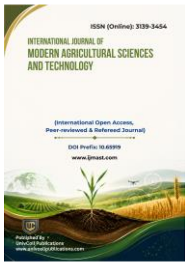
International Journal of Modern Agricultural Sciences and Technology
Volume 1 Issue 1, January-April 2026, pp. 1-13
ISSN (Online): 3139-3454
Homepage: https://ijmast.com/



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DOI:	
History:	Received: 15 December 2025, Accepted: 20 January 2026, Published: 18 February 2026
Citation:	Visen, A. (2026). Impact of Climate Change on Crop Productivity and Sustainable Adaptation Strategies. International Journal of Modern Agricultural Sciences and Technology, 1(1), 1-13.
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Conflict of Interest:	The author(s) declare no conflict of interest.
Funding:	This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.
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Published By:	UnivColl Publications

Impact of Climate Change on Crop Productivity and Sustainable Adaptation Strategies

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Abstract

Climate change is emerging as a serious challenge for global agriculture. Rising temperatures, erratic rainfall patterns, droughts, floods, and extreme weather events are directly and indirectly impacting crop productivity. The impacts of climate change are being felt particularly acutely in developing countries, where agriculture is a key pillar of the economy. Rising temperatures increase heat stress in crops, reducing photosynthesis, grain filling, and yield potential. Rainfall uncertainty and reduced soil moisture increase irrigation needs, and drought and flooding increase production risks. Increasing atmospheric carbon dioxide concentrations can stimulate growth in some crops, but this benefit is not sustainable due to nutrient deficiencies and high temperatures. Sustainable adaptation strategies are essential to address these challenges. Crop rotation, intercropping, development of improved and climate-resilient varieties, conservation agriculture, soil moisture conservation techniques, and precision agriculture-based management measures can prove effective. Additionally, weather-based advisories, insurance schemes, policy support, and institutional support strengthen farmers' adaptive capacity. Overall, food security and environmental sustainability can be ensured while safeguarding crop productivity only through coordinated efforts of scientific research, technological innovation and policy-based interventions.

Keywords: Climate Change, Crop Productivity, Heat Stress, Adaptation Strategies, Sustainable Agriculture, Food Security.

1. Introduction

Climate, the long-term average pressure, humidity, temperature, wind, precipitation, drought, floods, storms, soil moisture, salinization, desertification, carbon dioxide concentration, population, and economic patterns in the region or country of specific crops, has turned out to be widely influential and instrumental for the long- and medium-term production of crops. In the above connection, a thorough understanding and assessment of the various climate parameters concerning the crop, cropping pattern, and cropping methodology are crucial. To address the need to share current, timely, and relevant studies at the international level and to promote precautionary policies related to climate change in agriculture and food security, a kind of specific, concise and favourable address worthwhile in the above regard for the intended audience keeps on being designed. Current climatic changes can bring some fresh opportunities for crop production in some favourably situated climatic zones, but are also expected to pose an increasingly considerable risk of crop production failure and yield reduction in those areas which are already unfriendly or hostile and that are already being adversely affected by ongoing and predicted climate changes. The adverse effects of climatic change are expected be felt most severely and primarily by developing countries and regions whose economies depend mainly on agriculture due to the high sensitivity of the sector to climatic parameters and climatic change. In order to commercialize and further develop suitably and adequately collection and synthesis of current significant climate associated studies and research findings related to crop production, cropping systems and cropping methodologies some overtly climate change oriented updates and addresses are being framed to provide particular highlights on the continuing climatic situations to the desired audience. Climate is one of the important determinants of production of crops in quantities, lines, and qualities (Habib-ur-Rahman et al., 2022).

2. Climate Change Drivers Affecting Crop Productivity

Climate change will profoundly affect global agriculture, with crop productivity predicted to decline as temperature and rainfall patterns change. By 2050, crop productivity impacts may reach 30–40%. Climate change has the potential to reduce the production of staple crops and, thus, food security (Habib-ur-Rahman et al., 2022). Climate change has occurred and continues to unfold, with potential negative effects on agricultural production, particularly in low-development countries with agriculture-based economies. Adaptation strategies can minimize the negative effects of climate variability by conserving water through changes in irrigation and water harvesting techniques, and alterations in crop management practices such as sowing times, crop rotation, intercropping, diversification, and intensification. It is equally crucial, however, that actions taken to adapt to climate and water variability also address global sustainability challenges and contribute positively to environmental and human well-being. The impact of climate change on agricultural resources, particularly crops, is of increasing concern. It creates vulnerable regions and commodity groups that suffer from where extreme variability occurs with too much or too little precipitation.

