of resources as well as livelihoods of farmers. These challenges can be overcome by the development and the adoption of climate resistant crops, and the application of effective stress management strategies. Plant breeding, biotechnology and agronomic developments have made it possible to develop varieties of crops that can withstand environmental pressures like drought, heat, salinity and flooding. The combination of modern technologies, such as genome editing, omics methods, and precision agriculture, and the traditional farming knowledge is a holistic way of creating resilient agricultural systems. These inventions do not only increase crop productivity, but also ensure sustainability by minimizing the use of external inputs and natural resource preservation. The future studies ought to concentrate on creating crops that are resistant to various stresses, and incorporating digital technology like artificial intelligence and data analytics to make better decisions. Capacity building and access to technology will be important in Farmer-centric approaches to widespread adoption. To guarantee food security, sustain rural livelihoods, and sustainable development, climate-resilient agriculture is needed in the face of the prevailing environmental challenges.

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