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Climate Change Impact on Crop Productivity and Environmentin India: A Literature Review

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ABSTRACT

One of the biggest environmental issues the world is currently experiencing is climate change, and India is particularly vulnerable due to its varied agro-climatic conditions and heavy reliance on climate-sensitive industries. Climate change has been associated with a range of documented impacts on agriculture, water resources, forests and biodiversity, human health, and coastal systems, as well as rising temperature trends. Evidence from existing studies indicates that agricultural productivity is among the most affected sectors, as a large proportion of the Indian population depends directly or indirectly on agriculture for livelihood and food security. Climate variability, combined with pressures such as rapid industrialization, urbanization, and economic growth, is placing increasing stress on India's already vulnerable natural and social systems. This review paper examines existing research on the effects of climate change on crop productivity and environmental systems in India. Drawing on peer-reviewed studies, government reports, and secondary data sources, the review summarizes major trends, regional differences, and key environmental impacts, while acknowledging that many reported relationships are associative rather than based on direct cause-and-effect evidence.

Keywords: Climate change, Crop productivity, Indian agriculture, Climate extremes, Monsoon variability, Foodgrain production, Environmental impacts

Introduction

Climate change is widely recognized as one of the most critical environmental challenges of the twenty-first century. Driven primarily by anthropogenic emissions of greenhouse gases through fossil fuel combustion, deforestation, and unsustainable land use, global temperatures have risen at unprecedented rates, leading to increasing climatic variability and instability worldwide. These changes have been widely documented to influence natural ecosystems, socio-economic systems, and agricultural productivity, particularly in countries where livelihoods are closely intertwined with climate-sensitive sectors. Agriculture is globally one of the most vulnerable sectors to climate change because crop development, yield formation, and phenological cycles are closely controlled by temperature, rainfall, and atmospheric conditions, as reported across multiple studies [1]. India represents one of the most climate-sensitive agricultural economies in the world due to its high dependence on monsoon rainfall, predominance of smallholder farmers, and marked variability across agro-climatic zones. Nearly half of India’s population relies directly or indirectly on agriculture for employment and income, making climatic fluctuations particularly consequential for food security and rural development outcomes. A significant proportion of cultivated land is rain-fed, meaning that variation in monsoon onset, duration, or spatial distribution is closely associated with changes in sowing decisions, crop growth, and eventual productivity [2]. Increasingly erratic monsoons—characterized by delayed onset, shorter rainy periods, and extreme rainfall events—have also been reported to disrupt traditional agricultural calendars across multiple states.

Rising temperatures constitute one of the most immediate climate stressors affecting crop productivity in India. Existing literature indicates that thermal stress during critical stages such as flowering and grain-filling is associated with yield reductions in staple crops like rice and wheat. National climate assessments suggest that an increase of up to 2 °C may potentially reduce rice yields by approximately 6% and wheat yields by about 5%, with sharper declines projected under more severe warming scenarios [3]. Such projected yield impacts have important implications for national food security, given India's population size and reliance on these cereals as dietary staples. The combined effects of temperature rise and rainfall variability are also linked to broader environmental stresses, including soil degradation, water scarcity, and increased evapotranspiration. Erratic precipitation and rising temperatures have been associated with nutrient depletion, loss of soil organic carbon, and heightened soil erosion in both semi-arid and humid regions. Water availability is becoming increasingly uncertain due to altered monsoon behavior, reduced groundwater recharge, and rising irrigation demand, intensifying competition among agricultural, domestic, and industrial sectors. Climate change has further been observed to create favorable conditions for increased pest and disease outbreaks, thereby compounding risks for farmers and ecosystems.

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Climate impacts vary significantly across India's diverse agro-climatic zones, with different regions demonstrating varying sensitivities to rising temperatures and rainfall variability. Studies indicate that projected warming and altered precipitation patterns may lead to substantial yield reductions in the Indo-Gangetic Plains under high-emission scenarios. In contrast, semi-arid regions are expected to face intensified water stress, declining soil moisture availability, and greater production instability. These spatial differences in climate responses highlight the importance of developing region-specific and context-sensitive adaptation strategies tailored to local agro-ecological conditions [4].

The socio-economic consequences of climate-induced changes in agricultural productivity are equally profound. Declining crop yields can reduce household incomes, aggravate rural poverty, and increase food insecurity, particularly among smallholder and resource-constrained farmers. Limited access to irrigation, financial capital, and climate-resilient technologies further increases vulnerability, often widening existing socio-economic inequalities. In this context, climate change emerges not only as an environmental issue but also as a significant developmental challenge that necessitates integrated mitigation and adaptation measures to safeguard rural livelihoods and national food security [5].