2.1. Temperature Extremes and Heat Stress

Rising ambient temperatures have serious adverse effects on crop growth, development, and productivity. With the increase in average global temperatures due to climate change, various crops are likely to witness a rise in the frequency of heat stress, especially in the tropics and subtropics (Frimpong et al., 2020). A farm-level survey shows that at temperatures above 32 °C, changes in the physiological processes of crops, particularly cereals, alter the overall productivity. Similarly, the number of days of extreme temperature above critical thresholds rises steadily from the year 1981 to 2010, with the Southern African region showing the highest increase. Increase in temperature results in enhanced plant respiration, which affects both photosynthesis and yield because crops are already operating at their optimal temperature levels (Fischer et al., 2007). The impact of climate change on crop yield due to changes in temperature has been assessed for several countries. For a range of South Asian countries, the estimated yield loss is between 10 and 20% for wheat and maize and even higher towards the end of the century, while rice yield is projected to decrease by 4 to 9% (Fischer et al., 2007).

2.2. Altered precipitation and drought dynamics

Climate change is affecting global precipitation distribution and dryland areas. The IPCC Fourth Assessment Report projected more droughts and flood events with climate change (Habib-ur-Rahman et al., 2022). Weather variability may increase due to climatic and socio-economic drivers. Generally, increased temperature can promote evaporation from water bodies and plants. Higher temperature can also accelerate soil moisture depletion and increase demand for irrigation (A Jat et al., 2012). Precipitation and drought can broadly limit environmental conditions for crop production. An increase in the frequency of dry events, extreme rainfall, humidity and wind intensity, and the occurrence of precipitation will alter drought dynamics and water availability.

Historical soil water content data showed a trend reduction in many areas. Soil moisture content is changing due to complex local conditions that do not have a simple spatial pattern. Many efforts have been made to study the effects of rising carbon dioxide concentration on crop productivity. Individual crops respond differently to elevated CO_2 level, and responses vary with resource availability and environmental changes. the CO_2 level is projected to rise to around 550 ppm for climate stabilization. Studies indicated a potential yield increase of 20% to 30% for C3 crops, few major C4 crops would respond to elevated CO_2. Such a major difference in plant responses to atmospheric CO_2 arises from differences in photosynthetic uptake, C14 versus C3 pathway, damage response, and many other physiological and structural factors.

2.3. Elevated atmospheric CO2 and crop responses

Summary: Warmer temperatures and altered precipitation patterns, the other important climate change factors for crops, are largely region specific. Meanwhile, increases in atmospheric carbon dioxide (CO2) concentration are globally uniform due to the long residence time of CO2 in the atmosphere. Elevated CO2 can directly affect crops and other plants by stimulating photosynthesis through the enhancement of the carbon-fixation process. Most of the important crops in the world are either C3 crops or C4 crops. C3 crops show greater photosynthetic stimulation and ultimately higher productivity than C4 crops under identical conditions of temperature and other factors when atmospheric CO2 increases, and they potentially respond more favorably to elevated CO2 under sustained high temperature. However, temperature rise and moisture deficiencies frequently influence root zone water supply, with severe implications for crops and crop production in many areas. Even C3 crops such as rice, wheat, and soybean do not always guarantee higher crop yields and might be lower at high atmospheric CO2 compared to present CO2 when nitrogen or other deficiencies occur (Kumar Shanker et al., 2022).

2.4. Extreme weather events and their implications

The projected increase in precipitation and temperature extremes and the rising frequency and intensity of extreme weather events is likely to damage crops and have control over pest pressures. The effect of climate change on crop yield and ecosystem services is a major concern for the agricultural community and is considered one of the most prominent issues by the United Nations. Losses in agricultural productivity due to climate change and extreme weather events will expose farmers to higher risks and diminish food security.

The climate and food security nexus has been analyzed for the last three decades and climate-smart adaptation strategies have been recommended, specifically for developing regions. However, the proposed practices have not reached a sizable section of the farming community. The agricultural system is still suffering from the ill effects of climate change and farmers are exposed to an increasing level of risk. The anticipated losses in food production will not only add to local poverty but also have far-reaching effects on regional and global markets.

3. Mechanisms Linking Climate Change to Crop Yields

In warmer climates, C3 crops generally experience greater yield loss than C4 crops due to differences in photosynthetic pathways; but growing degree days may escape water-limited C3 crops, which probably do not perform better than water-limited C4 crops. Changes in temperature and other climatic variables also influence respiration, the source-sink balance, and canopy development. Wheat and pulses are often considered the initial options for diversification of C4 crops into diverse cropping systems, while rice remains as the primary aquatic option for diversifying C4 crops at system level.

