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Impact of Climate Change on Agriculture and Adaptive Strategies: A Comprehensive Review

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ABSTRACT

Climate change has emerged as a critical global challenge, significantly impacting agricultural systems worldwide. This synthesis examines recent studies on how agriculture is affected by climate change and delves into diverse strategies for adaptation. Increasing temperatures, changing precipitation patterns, and more frequent extreme weather events are disrupting crop yields, soil conditions, and water resources. According to the IPCC, global temperatures could rise by 0.3-4.8°C by the end of 21st century, bringing about intense weather occurrences, altered rainfall patterns, and rising sea levels. Climate change significantly impacts the yields of primary global food crops such as maize, wheat, and rice. Elevated temperatures, evolving precipitation patterns, and heightened extreme weather events are major contributors to these changes. Various studies have shown that these climatic factors lead to substantial yield reductions and decreased crop productivity across different regions. Vulnerability is especially pronounced among small-scale farmers due to their dependence on natural resources. Adaptation strategies, such as crop diversification, improved irrigation, and climate-resilient crop varieties, are critical. Collaborative efforts among farmers, policymakers, and researchers are essential for developing and implementing these measures. This review endeavors to enrich comprehension of climate change impacts and effective adaptive strategies, thereby bolstering robustness and long-term viability in agricultural systems.

Keywords: *Climate change, Vulnerability, Food crops, productivity, small-scale farmers, Adaptation strategies*

INTRODUCTION

Climate change has become a prominent global challenge, involving various environmental shifts. It is defined as climate change as "a change in the state of the climate that can be identified by changes in its mean and/or variability over an extended period, typically decades or longer" [1]. This definition encompasses changes in climate attributes identifiable through statistical analysis, recognizing that these shifts may stem from natural fluctuations or human actions. In contrast, the United Nations Framework Convention on Climate Change (UNFCCC) offers a more targeted definition, describing climate change as "changes in climate attributable directly or indirectly to human activity that alters the composition of the global atmosphere, distinct from natural climate variability observed over similar periods" [2]. This definition highlights the role of human activities in causing climate change, emphasizing their influence on atmospheric composition and their impact on the global climate system, surpassing natural fluctuations.

Agriculture is both an emitter and absorber of greenhouse gases in the atmosphere, contributing primarily to CO_2, N_2O, and CH_4 emissions. GHG emissions from agriculture mainly arise from energy use (including the production and deployment of agricultural inputs and machinery) and practices for land management [3]. The food system alone contributes approximately one-third of global anthropogenic emissions, with agriculture being a significant source of non-CO2 GHGs such as nitrous oxide and methane, especially in developing countries. In developed nations, most emissions stem from post-processing activities, whereas in developing countries, two-thirds arise from agricultural production.

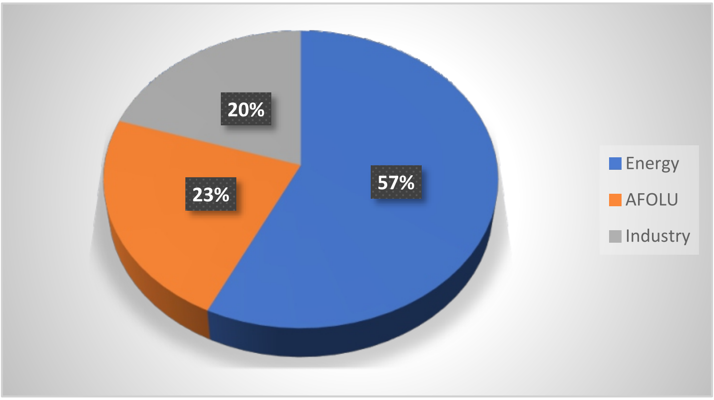

Fig. 1: Contribution of different sectors in Global Green House Gas emissions

In India, GHG emissions are primarily contributed by various sectors namely energy sector (62%) which includes electricity and heat production (49%) and transport (13%), followed by industries (23%), agriculture (14%) [4] and waste (3%) [5]. The agriculture sector contributes significantly to GHG emissions through various activities across different categories of agriculture namely livestock (30-35%) [6], rice cultivation (10-12%) [7], biomass burning [8] and fertilizer use [9].