Given these interconnected challenges, a systematic synthesis of existing literature on the impacts of climate change on crop productivity and environmental systems in India is critical for informing effective policies and management strategies. Such an analysis is essential for strengthening agricultural resilience, ensuring sustainable natural resource use, and safeguarding food security in the face of a rapidly changing climate.

Methodology

This study adopts a structured literature review approach to examine the impacts of climate change on crop productivity and environmental systems in India. The review focuses on synthesizing existing scientific evidence, policy analyses, and institutional assessments rather than generating new experimental or causal findings. A comprehensive literature search was conducted using major academic databases, including Scopus, Web of Science, Google Scholar, and ScienceDirect. In addition, government reports, institutional publications, and policy documents from sources such as the Indian Council of Agricultural Research (ICAR), Ministry of Agriculture and Farmers Welfare, India Meteorological Department (IMD), Food and Agriculture Organization (FAO), and Intergovernmental Panel on Climate Change (IPCC) were reviewed to capture national-level trends and policy-relevant insights. The search strategy employed combinations of keywords such as "climate change," "Indian agriculture," "crop productivity," "monsoon variability," "climate extremes," "foodgrain production," "environmental impacts," and "climate adaptation." The review primarily covers literature published between 2000 and 2024, with particular emphasis on studies and datasets from 2014 to 2024 to align with recent climatic variability and production trends in India. Peer-reviewed journal articles were prioritized to ensure scientific rigor; however, relevant grey literature (including government assessments and institutional reports) was also included due to its importance in providing empirical data, regional assessments, and policy perspectives. Studies were included if they explicitly addressed climate–agriculture interactions, crop yield responses, environmental impacts, or adaptation strategies within the Indian context. Articles focusing on unrelated sectors or lacking relevance to climate impacts on agriculture were excluded.

In addition to literature synthesis, secondary data on foodgrain production and reported climate shocks were compiled from publicly available national datasets to provide contextual and descriptive insights into recent trends. These data were used solely for descriptive analysis, and any observed relationships are interpreted as associative patterns rather than causal relationships. The main limitation of this review lies in its reliance on secondary data and published studies, which may differ in regional coverage, methodologies, and underlying assumptions. The organized synthesis, However, the structured synthesis provides a comprehensive overview of current knowledge, regional variability, environmental implications, and research gaps related to climate change impacts on Indian agriculture.

1.Impact Of Climate Extreme on Crop Productivity and Indian Agriculture sector-

The Indian agricultural sector is a vital component of the national economy and rural livelihood system, supporting more than half of the country's population through direct and indirect employment in agriculture and allied climate-sensitive sectors such as forestry and fisheries. Indian agriculture, which is central to the nation's food security and rural livelihood systems, remains highly vulnerable due to its strong dependence on natural climatic conditions, particularly the southwest monsoon. Much of the cultivated area continues to remain under rain-fed conditions, making agricultural productivity highly sensitive to variations in the timing, intensity, and spatial distribution of rainfall. According to the Agricultural Statistics at a Glance, variability in the monsoon performance has been associated with adverse impacts on crop yields, particularly of rain-fed crops such as pulses and coarse cereals, thereby placing farmers at considerable production risk [6]. In addition to climatic exposure, the agriculture sector also faces persistent structural and economic challenges. Although agriculture provides a substantial share of employment, its contribution to national economic output has declined steadily over time. Recent official reports indicate that the share of agriculture and allied sectors in India’s gross domestic product has remained significantly lower than its employment share, highlighting an imbalance between livelihood dependence and economic returns [7].

This imbalance has contributed to heightened socio-economic sensitivity within the farming community, with the livelihoods of small and marginal farmers being increasingly constrained by limited landholdings, low income diversification, and rising input costs. When combined with high climatic exposure due to rain-fed agriculture, these structural constraints have increased the overall vulnerability of the sector to climate variability and extreme weather events, Existing studies suggest that such compounded vulnerabilities are closely linked to fluctuations in crop productivity, farm incomes, and long-term agricultural sustainability, rather than representing isolated climatic effects.

2.Decadal Production Trends of Major Foodgrains (2014–2024)-

India's The annual production has exhibited a sustained upward trend over the last decade, reflecting the combined effects of agricultural policy support, technological advancement, and adaptive responses to climatic variability. Table 1 presents the all-India Production of major foodgrains from 2014-15 to 2023-24, based on official statistics Published by the Ministry of Agriculture & Farmers welfare and related government agencies. The total amount of foodgrain increased from 252.03 million tonnes (MT) in 2014-15 to 332.30 MT in 2023–2024, representing a clear increase in overall food availability during this period, this growth can be linked to better farming practices, improved crop varieties, and supportive production conditions in some years. Rice and wheat production remained relatively stable relative-because of irrigation and improved cultivars, pulses and coarse cereals exhibited greater variability, reflecting their greater dependence on rainfall and weather conditions.