Climate change affects the timing of phenological growth stages and length of crop cycles in various regions across the world. Phenological shifts can occur in crops regardless of the growing environment or native regions. Climate change has influenced flowering and grain-filling stages of crops. Major crops respond differently to shifts in growth stages. Shifting flowering time shifts the end of the grain-filling period, affecting crop yield and quality. Spreading of flowering has a greater influence on yield than concentration of flowering at the same time in crops. Accurate prediction of future phenology is vital for anticipation of potential impacts on yields. When the duration of important phenological periods does not adjust to a changing climate, crop productivity declines rapidly.

Climate change also affects soil health, moisture availability, and nutrient cycling. Increasing temperature and shifting precipitation patterns negatively impact soil microbial activities and organic matter decomposition. In turn, soil health, nutrient cycling, and plant nutrient use efficiency are affected adversely. Crop yield is directly related to soils and nutrients. High-potassium soils can yield continuous cereal crops like rice, maize, and wheat. Cereal yield also depends strongly on N, P, Mg, and S in addition to K in low-potassium soils. Soil degradation threatens climate-resilient crops. The speed of soil regeneration under crops is critical to ensuring food security. Certain management options improve soil nutrients under diverse climate conditions for different soils and crops. (Habib-ur-Rahman et al., 2022)

3.1. Physiological responses in foundational crops

Foundation crops constitute a major portion of the global agricultural production. Maize, wheat, and rice together form a staple food for about 50% of global population (Habib-ur-Rahman et al., 2022). Due to rising temperature and changing carbon dioxide (CO2) concentration and precipitation regimes caused by global climate change, crop productivity is increasingly threatened. Although increasing CO2 has a positive effect on C3 crops via photosynthesis, increased atmospheric temperature is adversely impacting wheat, rice, and maize (J. Snowdon et al., 2021). The potential for simultaneous temperature increase and reduction in precipitation with most climate projections will critically compromise rainfed crops, particularly those grown in semi-arid regions (Zhang & Zhao, 2017).

3.2. Phenological shifts and yield components

The impacts of climate change on crop production are modulated by direct physiological effects, which vary by crop, variety, and cultivar, as well as each crop’s sensitivity to temperature, precipitation, CO2, and elevated atmospheric pollution. These direct effects are integrated mechanistically through physiological processes to predict crop yields. Wheat, rice, maize, barley, soybean, and potato account for over 60% of global crop production. The increase in CO2 is expected to accelerate crop development but has a fertilization effect on crops and may positively influence yield (Huda et al., 2011). C3 crops such as wheat and rice are likely to benefit more than C4 crops such as maize and sugarcane. Heat extremes adversely affect crop yield potential, grain number, and grain weight and damage the leaves and stems (Minoli et al., 2022). The impact of climate on crop development is therefore crucial. Statistical models indicate intensive phenological changes driven by temperature that have been closely linked to crop yield KPI worldwide. Temperature correlation analysis suggests that rising temperatures have advanced the sowing-to-anthesis and sowing-to-maturity durations while simultaneously shortening the anthesis-to-maturity and sowing-to-maturity durations.

3.3. Soil health, moisture availability, and nutrient cycling

Soil is a living ecosystem supporting an abundance of microbes and earthworms. Microbial activity is fundamental to the soil-plant-water-nutrient system as it promotes organic matter decomposition, nutrient release, and nutrient-use efficiency. Excessive fertilizer and agrochemical use, combined with temperature and moisture increase, have negatively influenced soil health. Global warming increases the rate of organic matter decomposition, while erratic rainfall regimes result in nutrient leaching. Soil organic carbon (SOC) is a limitation in many rainfed dryland areas, and is declining in all agro-ecological zones. SOC is critical because it enhances soil aeration, promotes root health, and improves water-holding capacity (Kannan et al., 2015).

4. Regional Variability in Impacts

Climate change will result in variable temperature and precipitation changes, with significant regional differences in climate change projections across Asia. Crop yield analysis shows decreasing trends for several staple crops, including wheat, rice, maize, and pulses, and Asia has been identified as a high-risk region for potential climate change impacts on agricultural production (Habib-ur-Rahman et al., 2022). In particular, South Asia is vulnerable, as a considerable proportion of agriculture relies on rainfall. Furthermore, the impacts of climate change on agricultural production are expected to be more severe in developing countries than in developed countries.