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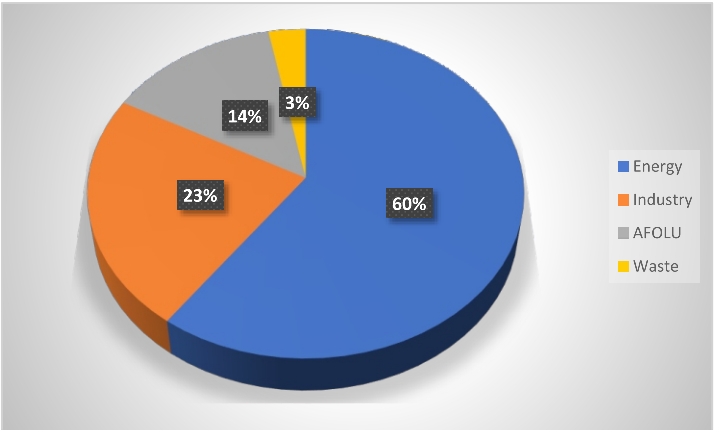

Fig. 2: Contribution of different sectors in Indian Green House Gas emissions

Numerous indicators which include rising global temperatures, declining groundwater levels, droughts, variable rainfall patterns, floods, soil erosion, changes in wind speed, sea level rise due to glacier melting, cyclones, hailstorms, fog, earthquakes, landslides, increasing ocean temperatures, ocean acidification stress the reality of climate change [10].

Table 1: Various approaches to understanding the potential impacts of climate change include:

Approaches	Indicators	References
Controlled Experiments in Greenhouses	Agronomists conduct controlled experiments with varying temperatures to study crop sensitivity	[11-13]
Agronomic Crop Simulations	Models simulate key crops like maize, wheat, soybeans, and rice to assess their sensitivity to climate change	[14,15]
Cross-sectional Studies of Yields	Analyzing grain yields across different climate zones helps to understand vulnerability to climate change	[16-18]
Cross-sectional Economic Models	Economic models, such as Ricardian regression and panel data regression models, assess the influence of climate change on agricultural outcomes by analyzing land values and net revenues across different climate zones	[19,20]

Source: [1, 21]

Studies consistently indicate that crops are highly sensitive to changes in temperature, suggesting strong confidence in their potential vulnerability to climate change [1.21]. Climate change is not only a challenge for India but for all countries facing its adverse effects. The diverse effects of climate change on agriculture underscore the necessity for tailored adaptation and mitigation strategies, particularly in vulnerable developing economies. Extreme climate changes will significantly impact agricultural productivity and food supplies without mitigation and adaptation measures. This poses risks to the livelihoods of farming communities and undermines government efforts to improve food security, combat malnutrition, and reduce poverty. Many researchers emphasize adaptation as a crucial policy approach to address the unavoidable consequences of climate change [22-24]. The combined findings from these approaches can offer valuable policy insights. In this study, we explore the potential effects of climate change on the productivity of key food crops and investigate the adaptation strategies adopted by farmers in response to these shifts.

Projected impact of climate change

The report from IPCC highlighted that climate change has already impacted food security through rising temperatures, shifting precipitation patterns, and more frequent extreme weather events [25]. Previous IPCC assessments projected future global temperature increases of 1.8–4°C by the end of 21st century, alongside increased variability in rainfall and heightened occurrences of extreme events like heat waves, cold spells, droughts, and floods [1]. Since the 19th century, average global surface temperatures have risen by 0.6 ± 0.2 °C and are anticipated to increase by 0.3–2.5 °C in the next 50 years and 1.4–5.8 °C by the end of this century [1]. According to NASA, 19 of the 20 warmest years since 2001 (excluding 1998) have occurred in the 21st century, with 2016 marking a record high [26].

Current climate projections indicate ongoing warming trends, with existing greenhouse gas concentrations committing to at least an additional 1.1°F (0.6°C) of warming by 2100 [27]. Depending on emission scenarios, global temperatures are expected to rise by 0.3 to 4.8°C by the end of the 21st century, leading to more severe extreme weather events, altered precipitation patterns, prolonged droughts, heavy rainfall, glacial melting, and rising sea levels [28]. The IPCC predicts global precipitation may increase by 0 to 14 percent, with an estimated best guess of an 8 percent rise, impacting ecosystems, water resources, and agriculture [29]. Reports from the World Glacier Monitoring Service indicate significant shrinkage of mountain glaciers, including those in the Himalayas, potentially disappearing by 2035 [30]. By the end of the 21st century, global temperatures are projected to increase between 0.5°F and 1.3°F (0.3°–0.7°C), influenced by uncertainties in natural sources affecting short-term trends. The extent of future climate change hinges significantly on the accumulation of greenhouse gas emissions, projecting scenarios from 4.7°–8.6°F (2.6°–4.8°C) under higher emissions to 0.5°–1.3°F (0.3°–1.7°C) under lower emissions by 2081–2100 [27].

