

## THE ROLE OF CLIMATE CHANGE ON GLOBAL FOOD SECURITY

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**ABSTRACT:** Climate change poses a significant threat to global food security, impacting crop yields, food availability, health and access to nutrition. Rising temperatures, altered precipitation patterns, and increased frequency of extreme weather events are altering the conditions under which crops are grown, livestock are raised, and food systems operate. This review examines the current state of knowledge on the impacts of climate change on global food security, highlighting the effects on crop yields, food prices, and human nutrition. We discuss the potential adaptation and mitigation strategies that can help reduce the vulnerability of food systems to climate change, including climate smart agriculture, improved irrigation management, crop insurance, geoinformatics and enhanced food storage and distribution systems. Our analysis reveals that climate change affects not only crop productivity but also food access, utilization, and stability, with far reaching implications for human well being, particularly in vulnerable populations. We emphasize the need for a comprehensive approach to addressing the impacts of climate change on food security, including policy, technological, and institutional innovations that support climate resilient food systems. This review aims to inform policymakers, researchers, and practitioners about the complex relationships between climate change and food security, and to identify opportunities for building more resilient food systems in the face of a changing climate.

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**Keyword:** Public Health; Climate Change; Food Security; Crop Yields Adaptation Strategies; Vulnerable Populations

### INTRODUCTION

The Food and Agriculture Organization of the United Nations (FAO) defines food security as a situation in which “all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active and healthy life.” This concept is built on four key dimensions: availability, accessibility, utilization, and stability. Despite progress in agricultural productivity over the past decades, food security remains a pressing global challenge (Seppelt *et al.*, 2022). According to the (FAO, 2023) State of Food Security and Nutrition in the World (SOFI) report, between 691 and 783 million people faced hunger in 2022, representing nearly 9% of the world’s population. Moreover, about 2.4 billion

people experienced moderate to severe food insecurity, driven by persistent poverty, conflict, economic downturns, and growing environmental stressors (Fotakis *et al.*, 2024). While regions such as Europe and North America maintain relatively stable food supplies, Sub-Saharan Africa, South Asia, and parts of Latin America continue to experience high vulnerability due to dependence on rain fed agriculture, fragile economies, and limited adaptive capacity. The challenge is further compounded by demographic growth, with the global population projected to reach 9.7 billion by 2050, intensifying pressure on natural resources and food systems (Ikuemonisan, 2024). Climate change is widely recognized as a critical threat multiplier that exacerbates existing challenges to global food security (Dheeraj and Shikha, 2024).

Unlike isolated drivers such as poverty, market instability, or conflict, climate change interacts with these stressors simultaneously, intensifying their impacts and creating cascading risks across food systems. Rising global temperatures, erratic rainfall patterns, prolonged droughts, floods, and the increasing frequency of extreme weather events directly disrupt agricultural production, reduce yields, and compromise the nutritional quality of food (Omokaro, 2025).

Climate change aggravates structural vulnerabilities in already fragile regions. For example, in low income countries that rely heavily on subsistence farming and rain fed agriculture, even slight changes in rainfall or temperature can lead to severe harvest losses, heightening the risk of hunger and malnutrition. Climate-related shocks also undermine livelihoods by increasing food prices, reducing household incomes, and deepening inequality, thereby threatening both physical and economic access to food (Tchonkouang *et al.*, 2024). The indirect impacts are equally significant. Climate variability contributes to water scarcity, soil degradation, pest and disease outbreaks, and loss of biodiversity all of which diminish the resilience of agricultural systems. Additionally, climate-driven displacement and conflict over scarce resources further destabilize communities, amplifying food insecurity. By acting as a force that magnifies existing risks while introducing new ones, climate change threatens to derail progress toward global food security and the achievement of the Sustainable Development Goals (SDGs), particularly SDG 2: Zero Hunger. The relationship between climate change and food security has therefore emerged as one of the most urgent global concerns of the 21st century. Although efforts to improve agricultural productivity, reduce poverty, and strengthen food distribution systems have yielded progress, these gains are increasingly undermined by climate induced disruption (Zenda,

2025). The climate food nexus highlights how rising temperatures, erratic precipitation, extreme weather events, and shifting ecological conditions directly and indirectly compromise food systems at local, regional, and global scales. Understanding this nexus is particularly urgent. Agriculture is highly climate-sensitive, and even small variations in temperature or rainfall can reduce staple crop yields, threaten livestock health, and disrupt fisheries, thereby jeopardizing food availability in regions that depend heavily on subsistence farming (Said *et al.*, 2025). The effects are unevenly distributed, with developing nations especially in Sub-Saharan Africa, South Asia, and Latin America facing disproportionate risks due to limited adaptive capacity, which further widens global disparities in food access and nutrition.