4.1. Global patterns in major agro-ecological zones

Climate change will increasingly distress major crops worldwide, but regional vulnerabilities and adaptation needs vary widely. The deepening threat not only derails food security and nutrition goals but introduces an added layer of risk to rural farmers caught between problematic agro-climatic and socioeconomic conditions. The global patterns observed across different agricultural systems point to a few relevant principles. Globally, cropping practices are shifting away from the dominant C3 crops—wheat, rice, and maize—across large swathes of Africa and Asia toward C4 crops and other commodities (María Loboguerrero Rodriguez et al., 2018). Affected areas, including Central and Southern Africa, East Africa, and the Indian subcontinent, face concurrency of climate exposure with socioeconomic fragility. Where climate risks are exceptionally high, further degradation of agricultural viability is predicted; a substantial part of the advanced crop system also complies. Thus, higher attention and priority for adaptation investment are warranted.

The starkest projected consequences arise from climate-change exposure during the high-risk, short-duration, high-input cropping system typical of rice-wheat systems in South Asia. Here, the damage estimate reaches 100% of current productivity levels, corresponding to income losses amounting to USD 56 billion annually. Farmers cannot easily moderate these profound threats; climatic extremes occur on scales that current management cannot accommodate. Under climate-stabilization scenarios, yet-at-risk C3 crops such as wheat or barley require higher consideration in both investment and research than widespread evaluations along with concomitant C4 or non-staple alternatives (Habib-ur-Rahman et al., 2022).

4.2. High-risk regions and crops

Climate resilience and food security remain major concerns across the globe. Climatic extremes, such as droughts, floods, and high-temperature stress, have already significantly affected crop productivity. At the end of the twenty-first century, global warming, on the average, may reach 2−4 °C above the pre-industrial level, with boreal and tropical regions warming even more (Habib-ur-Rahman et al., 2022). Agricultural trees and crops that are already stressed by biotic and abiotic factors may face even more pressure. Thus, it is essential to identify crops and regions that are most at risk from climate change so that the focus can be directed toward them for potential adaptation.

4.3. Socioeconomic consequences for farmers and food systems

The socioeconomic consequences of climate change on agricultural crops profoundly affect farmer income, decision-making, and overall market performance. Predicted yield declines and heightened climate-related risks limit productivity and ultimately jeopardize food security. Anticipated changes in the price of staple crops could have significant adverse implications for socioeconomic progress in regions already burdened by other stressors such as conflict, land degradation, and natural resource scarcity. Equity issues may arise in both the domestic and international markets, whether through disproportionate price movements for staple versus cash crops, instability in staple crop supply and prices, or correlations between the prices of staples and other food items. These multifaceted issues underscore the pressing need for proactive investments and crucial assistance by national and international stakeholders to bolster farmers’ adaptation capacities (J. Vermeulen et al., 2011).

Climate change not only exacerbates the hazards affecting cropping systems, but also intensifies vulnerability by amplifying the damaging effects of wider socioeconomic stresses. Growing competition in land, water, and capital from non-agricultural pressures further threatens agricultural productivity, fueling food insecurity and creating important feedback effects. In many low-income regions beset by protracted crises, rising staple crop prices have already constrained purchasing behavior and made consumption and production decisions more difficult. The situation continues to be aggravated by rising energy prices, expensive fertilizer, and competition for biomass energy, driving up input costs and land bids even in regions with poor water control technology (E. Brown & C. Funk, 2008).

5. Adaptation Frameworks for Sustainable Crop Production

Throughout the world, climate change poses risks to agricultural production, limits food security, and prevents sustainable development. Sustainable crop production will be crucial to meet the needs of a growing population without compromising ecosystem health. Various adaptation frameworks can support the design and implementation of sustainable crop production strategies (Habib-ur-Rahman et al., 2022).

Agronomic practices and management strategies enhance sustainable productivity. Optionally combined with agroecological practices, mulching, irrigation scheduling, and soil moisture conservation help increase productivity while managing climate risks. Cropping systems that recycle soil nutrients and organic matter associated with crop residues, composts, and volatile biomass from various sources encourage such objectives. Advanced breeding and genetic improvement contribute to sustainable crop production by enhancing resilience and minimizing negative climate change impacts. Target traits include tolerance to heat, drought, flooding, salinity, and disease, and consistency of phenology with changing climate conditions to ensure high and resilient productivity. Stress-tolerant hybrids and varieties further stabilize food availability in vulnerable areas. Technologies and data-driven approaches facilitate the adoption of various agricultural practices and management strategies. Remote sensing and meteorological information, along with decision-support and precision agriculture tools, help farmers identify appropriate practices. Climate forecasts for average conditions, extremes, and the timing of factors affecting cropping systems inform the development of adaptation strategies.

Laws, regulations, policies, structures, incentives, governance, and capacity-building for resource management and operational needs likewise determine the sustainability of crop production. Supportive policies increase the likelihood of sustained adoption or expansion of agronomic practices and management strategies.