In India, temperature trends indicate a rise of 0.4°C after every century and 0.25°C after every decade, with mean surface temperatures expected to increase by approximately 4.4°C by the century's end [31]. This temperature rise is anticipated to alter weather patterns and extremes, with increasing occurrences of hot temperature extremes and decreasing cold extremes across India's diverse climate zones. The Indian Summer Monsoon (ISM) is already undergoing changes due to climate change, leading to shifts in precipitation patterns characterized by increased probabilities of extreme dry and wet spells, impacting ecosystems and human systems through droughts, floods, and prolonged dry periods [32].

There have been escalating temperatures, heat waves, droughts, floods, and rising sea levels as reported by the Indian Meteorology Department and the Indian Institute of Tropical Meteorology, Pune in 2022. In 2022, the average land surface air temperature was +0.51°C above the 1981-2010 average, marking it as the fifth warmest year recorded since 1901. The warmest years, listed from highest to lowest temperatures, include 2016 (+0.71°C), 2009 (+0.55°C), 2017 (+0.541°C), 2010 (+0.539°C), and 2022 (+0.51°C). Remarkably, 11 of the 15 warmest years occurred in the past fifteen years (2008-2022). As per the IPCC (2014), projections from the PRECIS regional climate model indicate significant changes in rainfall and temperature patterns. During the mid-century period (2021–2050), average temperatures are forecasted to increase by 1.4 to 2.3°C, with projections indicating a rise of 3.0 to 6.0°C by the end of the century (2071–2098). By the end of the 21st century, most states in India, except coastal regions, are anticipated to see temperature rises of 4°C to 5°C. Year 2013 to 2022 was recorded as the warmest on record, with a decadal averaged annual mean temperature anomaly of 0.41°C compared to the long-term average [33]. These trends emphasize the urgent requirement for well-informed policy development and adaptation strategies to address the anticipated effects of climate change on water resources and agriculture in India [14, 34].

In conclusion, the overwhelming evidence from numerous indicators, including rising global temperatures, declining groundwater levels, droughts, variable rainfall patterns, floods, soil erosion, and the increasing frequency of extreme weather events, underscores the reality of climate change. These developments not only threaten agricultural productivity but also have profound implications for food security, livelihoods, and ecosystem stability. As these impacts continue to intensify, the urgency of implementing adaptive strategies and building resilience in agricultural systems becomes even more critical. Addressing the challenges posed by climate change will require concerted global efforts, with active participation from all sectors of society to ensure a sustainable and secure future [10].

The objective of this review is to enhance understanding of the impacts of climate change on agriculture and explore effective adaptation strategies that can help safeguard food security and strengthen the resilience of agricultural systems.

METHODOLOGY

This review paper follows a systematic approach to examining the impacts of climate change on agriculture and evaluating adaptation strategies. The methodology encompasses the identification, selection, and analysis of relevant studies, data, and reports to provide a comprehensive synthesis of current knowledge in this field. A comprehensive literature search was conducted using academic databases such as Google Scholar, Scopus, and Web of Science. Key search terms included "climate change impacts on agriculture," "adaptation strategies in agriculture," "climate-resilient agriculture," "global warming and crop yields," and "climate change mitigation in agriculture." Studies published from 2010 to 2023 were prioritized, with a focus on peer-reviewed journal articles, reports from international organizations (e.g., IPCC, FAO), and government publications. The selected studies cover diverse regions, climate scenarios, and agricultural systems to ensure the inclusion of a broad spectrum of experiences and insights.