The policy and sustainability implications are equally profound. Without a coherent understanding of the climate food nexus, policymaking risks being fragmented and short sighted, jeopardizing both immediate responses and long-term strategies. A comprehensive synthesis of evidence is therefore necessary to inform adaptation and mitigation pathways that align with the Paris Agreement on Climate Change and the Sustainable Development Goals, particularly SDG 2. Moreover, the accelerating pace of climate change highlights the urgency of innovation, from climate-smart agriculture and biotechnology to digital technologies and ecosystem based approaches. The objective of this review is to critically examine how climate change affects global food security across its four dimensions availability, accessibility, utilization, and stability and further seeks to highlight regional vulnerabilities, explore adaptation and mitigation strategies, and identify gaps, by providing a foundation for guiding future research and policy actions toward resilient and sustainable food systems.

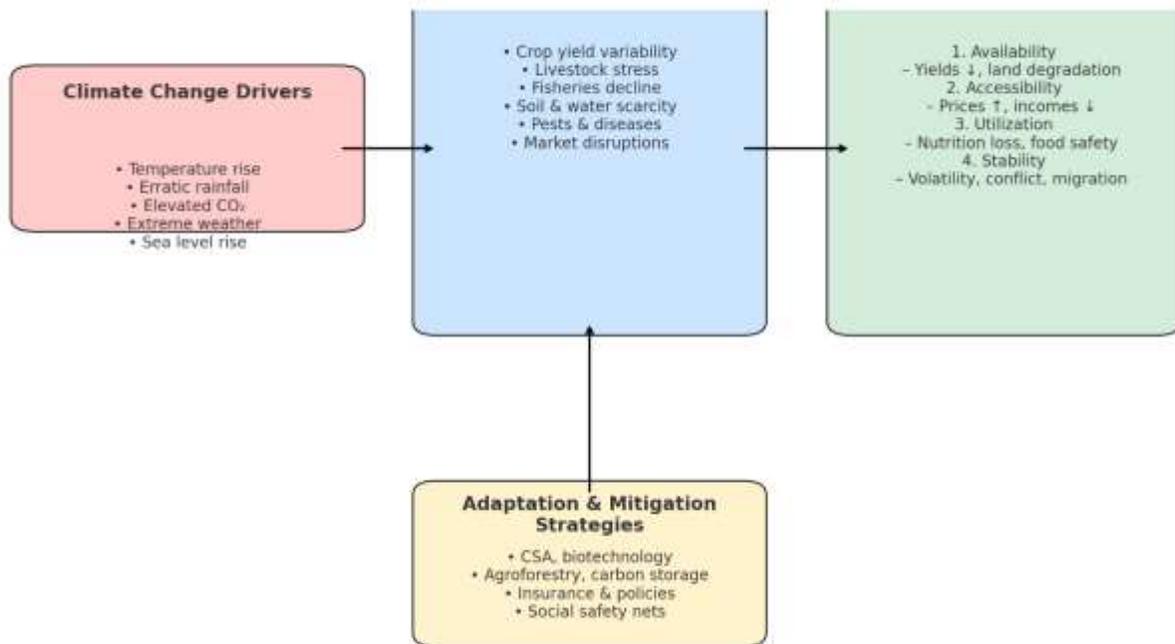


Figure 1: Conceptual Framework of Climate Change on Food Security

## 2. CLIMATE CHANGE AND GLOBAL FOOD SYSTEMS

Climate change is primarily driven by rising concentrations of greenhouse gases, particularly carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O), resulting in global warming and shifts in weather patterns (Cassia *et al.*, 2018; Hassan, 2024). Key manifestations include temperature rise, which alters crop growth cycles and livestock health; erratic rainfall patterns, leading to droughts or floods; elevated CO<sub>2</sub> levels, which can stimulate plant growth but often reduce nutritional quality; and an increase in the frequency and intensity of extreme weather events such as heatwaves, storms, and wildfires (Furtak, and Wolińska, 2023). Together, these drivers disrupt agricultural systems, ecosystems, and water resources, and threatening global food security.