5.1. Agronomic practices and management strategies

Climate change will affect crop production systems, directly and indirectly, with varying degrees of risk that depend on location and crop choice. Extreme weather events and climate variability will become more frequent, leading to adverse repercussions for crop production. Every agro-ecological region has a specific combination of temperature, precipitation, soil, and farming system. Changes in crop characteristics, agronomic practices, and farming systems must be based on adaptations tailored to local climate projections and site-specific conditions. Techniques alone cannot ensure sustainable production. Crop improvement, information technologies, and policy factors must also be integrated into processes. Developing a coherent adaptation approach combines short- and long-term strategies (A Jat et al., 2012).

Strategic cropping techniques allow farmers to keep growing crops under changing climatic conditions. Individual nations can form requests based on specific measures, even though climate change is not uniform around the world. Crop rotation, intercropping, mixed cropping, and other practices should be intensified (Habib-ur-Rahman et al., 2022).

5.2. Breeding and genetic improvement for resilience

Climate change threatens food supply by reducing major cereal production, including declines of 9% for maize, 11% for rice, and 14% for wheat. Increased temperatures, altered rainfall patterns, and extreme weather events contribute to this decline and promote pathogen and pest attacks (Balkovis et al., 2023). Increasing crop resilience to climate change is essential for food and nutritional security. This can be achieved through genetic engineering, which allows direct transfer or manipulation of genes, and molecular breeding, which involves introducing novel alleles via traditional breeding methods. Genomics-assisted breeding offers tools like DNA marker-based selection to improve crop adaptation. Defining stress factors affecting crop production under climate scenarios, combined with multi-environment testing and modeling, helps identify traits and germplasm suited for stress-prone environments. Techniques such as geographic information systems, DNA fingerprinting, and QTL mapping support the selection of promising accessions for developing climate-resilient crops. Breeding for climate change benefits from novel genetic variants, with gene editing offering opportunities to accelerate trait stacking. However, major-effect adaptation genes are often quickly fixed in modern crops, and pleiotropic effects may limit gains from single-gene modifications. Conventional selection, based on testing in diverse environments over many years, has proven effective for gradual adaptation. Historically, progress in climate adaptation was a by-product of selecting for high yield and stability across environments. Automated phenotyping, remote sensing, genomic selection, and AI-based prediction methods now enhance the ability to identify and incorporate complex adaptive traits. Yield performance remains the primary target for breeding in response to climate change, supported by expanding technological tools. Despite advancements, classical methods will continue to play a vital role in maintaining crop productivity amidst ongoing climate challenges (J. Snowdon et al., 2021).

5.3. Technological and data-driven approaches

Climate change induces a plethora of exposure risks pertinent to agricultural systems, necessitating the prioritisation of context-appropriate adaptation strategies (Habib-ur-Rahman et al., 2022). Data on climate and crop cultivation practices were consolidated across five agro-ecological zones to determine operational adaptation options utilising available technologies that are resilient under current and future climates (Gummadi et al., 2020). Such techniques assist in estimating climate change impacts and identifying measures that bolster adaptive capacity at multiple levels. Agricultural-dependent livelihoods prevail throughout Africa and in other developing countries, with the sector contributing 43% of GDP and over 80% of employment in Eastern Africa. High rainfall variability is endemic, with frequent, extensive droughts occurring annually. In Ethiopia, the agricultural sector intimately correlates with rainfall variability, rendering droughts detrimental to GDP and poverty rates. Predominantly rainfed, African agriculture remains predicated on climate-dependent factors—water availability in particular—and climate change is anticipated to further compound challenges in semi-arid rainfed systems.

Technological innovations and digitally-enabled adaptation strategies encompass a multitude of options for climate-smart crop production, ranging from stress-tolerant crop varieties to climate insurance and information sharing (María Loboguerrero Rodriguez et al., 2018). Breeding is increasingly focused on developing stress-tolerant varieties capable of withstanding water submergence, drought, high temperature, saline intrusion, and climate-sensitive pests, while multitrait crops that address multiple climatic stressors improve resilience overall. Timely climate information and index-based agricultural insurance constitute effective climate risk management strategies that have been successfully implemented in diverse contexts, including China, India, Kenya, and Mexico. National climate policies, however, often remain inappropriately aligned with local implementation, revealing a pressing need for adaptation actions that translate high-level commitments into effective, context-specific weather risk management.