RESULTS AND DISCUSSION

Climate Change and the Vulnerability of Agriculture: Global Scenario

The agricultural sector, crucial for advancing the United Nations Sustainable Development Goals (SDGs) like ending hunger and ensuring food security for the anticipated global population of 9.7 billion by 2050 [35, 36]. faces significant vulnerability to climate change. More frequent extreme weather events, shifts in precipitation patterns, and escalating temperatures are increasingly detrimental to crop yields and food security [37]. Over 475 million farms worldwide are smaller than two hectares, with small-scale farmers particularly vulnerable due to their reliance on natural resources and susceptibility to extreme weather events [38]. Agricultural system face significant challenges from climate change and variability, affecting both biophysical conditions such as land and water resources, crop and livestock productivity, and socio-economic factors including agricultural GDP, food security, and global trade [39]. Since the 1960s, global agricultural productivity growth has slowed by 21%, with tropical countries experiencing the most substantial impacts [40]. These climate-related risks complicate the achievement of sustainable development goals in agriculture [41].

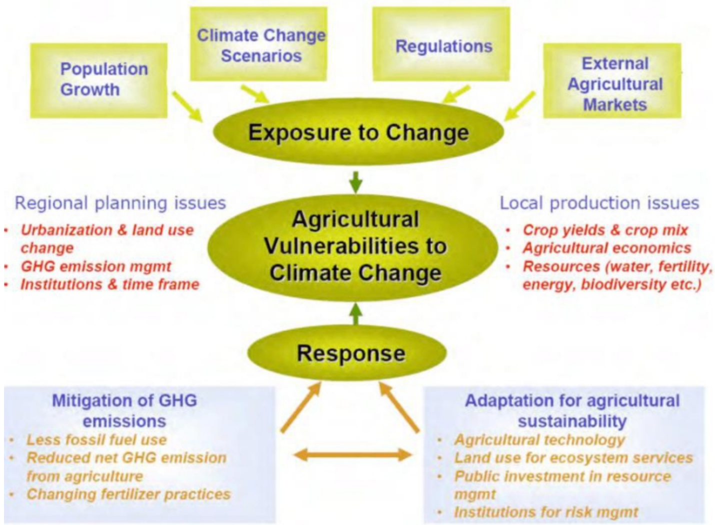

Fig. 3: Potential agricultural vulnerabilities from exposure to climate change

Climate impacts are also evident in regions across South America and Iran, prompting efforts to enhance resilience and reduce vulnerabilities among farmers [42, 43]. Similarly, Pakistan is developing adaptive strategies to address challenges posed by changing rainfall patterns, rising temperatures, and limited climate change mitigation technologies [44]. India has witnessed significant agricultural growth since independence, contributing to diversified production and resilience in the sector [45]. Food grain production has increased from 51 million tonnes (MT) in 1950-51 to 303.62 MT in 2022-23 [46]. India's food grain production has been critical in meeting food security needs amid population growth. Rain-fed agriculture, covering about 40% of India's total food production, is crucial for cultivating crops like pulses, coarse cereals, and oilseeds [47]. Although the agriculture sector has economic significance and contributes around 18.6% to GDP and employs about 45.76% of the population—India's agriculture remains highly vulnerable to climate change due to limited resources for mitigation and adaptation [48].

India as highly vulnerable to climate change impacts on food security, characterized by rising temperatures, shifting rainfall patterns, and an uptick in extreme weather events [10]. Ranked among the most affected by climate change in the Global Climate Risk Index, India faces significant risks to food security from climate-induced disruptions [49]. With India anticipated to have a population of 1.64 billion by 2050, the demand for food is set to rise sharply, requiring substantial increases in agricultural production amid environmental considerations [35]. Most Indian farmers are smallholders or marginal farmers, magnifying agriculture's susceptibility to climate change which highlights the urgent need for sustainable practices to ensure food security and livelihoods [45, 50]. Intensified climate variability in India's ecologically fragile and economically underdeveloped regions, compounded by shifting rainfall patterns, poses significant challenges to rain-fed agriculture [51]. Without effective adaptation measures, climate change could lead to 10 to 40% decline in India's agricultural productivity by 2100 which necessitates urgent strategies to enhance resilience [52]. The adoption of heat-tolerant crops, smart agricultural practices, and innovative technologies is critical for mitigating climate risks and safeguarding agricultural systems against future uncertainties [53].