Table 1: Climate Change Impact on Major Staple Crops

Crop	Stressors	Observed impacts	Regional examples
Wheat	Heat Stress, Drought erratic Rainfall	Reduced yields, lower protein and micro nutrient content	Yield decline in South Asia, Europe and Africa
Rice	Heat Stress, Flooding,	Yield Loss, Reduced grain	South and South East Asia
Maize	Drought, Heat Stress, Pest expansion	Yield declines of 10-30%	Sub-Saharan Africa
Sorghum	Extreme heat	Yield Fluctuation despite drought tolerance	Semi- arid Africa, India

### *Agricultural Vulnerability Sensitivity, and Adaptive Capacity Exposure,*

Agricultural vulnerability to climate change can be understood through three interrelated components: exposure, sensitivity, and adaptive capacity (Hossain *et al.*, 2023; Ojo *et al.*, 2024). Exposure reflects the degree to which agricultural systems are subjected to climate related hazards such as rising temperatures, droughts, floods, and extreme weather events. This is particularly critical in regions heavily dependent on rain fed agriculture, including Sub-Saharan Africa and South Asia, where climatic variability directly threatens production systems. Sensitivity refers to the extent to which agricultural production responds to these changes; crops with narrow temperature or water thresholds, such

as maize and wheat, and livestock systems prone to heat stress, exhibit high sensitivity, often resulting in substantial yield fluctuations under relatively small climatic shifts (Hassnain *et al.*, 2021). Adaptive capacity represents the ability of farmers, communities, and nations to adjust to or recover from climate-related shocks. Developed countries generally exhibit higher adaptive capacity due to access to advanced technologies, irrigation systems, crop insurance, and strong institutional support, while many developing nations remain constrained by limited resources, weak infrastructure, and inadequate policy frameworks (Jamshidi *et al.*, 2020; Gören, 2025). Collectively, these three components define the overall vulnerability of agricultural systems, with the highest risks concentrated in regions that are both highly exposed and sensitive yet possess low adaptive capacity.

#### *Regional Differences in Climate Change Impacts*

The effects of climate change on food security vary significantly across regions. Developed nations, often located in temperate zones, may initially experience mixed outcomes such as extended growing seasons and higher yields for some crops, supported by advanced technology, irrigation, and insurance systems. Developing nations, particularly in tropical and subtropical regions, face severe challenges due to heavy dependence on rain fed agriculture, limited adaptive capacity, and fragile economies.

In the tropics, higher temperatures and erratic rainfall already exceed critical thresholds for staple crops like maize, rice, and sorghum, increasing vulnerability to droughts, floods, and pest outbreaks. Meanwhile, temperate regions may be less immediately affected but remain exposed to shifting pest dynamics, heat waves, and extreme weather events that can destabilize global food markets. These disparities underscore the uneven burden of climate change, with the poorest and most food-insecure regions bearing the greatest risks.

### **3. IMPACT PATHWAYS OF CLIMATE CHANGE ON FOOD SECURITY**

Climate change impacts global food security through multiple interlinked pathways. Its effects can be categorized using the FAO's four dimensions: availability, accessibility, utilization, and stability.

#### *3.1 Food Availability*

Climate change significantly influences the quantity and quality of food produced worldwide, primarily through its effects on crop yields, livestock systems, fisheries, and the natural resource base (Cheng *et al.*, 2022). Rising temperatures and associated heat stress reduce photosynthetic efficiency and shorten grain filling periods in major cereals such as wheat, maize, and rice, leading to lower yields (Lalit *et al.*, 2022; Abu *et al.*, 2025). Prolonged droughts and episodes of excessive rainfall further exacerbate yield losses, undermining the stability of staple food supplies. Shifts in temperature and rainfall patterns are also altering agroecological zones, forcing adjustments in cropping calendars, reducing arable land suitability, and in some cases eliminating traditional production areas altogether (Olugbenga *et al.*, 2025).