5.4. Policy, institutional support, and governance

Crop productivity is closely linked to climate conditions, and with climate change increasing variability in climate, this impact is set to become more pronounced. In developing countries, where livelihoods depend on climate-sensitive sectors such as agriculture and forestry, adaptation and mitigation strategies are key. These strategies must consider a country's specific climate conditions so as to take into account the four pillars of food security—availability, access, utilization, and stability—both in the short and long term. Because the impact of climate change varies among regions, adopting and implementing strategies tailored to individual country needs is crucial to keeping pace with climate change (Tetteh et al., 2014).

Adaptation measures are often not taken because of uncertainty concerning a project's future viability. The actions of agricultural policymakers must try to resolve this, so that aid can proactively be offered during the design stage of agricultural and development projects (R. Rhodes et al., 2014). Simple techniques can conserve moisture at the soil surface and help farmers avoid drought damage (Habib-ur-Rahman et al., 2022).

7. Evaluation of Adaptation Effectiveness

Climate change adaptation strategies aim to enhance crop yield resilience, allowing production to withstand a shifting climate more effectively while maintaining affordability for consumers (Habib-ur-Rahman et al., 2022). Current adaptation formulations, however, often overlook considerations of adaptation effectiveness, yield resilience, or the sustainability of newly introduced technologies; robust evaluation of various adaptation options must encompass climate influence, environmental sustainability, economic impacts, and transferability to additional situations (Iqbal et al., 2015). Proposed adaptation assessment frameworks incorporate sets of 16 indicators clustered into 5 evaluation dimensions addressing agricultural productivity, resilience to climate extremes, economic sustainability, environmental-impact mitigation, and the potential for scaling adaptation strategies to address climate change in other contexts.

The harsh economic environment for farming in many parts of the world prohibits practically all adaptation except those at no cost or even capable of boosting revenues. Further high-value adaptation options, if identified, could unlock new pathways for enhanced farm sustainability during climate change. In other agricultural systems without obstacles to higher investment, the introduction of a further, more cost-effective set of options, if identified, could help mobilize scarce capital toward still more drought-resilient crops, production practices, or value-adding techniques at farm or processing levels. Addressing these priority gaps reduces production and marketing vulnerability to climate change while additionally ensuring that the suite of responses chosen incurs negligible cost.

Discussion of possible adaptation options often characterizes them in terms of cost–benefit or opportunity-cost indicators, together with the presence of externalities not sufficiently covered elsewhere in farming or marketing approaches. Exploration of framework evaluation dimensions thus embraces multiple economic factors alongside further environmental concerns. Major impediments arise for monitoring or estimating yield variations accountable to climate change attributable to still limited access to the necessary precipitation and temperature data.

7.1. Metrics for productivity, resilience, and sustainability

Potential trade-offs across productivity, resilience, and sustainability complicate both adaptation decisions and metric selection. Cost-benefit analysis usually guides those choices, considering not only financial outcomes but also opportunity costs of unadopted alternatives and a wide range of climate impacts. Nevertheless, many economically motivated strategies also enhance climate resilience and sustainability, and adaptation planning increasingly incorporates legal, social, and technological externalities beyond mere dollars and cents. Such path dependencies and complex outcome interrelationships generate a diverse and context-specific range of relevant indicators (Habib-ur-Rahman et al., 2022). No standardized set fulfills all needs across diverse circumstances; a few representative frameworks for production, resilience, and sustainability in the agricultural sector illustrate the broader approaches available.

7.2. Economic and environmental trade-offs

Rural economies and livelihoods depend on agriculture, which generates enormous income and employment opportunities. Farming, especially for smallholders, remains a significant activity. Globally, agriculture is a keystone sector because it helps produce food and other raw materials essential for domestic and industrial use. It contributes about 3% to GDP and accounts for over 60% of employment in developing economies. A reduction in agricultural productivity increases food prices and lowers the purchasing power of poverty-stricken people, resulting in greater food insecurity.

Several sectors are impacted due to climate change, including agriculture, which is highly vulnerable. Crop competitiveness diminishes in farming systems exposed to high risk due to climate change, soil erosion, depletion, land degradation, pollution, and industrialization (Habib-ur-Rahman et al., 2022). Rising population along with demand for crops and animal products continues to grow. Coping with climate change by employing various adaptive technologies in this sector is of utmost importance. Crop output and various cereals, pulses, oilseeds experience substantial losses in yield. Implementation of these options could ensure sustainable food security, improve incomes, reduce health hazards caused by pesticides and chemical fertilizers, and minimize resource wastage (Stevanovic et al., 2016).