Table 2: Climate Change's Effect on Crop Production

Parameters	Impact	References
Increase in temperature	• Reduced crop yields • Increased evapotranspiration • Higher crop • Respiration rates, • Rapid mineralization of nutrients, • Decreased nutrient use efficiency • Increased pest and disease outbreaks	[54, 55].
Heat waves and Heat extremities	• Higher plant mortality • Reduced Photosynthesis • Impaired Reproductive Development • Slower growth rates • Increased leaf abscission • Photooxidative stress • Reduced pollen viability	[56, 57].
Increased or reduced rainfall	• Decreased soil fertility and productivity	[58]
Heat and water stresses	• Weaken the plant defense system • Affecting the fertilizer supply, pathogens, and pests • Distrurb hormonal functions	[59, 60]
Change in precipitation	• Reduced crop growth and yields • Reduced leaf area • Impaired photosynthesis	[61]

Climate Change's Influence on Agricultural Productivity

Numerous studies, both in India and globally, have underscored the harmful impacts of climate change on agricultural productivity. They reveal that climate change diminishes the yield and economic value of staple and non-staple crops. Various empirical and descriptive studies offer compelling evidence of climate change's detrimental effects on agricultural productivity in India and elsewhere. The following sections detail the impact of climate change on different crop types:

Impact on Cereal Crops

Maize, wheat, and rice constitute the predominant food crops worldwide, collectively accounting for around 90% of global cereal crop production. Climate change significantly impacts the yield of these cereal crops, including wheat, maize, and barley, across various regions. Studies from Afghanistan [20], India [62], and Pakistan [63] have highlighted the negative effects of rising temperatures, reporting substantial yield reductions and decreased crop productivity. Global maize and wheat yields have declined by 3–12% and 3–9%, respectively, for every 1°C increase in temperature. The impact of climate warming on yield losses is more severe in tropical regions, with tropical maize and wheat experiencing a 5–12% reduction per degree of warming, compared to less than 5% in temperate regions [64]. Numerous studies have projected a loss of 10–40% in crop production in India by the end of the 21st century, and for every 1°C rise in temperature, yields of mustard and groundnut are expected to decrease by 3–7% [52]. Singh [65] suggest that wheat yields on plains farms could decline by 10.11%, whereas yields in hilly farms may increase by 6.70% by the year 2100. Additionally, paddy crop production is expected to decline by 15.04% in plains farms and 12.83% in hilly farms by the end of the 21st century. Projected results suggest that food-grain production may decline by 5.25%, 6.64%, 8.03% and 9.57% by 2040, 2060, 2080, and 2100, respectively [66]. In India, Rao *et al.* [67] highlighted that rice, wheat, and maize yields could decrease by 6-10% by 2030 due to climate-induced temperature and precipitation changes. Auffhammer *et al.* [68] examined how climate change affects monsoon patterns and rice yields in India, projecting that rice yields could decline by 10-15% by 2050 due to more intense and erratic monsoon rainfall coupled with higher temperatures. The details of the studies conducted in India and abroad on cereal crops is given in Table 3.