Livestock production is equally vulnerable, as heat stress, declining pasture quality, and increasing water scarcity negatively affect growth rates, reproductive efficiency, and yields of milk and meat (Godde *et al.*, 2021). Fisheries and aquaculture face mounting challenges from ocean warming, acidification, and altered current systems, which reduce fish stocks, disrupt breeding cycles, and heighten disease prevalence in aquaculture systems. Soil health further compounds these challenges: climate-induced processes such as erosion, nutrient depletion, salinization caused by sea-level rise, and advancing desertification diminish the productive capacity of agricultural land. In addition, post-harvest losses are likely to increase, as extreme events including floods and storms damage stored produce, shorten storage lifespan, and accelerate spoilage. Collectively, these impacts underscore how climate change threatens food availability by reducing both the volume of production and the quality of resources upon which agricultural systems depend.

#### *3.2 Food Accessibility*

Even when food is physically available, climate change can severely constrain access through interconnected economic and social pathways. Reduced agricultural supply often results in food price spikes, which disproportionately affect low-income households that already spend a large share of their income on food (Gustafson, 2013). Extreme weather events further disrupt markets by damaging transportation infrastructure, blocking supply chains, and restricting access to local and regional markets (Touloumidis *et al.*, 2025). At the household level, the loss of crops or livestock directly reduces income, thereby weakening purchasing power and limiting the ability of vulnerable families to secure sufficient food. Regional disparities compound the problem, as areas heavily dependent on rain-fed agriculture, such as Sub-Saharan Africa and South Asia, face more frequent disruptions in access compared to industrialized nations with stronger infrastructures and diversified economies (Omokpariola *et al.*, 2025). Climate induced scarcity of key resources like water and arable land can intensify social unrest, drive forced migration, and fuel conflict, all of which contribute to restricted food accessibility and heightened vulnerability among marginalized populations.

### 3.3 Food Utilization

Climate change not only influences the availability and accessibility of food but also affects how people can safely and nutritiously utilize it. Elevated atmospheric CO<sub>2</sub> concentrations have been shown to reduce the protein and micronutrient content of staple crops (Sadek and Youssef, 2014), particularly iron and zinc, thereby diminishing dietary quality and exacerbating hidden hunger (Kidane *et al.*, 2025). Crop failures, along with the decline of fisheries and livestock production, also reduce dietary diversity, limiting access to essential micronutrients and increasing the risk of nutritional deficiencies (Meenakshia and Quisumbing, 2025). Food safety is further compromised as higher temperatures and humidity promote the proliferation of mycotoxins, pathogens, and spoilage organisms across food chains. In parallel, climate-related water scarcity and flooding heighten the risk of waterborne diseases, undermining sanitation systems and reducing the body's capacity to effectively utilize food (Lake *et al.*, 2018). These dynamics contribute to deteriorating health outcomes, particularly among vulnerable groups such as children, pregnant women, and immunocompromised populations, where malnutrition and micronutrient deficiencies are likely to rise under worsening climate conditions.

### 3.4 Food Stability

Food security depends not only on the availability and accessibility of food at a given point in time but also on the consistency of supply and access over the long term. Climate change poses a major threat to this stability by amplifying risks across production systems, markets, and ecosystems. Extreme weather events such as droughts, floods, storms, and heat waves cause sudden production shocks that reduce yields and destabilize agricultural outputs (Du and Xiong, 2024). These disruptions often translate into heightened price volatility, undermining both affordability and market stability, particularly in low-income economies. The fragility of supply chains further compounds these risks, as damage to transport networks, storage facilities, and distribution systems interrupts the steady flow of food from producers to consumers. Beyond these immediate impacts, climate-induced migration and population displacement place additional strain on food systems in host regions, often exacerbating competition for already scarce resources. At the ecological level, the degradation of biodiversity, soil fertility, and pollination services diminishes the resilience of agricultural systems, making them less capable of recovering from repeated shocks (Arndt and Helming, 2025). In regions with low adaptive capacity, recurrent climatic disturbances reinforce chronic vulnerability, trapping populations in cycles of long-term food insecurity. Together, these dynamics highlight how climate change threatens the stability dimension of food security by eroding both the reliability of production and the resilience of food systems over time.

### 3.5 Cross-cutting considerations

The impacts of climate change on food security are rarely confined to a single dimension; rather, they are deeply interconnected, with disruptions in one area cascading into others. For example, reduced crop yields can drive food price increases, which in turn limit household access and ultimately exacerbate malnutrition and poor health outcomes which definitely will affect the health.