Adverse climatic conditions influence biomass and grain production systems through changes in mean values and the frequencies of extreme events. Altered frequency of conflicting rituals results in poorly coordinated vegetative and reproductive transformation. Crop failure, followed by severe market fluctuation and price volatility, leads to extremely critical risk for the farming community. Adaptation of crops through adjustments in cropping pattern, land use, irrigation, multiple cropping, crop diversification using short-duration and other matured varieties, changing dates of sowing and harvesting, planting of hybrid-multicut crops and varieties, modification of agronomic practices, incorporation of crops and cropping schemes to facilitate moisture conservation, integrated nutrient production and farm management; and substitution with climate-resilient crops through introduction of drought, salinity, shift, climate-adaptive varieties and improved cultivars is vital.

7.3. Scalability and transition pathways

A pathway from current practice to climate-smart production requires adaptation that increases resilience and reduces vulnerability while maintaining or enhancing productivity. Adaptation pathways for climate-smart crop production must fit local contexts to remain effective and sustainable. Given this, assessments and evaluations of climate adaptation should consider context-specific approaches, thresholds, and milestones that reflect local challenges (María Loboguerrero Rodriguez et al., 2018). The notion of climate-smart outcomes can similarly serve to connect locations across regions, bridging diverse climatic and socioeconomic settings.

Scaling up from local adaptations to broader climate-smart transitions remains challenging without enabling policies, investments, and institutions to support farmer uptake and implementation. Identifying national milestones to coordinate climate-smart adaptation actions can facilitate wider climate-smart transitions adapted to local situations, providing national, localized, or regionally-specific focal points for attention.

National climate-smart adaptation assessments that consider context and regional interlinkages address scales between the local and national. Regional connectivity has influenced crop transitions and adaptation patterns under diverse climates and economic structures, allowing for linkages across contexts. Guidance for institutional frameworks that prioritize climate-smart adaptation at all levels can further support the uptake of local adaptations and wider transitions (Habib-ur-Rahman et al., 2022).

8. Gaps and Research Needs

Several gaps, uncertainties, and research needs should be addressed to enhance knowledge of ongoing and anticipated climate impacts on crop productivity and inform the design of effective climate adaptation practices.

First, important uncertainties remain in projecting crop impacts as a function of climate variables. Gaps include a poor understanding of ecosystem adaptation thresholds. Considerable differences exist in projected climate change impacts between quantitative assessments, where models exhibit regional similarity, and qualitative reports, which attributed greater safety to production in large countries. The feasibility of offsetting increased production risks via green revolution improvements becomes uncertain.

Second, few systematic assessments are available to quantify regional exposure under projected climate scenarios. Most crop-climate studies either focus on selected countries or employ models not representative of major crop-producing regions. Evaluation of general circulation models (GCMs) reveals uncertainty regarding climatic average and variability as well as the region-specific expression of global changes. In Africa, for example, both a moderate increase in rainfall and a marked decrease in variability align with GCM projections. Systematic evaluations could thus define a limited number of relevant countries or crop systems while acknowledging potential biophysical and socio-economic compounding.

Finally, the socio-economic dimensions associated with climate investment remain inadequately characterized and justified. Few multi-disciplinary studies integrate economic and climatic investigations, even as recognized climate adaptation measures would likely boost production and raise global prices. Price increases may reinforce climate investment incentives. A better etween higher food prices and short- and medium-run vulnerability could further substantiate the need for agricultural extension, infrastructure, and improved-input access measures to address backward and forward linkages. Relevant biophysical, economic, and social data gaps hinder comprehensive assessment of agricultural climate vulnerability and consequent policy recommendations (Habib-ur-Rahman et al., 2022) , (J. Vermeulen et al., 2011).

9. Conclusions

Population growth and lifestyle changes, coupled with increasing climate variability and uncertainty, place agriculture, particularly crops, under relentless pressure. Globally, annual average crop productivity growth has declined. Historically, overall cereal yields, primarily from wheat, rice, and maize, increased at more than 1.5% per year. However, in the last two decades, rates fell below 1% and are still declining with climate change (Habib-ur-Rahman et al., 2022). Climate change already disrupts agricultural systems, and the Intergovernmental Panel on Climate Change (IPCC) projects global increases in temperature, extreme weather, and variable rainfall, further aggravating existing pressures. Crop productivity is expected to be severely affected in some regions, compromising food security and climate-smart crop production.

Adaptation frameworks to achieve sustainable crop production under climate change must be based on sound scientific evidence. A framework can aid systematic analysis of required strategies and approaches and the interconnections between them or guide the selection of options suitable for specific contexts. Extensive research provides insights into major dimensions that climate change affects crop production systems, the severity of impact varies significantly by region and cropping system, and adaptation strategies can mitigate adverse effects while maintaining long-term sustainability.