Table 3: Effects of Climate Change on Food Grain Productivity

S. No.	Crop	Location	Methodology	Temperature variation	Yield Variation	References
1.	Rice	China	Longitudinal analysis (e.g., mixed-effects models)	Increase in temperature by 1.0°C	Decrease in 4-7%	[69]
2.	Rice	Philippines	Statistical analysis	Increase in temperature by 1.0°C	Decrease in 10% in irrigated and 15% in rainfed areas	[70]
3.	Rice	Bangladesh	Panel data estimation	Increase in temperature by 1°C	Decrease in 8-13%	[71]
4.	Rice	Japan	Statistical analysis	Increase in temperature by 1°C	Decrease in 8-13%	[72]
5.	Rice	India	Longitudinal study	Each 1.0°C increase in temperature during the growing season	Decrease in 12-17%	[73]
6.	Rice and Wheat	Vietnam	Field experiments	Increase in temperature by 1.0°C	Decrease in 9-14%	[74]
7.	Rice, Maize, Sorghum and Ragi	India	Prais-Winsten models with panel-corrected standard errors (PCSEs)	Increase in maximum temperature by 1.0°C	Decrease in 2.23%, 3.22%, 1.67% and 3.59%	[75]
8.	Rice, Maize, and Wheat	India	Fixed-effects panel data analysis	Increase in maximum temperature by 1.0°C	Decrease in rice yield by 2.5%, maize yield by 3.8%, and wheat yield by 2.1%	[76]
9.	Maize	Sub-Saharan Africa	Econometric analysis	Increase in 1°C temperature	Decrease in yield by 4.2%	[77]
10.	Maize	United States	Simulation modeling (DSSAT)	Increase in temperature by 1.0°C	Decrease in yield by 5-25%	[78]
11.	Sorghum	United States	Long-term field experiments	Increase in each 1°C temperature in growing season	Decrease in yield by 2.9% on average	[79]
12.	Wheat	Canada	Integrated assessment modelling (CMIP6 models)	Increase in 1.5°C temperature	Decrease in yield by 10-20%	[80]
13.	Wheat	Uttar Pradesh (India)	Long-term agricultural data analysis	Increase in 1.5°C temperature	reduction in wheat yields by 8-18%	[81]
14.	Wheat	Maharashtra(India)	Integrated assessment modeling and scenario analysis	Increase in temperature by 1.5°C	Decline in wheat yields by 15-25%	[82]
15.	Wheat and barley	Afghanistan	panel regression model	Increase in mean temperature by 1°C	Decrease 2.71 and 2.21q/ha	[20]
16.	Wheat, barley, gram, and rice crops	India	Prais-Winsten models with panel-corrected standard errors (PCSEs)	Increase in minimum temperature by 1.0°C	Decrease in 0.94%, 0.46%, 0.25%, and 0.63%	[75]
17.	Wheat and Barley	Australia	Statistical modeling (e.g., generalized additive models)	Increase in average temperature by 1.0°C during the growing season	Yield reductions of 5-10% for wheat and 8-12% for barley.	[83]
18.	Potato	Europe	Econometric analysis (e.g., fixed-effects models)	Each 1.0°C rise in growing season temperature	Decrease in yield by 6-8%	[84]
19.	Potato	Punjab (India)	Longitudinal study and statistical modeling	Each 1.0°C rise in growing season temperature	Reduction of 5-9% in potato yields,	[85]

a) Impact on Pulse Crops

Pulses are an essential source of vegetable protein, minerals, and vitamins. They significantly contribute to maintaining soil fertility by fixing atmospheric nitrogen [86]. Climate models predict that pulse production in South Asia could decrease by 15-30% by 2050 due to rising temperatures and altered precipitation patterns, posing a threat to regional food security [87]. India, the largest producer of pulses globally, accounts for 25% of the world's production.

The IPCC projects a 3-4°C temperature increase after 2050, with significant impacts on rainfed crops [88].
Studies from India and Tanzania have documented these negative impacts, showing that rising temperatures and rainfall variability threaten pulse crop productivity [89-91]. The predicted rise in global temperatures and CO_2 concentration poses a serious threat to pulse crops, especially those sensitive to heat stress, resulting in yield losses during critical growth stages [57] used simulation models to predict a 10-20% reduction in lentil yields by the end of the 21st century under high-emission scenarios, attributing this to increased heat stress and reduced growing periods. The details of the studies conducted in India and abroad on cereal crops is given in Table 4.

Table 4: Impact of Climate Change on Pulse Crop Productivity

S. No.	Crop	Location	Methodology	Temperature variation	Yield Variation	References
1. 12.	Lentil	Canada	Field experiments and statistical analysis	1°C rise in seasonal temperature	Decrease in 8-12%	[92]
2.	Lentil	Canada	Long-term observational study	Each 1.0°C rise in growing season temperature	Decrease in yield by 10-20%	[93]
3.	Chickpeas	Ethiopia	Longitudinal study and regression analysis	Each 1.0°C rise in seasonal temperature	Decrease in 5-9%	[94]
4.	Chickpea	Australia	Long-term field trials	Each 1.0°C rise in average temperature	Decrease in yield by 5-15%	[95]
5.	Chickpea	Haryana, Punjab, and Rajasthan (India)	Field experiments and statistical analysis	Each 1.0°C rise in seasonal temperature	Decrease in chickpea yields by 4.5%, 3.2%, and 2.9% in Haryana, Punjab, and Rajasthan	[96]
6.	Mash (Black Gram)	India	Field experiments and data analysis	Each 1.0°C rise in average temperature	Decrease in yield by 8-14%	[97]
8.	Pea	Australia	Simulation modeling (APSIM)	Increase in temperature of 1.5°C	Decrease in 10-18%	[98]
9.	Pigeonpea	Maharashtra (India)	Long-term agricultural data analysis	Each 1.0°C rise in growing season temperature	Decline of 2.1%	[99]