## 4. Evidence of Climate Change Effects on Major Food Crops

Climate change has already produced observable effects on both staple and cash crops worldwide, with regional variations driven by differences in climate exposure, agricultural practices, and adaptive capacity. The evidence spans yield reductions, altered growth cycles, changes in nutritional quality, and shifts in pest and disease dynamics.

### 4.1 Staples

Climate change exerts significant pressure on staple food crops, which form the foundation of global diets and livelihoods (Fanzo *et al.*, 2023). Wheat production is highly sensitive to rising temperatures, with heat stress during flowering and grain-filling stages leading to yield declines across South Asia, Europe, and North America (Farhad *et al.*, 2023). While elevated atmospheric CO<sub>2</sub> may stimulate biomass accumulation, this effect is often offset by reductions in protein and micronutrient concentrations, thereby lowering the nutritional quality of wheat. In regions such as Africa and Asia, drought and increasingly erratic rainfall have heightened yield variability, threatening both food availability and farmer incomes. Rice, the primary staple for much of Asia, is also profoundly affected by climatic stressors. Heat stress during flowering reduces grain set and yield, while flooding and salinity intrusion particularly in low-lying areas of South and Southeast Asia further compromise productivity. Although elevated CO<sub>2</sub> concentrations may enhance rice yields, this physiological benefit is accompanied by declines in grain protein, iron, and zinc levels, raising concerns about nutritional quality in populations already at risk of micronutrient deficiencies.

Maize, one of the most widely cultivated cereals, is especially vulnerable to climate extremes. Its sensitivity to both drought and heat is projected to result in yield declines of 10–30% in sub-Saharan Africa and Latin America by 2050 under high-emission scenarios (Du and Xiong, 2024). In addition to climatic stress, rising pest pressures such as the expansion of fall armyworm under warming conditions compound production losses, placing millions of smallholder

farmers at risk. Sorghum, often regarded as more drought-tolerant than wheat or maize, provides an important safety net in semi-arid regions of Africa and India (Singh *et al.*, 2022). However, even this resilient crop is not immune to climate variability, with extreme heat events and erratic rainfall driving yield fluctuations that directly threaten the food security of populations that depend on sorghum as a staple.

#### 4.2 Cash Crops

Climate change also poses significant risks to cash crops such as coffee, cocoa, and tea, which are critical for global trade, rural livelihoods, and export revenues in many developing countries. Coffee cultivation, particularly of Arabica varieties, is highly sensitive to temperature increases (Bilen *et al.*, 2022). Rising temperatures are progressively reducing suitable cultivation zones in Latin America and East Africa, forcing shifts to higher altitudes and cooler microclimates. In addition, climate change is exacerbating pest and disease pressures, most notably coffee leaf rust, which threatens both yields and bean quality. Cocoa production, concentrated in West Africa, is similarly vulnerable to shifts in temperature and rainfall. Projected warming and increased drought frequency are expected to reduce yields and compromise production sustainability (Ariza-Salamanca, *et al.*, 2023). Changes in pest dynamics, including the prevalence of mirids, are further undermining productivity, adding to the uncertainty faced by smallholder farmers who dominate the sector. Tea production is also being reshaped by climate variability, as optimal temperature ranges for growth shift across traditional cultivation zones. In regions such as India, Sri Lanka, and East Africa, irregular rainfall patterns have already caused substantial fluctuations in annual yields (Jayasinghe *et al.*, 2019; Sahu *et al.*, 2025). Beyond quantity, climate-induced stress can also influence the biochemical composition of tea leaves, altering flavor profiles and the rebuy affecting quality, marketability, and farmer incomes.