References:

Habib-ur-Rahman, M., Ahmad, A., Raza, A., Usama Hasnain, M., F. Alharby, H., M. Alzahrani, Y., A. Bamagoos, A., Rehman Hakeem, K., Ahmad, S., Nasim, W., Ali, S., Mansour, F., & EL Sabagh, A. (2022). Impact of climate change on agricultural production; Issues, challenges, and opportunities in Asia. ncbi.nlm.nih.gov

Frimpong, K., T. Odonkor, S., A. Kuranchie, F., & Fannam Nunfam, V. (2020). Evaluation of heat stress impacts and adaptations: perspectives from smallholder rural farmers in Bawku East of Northern Ghana. ncbi.nlm.nih.gov

A Jat, R., Q Craufurd, P., L Sahrawat, K., & P Wani, S. (2012). Climate change and resilient dryland systems: experiences of ICRISAT in Asia and Africa. [PDF]

Kumar Shanker, A., Gunnapaneni, D., Bhanu, D., Vanaja, M., Jyothi Lakshmi, N., Kumar Yadav, S., Prabhakar, M., & Kumar Singh, V. (2022). Elevated CO(2) and Water Stress in Combination in Plants: Brothers in Arms or Partners in Crime?. ncbi.nlm.nih.gov

J. Snowdon, R., Wittkop, B., Chen, T. W., & Stahl, A. (2021). Crop adaptation to climate change as a consequence of long-term breeding. ncbi.nlm.nih.gov

Zhang, Y. & Zhao, Y. (2017). Ensemble yield simulations: Using heat-tolerant and later-maturing varieties to adapt to climate warming. ncbi.nlm.nih.gov

Huda, S., Sadras, V., P Wani, S., & Mei, X. (2011). Food Security and Climate Change in the Asia-Pacific Region: Evaluating Mismatch between Crop Development and Water Availability. [PDF]

Minoli, S., Jägermeyr, J., Asseng, S., Urfels, A., & Müller, C. (2022). Global crop yields can be lifted by timely adaptation of growing periods to climate change. ncbi.nlm.nih.gov

Kannan, P., Arunachalam, P., & Govindaraj, M. (2015). Implications and Ways to Enhance Nutrient Use Efficiency Under Changing Climate. [PDF]

María Loboguerrero Rodriguez, A., Birch, J., K. Thornton, P., Meza, L., Sunga, I., Ba Bong, B., Rabbinge, R., Reddy, M., Dinesh, D., Korner, J., Martínez Barón, D., Millan, A., Hansen, J., Huyer, S., & M. Campbell, B. (2018). Feeding the World in a Changing Climate: An Adaptation Roadmap for Agriculture. [PDF]

J. Vermeulen, S., K. Aggarwal, P., Ainslie, A., Angelone, C., M. Campbell, B., J. Challinor, A., Hansen, J., Ingram, J. S. I., Jarvis, A., M. Kristjanson, P., Lau, C., K. Thornton, P., & K. Wollenberg, E. (2011). Agriculture, food security and climate change: Outlook for knowledge, tools and action. [PDF]

E. Brown, M. & C. Funk, C. (2008). Food Security Under Climate Change. [PDF]

Balkovis, J., et al. (2023). Climate change threatens cereal crop yields: Study. *Nature Reviews Earth & Environment*. [PDF]

Gummadi, S., D. M. Kadiyala, M., P. C. Rao, K., Athanasiadis, I., Mulwa, R., Kilavi, M., Legesse, G., & Amede, T. (2020). Simulating adaptation strategies to offset potential impacts of climate variability and change on maize yields in Embu County, Kenya. ncbi.nlm.nih.gov

Tetteh, E., Obirih Opareh, N., Ampadu, R., & Antwi, B. (2014). Impact of Climate Change: Views and Perceptions of Policy Makers on Smallholder Agriculture in Ghana. [PDF]

R. Rhodes, E., Jalloh, A., & Diouf, A. (2014). AfricaInteract : enabling research-to-policy dialogue for adaptation to climate change in Africa. [PDF]

Iqbal, M., Ahmad, M., & Mustafa, G. (2015). Impact of Farm Households' Adaptation on Agricultural Productivity: Evidence from Different Agro-ecologies of Pakistan. [PDF]

Lechevallier, E. (2015). Cropping system sensitivity to climate change in the northern uplands of Lao PDR. An agroclimatic modeling approach. [PDF]

Stevanović, M., Popp, A., Lotze-Campen, H., P. Dietrich, J., Müller, C., Bonsch, M., Schmitz, C., L. Bodirsky, B., Humpenöder, F., & Weindl, I. (2016). The impact of high-end climate change on agricultural welfare. [PDF]