Building Resilience in Agriculture

With the effects of climate change on water resources and agriculture both now and in the future, adaptation is still necessary to build robust systems that can withstand these consequences and sustainably support economic development. Farmers are responding to shifting rainfall patterns and seasonal growing conditions by independently modifying local management strategies. For example, they are changing crop kinds, varying planting timings, and varying crop combinations [100]. A deliberate governmental decision to invest in certain measures targeted at improving the adaptive capacity of water and agricultural systems or communities is what is meant by planned adaptation activities. This include enhancing cattle breeds, creating resilient crop varieties and implementing effective irrigation systems [100].

In order to achieve sustainability and food security as well as to strike a balance between resource management and development, agricultural technological developments are essential [101]. Unmanned aerial vehicles (UAVs) and drones, in particular, have made remote sensing an indispensable tool for agricultural water management, especially when it comes to scheduling irrigation for smallholder and commercial sectors [102]. High-resolution drone photography and publicly available remote sensing data have made precision farming possible by allowing for precise mapping of wet and dry zones within farmed fields as well as precise calculation of crop water requirements. For variable watering schedules to be optimised, this information is necessary.

Real-time weather updates, rainfall forecasts, soil moisture data, and market information are increasingly being provided via social media platforms like Facebook, YouTube, and WhatsApp, as well as mobile applications like Mausam, Meghdoot, Kisan Suvidha, and AgriApp. According to Wolfert *et al.* [103], these technologies enable farmers to improve production, improve farm management techniques, and make well-informed judgements regarding market opportunities.

Several adaptation measures have been implemented to mitigate the impacts of climate change. Two primary strategies—introducing new heat-tolerant crop varieties and expanding irrigation infrastructure—have been adopted globally in major wheat-producing nations such as France, the United States, Pakistan, Germany, India, Canada, China, Russia, and Turkey. These adaptations should be customized according to each country's existing production capacities and yield objectives. Specifically, for Pakistan, China, and India, expanding irrigation coverage and adopting heat-tolerant crop varieties are recommended to meet future wheat production demands [104]. Diversifying crops is a significant adaptation strategy in agriculture, providing insurance against rainfall variability as different crops respond differently to environmental changes [105]. Adaptation is viewed as essential policy action to mitigate climate change's negative effects, as it protects livelihoods and ensures food security. Implementation of effective region-specific adaptation measures can result in a substantial increase in food production and enhancement of food security and increase agricultural productivity, even under adverse climate conditions [106]. The adaptation actions taken to address the climate change effort is given below:

Table 5: Adaptation Strategies for Food Grains

S. No.	Crop	Adaptation strategies	Reference
1.	Coconut	• Agronomic adaptations, encompassing soil moisture conservation, summer irrigation, drip irrigation, and strategic fertilizer application • Genetic adaptation strategies include the cultivation of enhanced local Tall cultivars and hybrids	[107]
2.	Wheat	• Growing improved varieties, alteration in time of sowing and harvesting date, conservation agriculture, improved nutrient and irrigation management, implementing deep ploughing with a chisel plough, laser land levelling (LLL), and applying potash	[108, 109]
3.	Maize	• Short-duration varieties, improving irrigation facilities and introducing alternative cultivars	[110]
4.	Rice	• Increased irrigation levels, cultivation of short-duration rice varieties, adjustments to planting and harvesting schedules, adoption of agroforestry practices, utilization of diverse crop varieties, and intercropping with crops such as jute and wheat • Integration of agroforestry practices and cultivation of non-rice crops alongside rice	[111, 112]
5.	Cereal crops	• Use of drought-tolerant crop varieties, diversification of crops, change of planting time • Mulching, intercropping with food security crops, and laser leveling of the fields	[113, 114]
6.	Pulses	• Addition of photo- and thermo-insensitiveness, Diversification, Fallow and conservation tillage, Maintaining adequate soil organic matter, Water harvesting and supplemental irrigation and Use of bio fertilizers	[115, 116]
7.	Millets	• Diversified cropping systems, conservation tillage, and water harvesting techniques, Maintaining adequate soil organic matter levels; Integration of biofertilizers and supplemental irrigation techniques	[117, 118]

Initiatives taken by the Government of India to address the climate effect These initiatives span various sectors and aim to mitigate the impacts of climate change while promoting sustainable development. Here are some of the key initiatives:

1. National Action Plan on Climate Change (NAPCC)
2. National Adaptation Fund for Climate Change (NAFCC)
3. Climate Smart Agriculture (CSA)
4. Zero Budget Natural Farming (ZBNF)
5. National Mission for Sustainable Agriculture (NMSA)
6. Paramparagat Krishi Vikas Yojana (PKVY)
7. Climate Services for Resilient Agriculture (CSRA)

Barriers to Climate Change Mitigation and Adaptation

Smallholder farmers dominate agriculture in many developing countries, including India. Access to finance has traditionally been a significant barrier to adopting improved technologies and practices [119, 120]. In regions such as South Africa, Zambia, and Zimbabwe, the availability of credit, extension services, and awareness plays a pivotal role in the effectiveness of adaptation strategies [121]. Understanding climate change and strategies for adaptation, access to financial resources and improved seeds, and availability of irrigation water are critical factors that facilitate successful adaptation efforts [122, 123] found that policy barriers significantly hinder farmers' adoption of various adaptation activities. These barriers include a lack of consideration for local contexts, shortage of land, inadequate climate information, lack of skills, shortage of labor, limited implementation capacity, and inadequate coordination. There are other critical obstacles namely technology, administrative and financial that are significantly hindering the adaptation needed to address climate change gradually. However, socio-economic, geographical, and meteorological conditions often pose barriers to effective adaptation efforts in developing countries [1, 10, 124-125]

By addressing these barriers and fostering collaboration among stakeholders, it is possible to enhance the resilience of agricultural systems and ensure sustainable adaptation to climate change.

Research conducted worldwide put forth the critical need for adaptive measures to mitigate the detrimental effects of climate change on agricultural productivity.

Key Players in Adaptation

Effective adaptation to climate change requires the collaboration and involvement of various stakeholders, including farmers, policymakers, NGOs, researchers, local groups, and businesses [126, 127]. Farmers play a crucial role in this collaborative effort, actively participating in planning, implementing, and innovating within their unique socio-economic, cultural, and ecological settings [128]. They possess valuable first-hand information on the effects of climate change and adaptation techniques, such as modifying planting schedules, diversifying crop varieties, and promoting soil conservation measures [113]. However, barriers like limited knowledge of adaptation strategies, high costs, and inadequate institutional support persist, highlighting the importance of understanding farmers' behaviors and experiences to inform effective policy-making and minimize maladaptation practices [126]. In order to address the vulnerability of the water and agriculture sectors and their contribution to sustainable development, planned adaptation will necessitate significant expenditures by farmers, the government, the private sector, and development partners. By integrating survey data, behavior modeling, and social network analysis, stakeholders can enhance decision-making processes, improve adaptive capacity, and address climate change risks at regional scales [129].

CONCLUSION

The world's food supply is in risk of not just being sustainable but also secure due to the wide-ranging and complex effects of climate change on agriculture. Precipitation patterns and rising temperatures have a major impact on crop yields and agricultural output. Major food crops suffering from the effects of rising temperatures, shifting precipitation patterns, and a rise in extreme weather events include maize, wheat, rice, and legumes.

These changes threaten to reduce agricultural productivity and increase vulnerability among small-scale farmers, who depend heavily on natural resources. Studies on pulse crops, including lentils, chickpeas, and peas, show how climate change leads to significant yield declines with a 1°C to 1.5°C rise in temperature, highlighting their vulnerability. For example, lentils in Canada experience a yield reduction of 8-20%, chickpeas in Ethiopia and Australia show declines of 5-15%, and pulses in India also face reductions of up to 14%. Food security emerges as a critical concern under climate change scenarios, particularly in regions like India, where variations in temperature and monsoon patterns can significantly affect crop quality and quantity. Agronomic practices such as improved irrigation, soil moisture conservation, and altered sowing times, alongside the cultivation of improved varieties, help manage climate variability. For wheat, conservation agriculture and deep ploughing are essential. In maize and rice, short-duration varieties, irrigation, and intercropping offer resilience. By investing in sustainable practices, fostering innovation, and enhancing adaptive capacities, global communities can secure food systems against future uncertainties, ensuring food security, livelihoods, and economic stability in a changing climate.

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CONFLICT OF INTEREST

All authors declare that they have no conflict of interest.

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