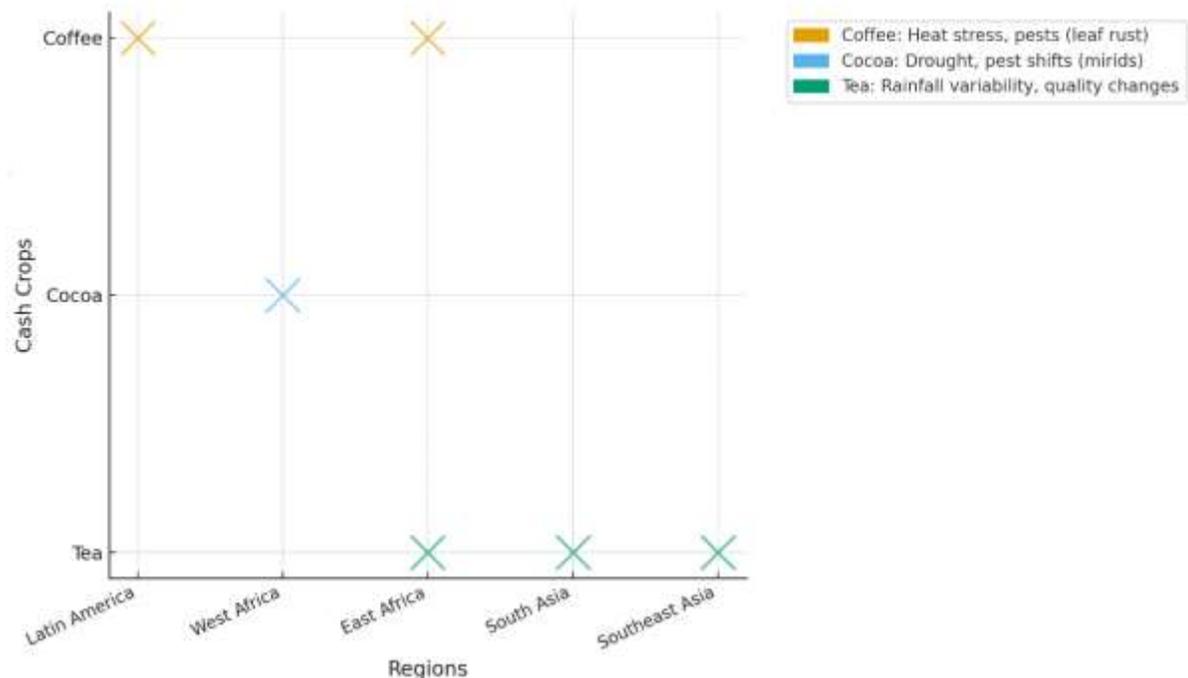


Figure 2: Climate Change effect on Cash Crop (Coffee, Cocoa, Tea)

#### 4.3 Regional Case Studies

In Africa, maize, sorghum, and millet in sub-Saharan regions are highly vulnerable to drought and heat stress, while coffee cultivation in Ethiopia is experiencing reductions in suitable growing areas. In Asia, rice-growing regions across South and Southeast Asia are increasingly affected by heat, flooding, and salinity intrusion, and wheat in South Asia is also showing heat-related yield declines. In Europe, wheat and barley yields display mixed trends, with northern regions benefiting from longer growing seasons, whereas southern regions are challenged by heat and drought stress. In the Americas, corn production in the U.S. Midwest is impacted by heatwaves and erratic rainfall, and coffee in Central and South America faces both temperature increases and heightened disease pressures.

## 5. SOCIO-ECONOMIC AND POLICY DIMENSIONS

Climate change not only affects crop yields but also has profound socio-economic implications that shape global food security. Understanding these dimensions is essential for designing effective adaptation and mitigation strategies.

### 5.1 *Smallholder Farmers and Rural Communities*

Smallholder farmers, who produce the majority of staple foods in developing countries, are highly vulnerable due to reliance on rain-fed agriculture, limited access to credit, and inadequate infrastructure.. Crop losses, livestock mortality, and reduced fisheries output directly threaten household food availability and income. Rural communities often face compounded risks from market disruptions, water scarcity, and soil degradation, limiting their capacity to recover from climate shocks.

### 5.2 *Gender Implications*

Women constitute a significant proportion of agricultural labor in many regions but often have limited access to land, inputs, extension services (Adebayo and Worth, 2024), and credit. Climate induced shocks disproportionately affect women, reducing household food security and increasing vulnerability to malnutrition. Gender-sensitive adaptation strategies are critical to empower women, improve agricultural productivity, and ensure equitable access to resources (Bryan *et al.*, 2024)

### 5.3 *Economic Costs of Climate-Induced Food Insecurity*

Crop and livestock losses, rising food prices, and reduced labor productivity impose both direct and indirect economic costs. Developing countries may experience GDP losses ranging from 2–10% under high emission scenarios, driven by agricultural decline and increased social vulnerability. Food insecurity exacerbates poverty, limits human capital development, and can trigger migration and social instability.

### 5.4 *Policy Responses*

International agreements, such as the Paris Agreement, emphasize adaptation and mitigation in agriculture to reduce vulnerability and greenhouse gas emissions. The Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger) and SDG 13 (Climate Action), provide a framework for integrating climate-smart agricultural practices and resilience-building policies. At the national level, countries are developing climate adaptation plans, promoting climate-smart agriculture, subsidizing irrigation, providing crop insurance, and investing in research and extension services.

## 6. ADAPTATION AND MITIGATION STRATEGIES

Addressing the impacts of climate change on food security requires integrated adaptation and mitigation strategies that operate at multiple scales from field-level practices to national policies and global frameworks. Effective strategies aim to enhance resilience, sustain productivity, and reduce greenhouse gas emissions.

### 6.1 *Agronomic Practices*

Climate-smart agriculture (CSA) integrates productivity, adaptation, and mitigation by promoting practices such as precision nutrient management, water-efficient irrigation, and crop diversification. Conservation tillage reduces soil erosion, improves water retention, and enhances carbon sequestration while maintaining yields. Intercropping and crop rotation improve soil fertility, reduce pest and disease incidence, and help spread production risk under climatic uncertainty. Additionally, the breeding and deployment of drought- and heat-tolerant crop varieties ensure more stable yields under temperature extremes and water scarcity.

### 6.2 *Technological Innovations*

Precision farming leverages sensors, drones, and satellite imagery to optimize resource use, such as water and fertilizer, thereby reducing vulnerability to climate variability. Digital agriculture, through mobile apps, climate information services, and early warning systems, enables farmers to make informed decisions on planting, irrigation, and harvesting. Biotechnology, including gene editing, CRISPR, and genetically modified crops, enhances tolerance to heat, drought, salinity, and pests, supporting both food availability and stability.

### 6.3 *Ecosystem-Based Approaches*

Agroforestry, which integrates trees with crops or livestock, improves the microclimate, enhances soil health, promotes carbon sequestration, and supports biodiversity. Soil carbon sequestration practices, including cover cropping, mulching, and compost application, increase soil organic matter, enhance fertility, and help mitigate greenhouse gas emissions. Integrated landscape management, combining forestry, agriculture, and water management, further contributes to building resilient agroecosystems.

### 6.4 *Policy and Institutional Frameworks*

Subsidies and financial incentives support the adoption of climate-smart practices, resilient seeds, and water-efficient technologies. Insurance schemes, including crop, livestock, and index-based programs, help reduce economic vulnerability to climate shocks. Early warning systems provide timely information on droughts, floods, and pest

outbreaks, enabling proactive adaptation. Additionally, research and extension services led by governments and NGOs enhance knowledge transfer, build capacity, and promote the adoption of best practices.

## 7. NESCIENCE AND RESEARCH NEEDS

Despite increasing research on climate change and food security, several critical gaps remain that limit the development of comprehensive and actionable strategies. Addressing these knowledge gaps is essential to strengthen evidence-based policymaking and ensure resilient food systems.

### 7.1 *Limited Regional Data and Modeling*

Many regions, particularly in Sub-Saharan Africa, South Asia, and small island states, lack high-quality, long-term climate and agricultural data. Limited observational networks and weak data infrastructure constrain the ability to model localized climate impacts on food systems. This, in turn, restricts the accuracy of early warning systems and the development of region-specific adaptation strategies.

### 7.2 *Uncertainty in Long-Term Projections*

Climate models vary in their projections of temperature, precipitation, and extreme events at local and regional scales. Uncertainty is further compounded by the difficulty of predicting how crops, livestock, and fisheries will respond to multiple simultaneous stressors, such as heat, pests, and water scarcity. Additionally, the nutritional impacts of climate change, including potential micronutrient losses, remain understudied in many staple and minor crops.

### 7.3 *Integration of Socio-Economic and Ecological Models*

Most models focus on biophysical impacts, such as yields, rainfall, and temperature, without adequately incorporating socio-economic factors, including poverty, migration, trade, and governance. There is an urgent need for interdisciplinary approaches that integrate ecological processes with market dynamics and household-level decision-making. Improved models could better capture feedback loops between climate, food systems, and human well-being.

### 7.4 *Bridging Science–Policy Gaps*

Scientific findings often fail to translate into policy action due to weak communication, institutional barriers, and competing political priorities. Policymakers require accessible, context-specific evidence to inform adaptation strategies, risk management, and investment planning. Participatory research that actively engages farmers, communities, and local institutions is essential to bridge this gap and enhance the adoption of climate-smart practices.

## 8. FUTURE PROSPECTS

### 8.1 *Potential Scenarios*

Under a business-as-usual pathway, if current trends continue with limited mitigation and adaptation, rising temperatures, erratic rainfall, and frequent extreme events are projected to cause significant yield declines in major staples such as maize, wheat, and rice. Fisheries and livestock systems will face heightened stress, while global food prices may rise, exacerbating hunger and malnutrition, particularly in vulnerable regions. This scenario could also widen disparities between developed and developing nations, intensifying global inequality in food access. In contrast, a climate-resilient pathway through proactive investment in climate-smart agriculture, renewable energy, water-efficient technologies, and resilient supply chains can stabilize production while reducing environmental degradation. Stronger food governance, improved trade policies, and nutritional diversification could lower vulnerability, and when combined with global commitments to reduce greenhouse gas emissions, this pathway offers a more sustainable balance between productivity, equity, and ecological integrity.

### 8.2 *Role of International Collaboration*

Climate change impacts on food security transcend national boundaries, making international cooperation indispensable. Initiatives such as the Paris Agreement, the Sustainable Development Goals (SDGs), and global climate funds play crucial roles in guiding adaptation and mitigation efforts. Collaboration is needed not only among governments but also across scientific communities, the private sector, and civil society to scale innovations and share best practices. Strengthening South–South cooperation can help vulnerable countries exchange adaptive knowledge, while North–South partnerships are essential for mobilizing finance, facilitating technology transfer, and building capacity.

### 8.3 *Prospects for Ensuring Resilience in Food Systems*

Building resilience in food systems requires a multi-dimensional approach that integrates technological, ecological, social, and policy innovations. Climate-resilient food systems are likely to be shaped by several interlinked developments. Promoting crop diversification, mixed farming, and resilient cropping systems reduces dependence on a few staples and spreads risk, while agroecological practices, agroforestry, and regenerative agriculture enhance soil health, biodiversity, and ecosystem services that buffer against climatic shocks. Advances in biotechnology, genomics, and digital agriculture offer opportunities to develop stress-tolerant crop and livestock breeds, optimize resource use, and reduce input waste, complemented by early warning systems and AI-driven climate modeling that provide timely

information for farmers and policymakers. Strengthening social and institutional systems through access to credit, insurance schemes, and training programs enhances smallholder farmers' adaptive capacity, while inclusive governance ensures equitable resource distribution and safeguards vulnerable groups, particularly women and rural communities. At the global and regional level, resilient food systems will increasingly rely on stable international trade, cooperative climate finance, and regional partnerships for knowledge exchange, with strengthened supply chains and localized production balancing efficiency with food sovereignty. Finally, shifts toward sustainable diets that are diverse, plant-rich, and resource-efficient reduce environmental pressures and improve human health, while minimizing food loss and waste across the supply chain provides an immediate opportunity to enhance resilience without requiring additional land expansion.

## 9. CONCLUSION

Climate change exerts profound and multi-faceted effects on global food security, disrupting agricultural production, food prices, nutrition quality, and supply chain stability. Its impacts extend across the FAO's four dimensions of food security availability, accessibility, utilization, and stability threatening the livelihoods of billions, particularly in vulnerable regions that lack the resources to adapt. Addressing these challenges requires holistic, interdisciplinary responses that integrate agronomic innovations, technological advances, ecosystem based solutions, and inclusive policy frameworks. Ensuring resilience will depend not only on scientific progress but also on empowering smallholder farmers, strengthening institutions, and fostering international cooperation. A concerted call to action is essential. Policymakers must prioritize climate resilient strategies, researchers should continue to close knowledge gaps and develop scalable innovations, and farmers need access to the tools, training, and support systems necessary for adaptation. Only through collective, coordinated action can we secure a sustainable and equitable food future in the face of climate change.

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