Table 1. All-India Production of Key Foodgrains (2014-15 to 2023-24) Million Tonnes -

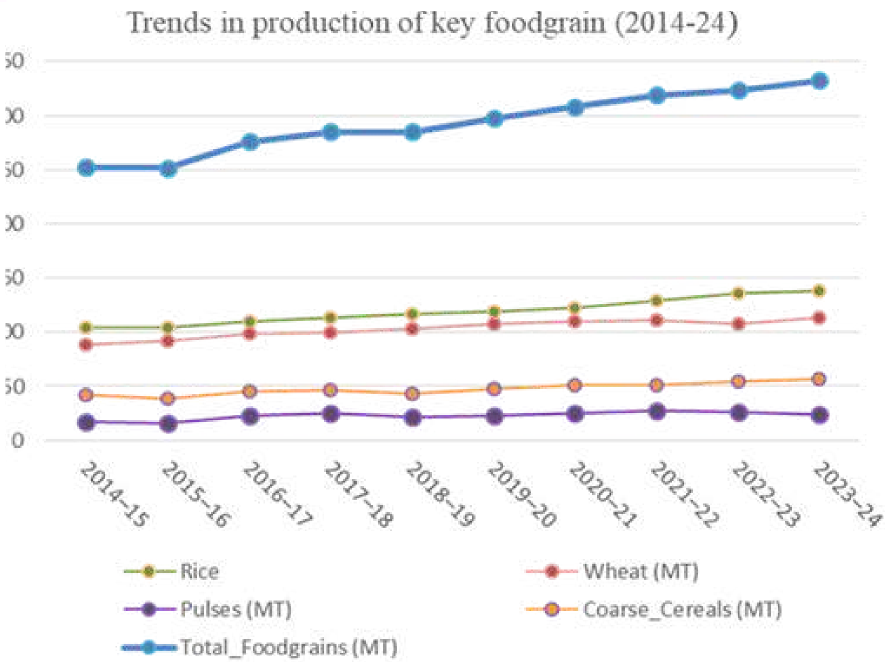
Crop Year	Rice	Wheat	Total Pulses	Total Nutri/Coar	Total Foodgrain
2014-15	104.8	88.94	17.19	41.75	252.03
2015-16	104.32	92.26	16.35	38.51	251.54
2016-17	109.67	98.66	23.13	43.83	275.11
2017-18	112.91	99.87	25.42	43.74	285.01
2018-19	116.48	103.6	22.08	43.06	285.21
2019-20	118.87	107.86	23.03	47.78	297.5
2020-21	124.37	109.59	25.72	51.32	310.74
2021-22	129.47	106.84	27.3	50.9	315.62
2022- 23	135.76	110.55	26.06	57.32	329.69
2023-24	137.83	113.29	24.25	56.94	332.3

Notes-

- All values are expressed in million tonnes (MT).
- Data for 2014–15 to 2021–22 are based on Fourth Advance Estimates of the Ministry of Agriculture & Farmers Welfare.
- Data for 2022–23 and 2023–24 are based on Final Estimates and were originally reported in lakh metric tonnes (LMT); these have been converted to MT for consistency (1 MT = 10 LMT).
- Nutri/coarse cereals include maize, jowar, bajra, ragi, and other minor millets.

sources-

Ministry of Agriculture & Farmers Welfare (MoA&FW); Press Information Bureau (PIB); Ministry of Finance (Economic Survey); USDA Foreign Agricultural Service; Indian Meteorological Department (IMD) [8,9,10].



This graphical representation facilitates a qualitative comparison between major climatic events and foodgrain production trends. For instance, the severe drought conditions reported in 2015 [6] coincide with a decline in total pulses production during 2015–16, reflecting the higher sensitivity of rain-fed pulses to rainfall deficits.

2.1 Climate Shocks and Crop Loss Analysis (2014–2024) - The agricultural sector in India experienced climate shock events between 2014-2024 including drought, heat waves, floods, cyclones, and irregular monsoon patterns. The rainfall deficit and drought condition reduced production of rain-fed crops such as pulses, and coarse cereals, while excess rainfall and flooding adversely affected rice growing regions. In recent years, Heat waves have emerged as a major constraint particularly impacting wheat productivity during the rabi season.

These repeated climate shocks have increased inter-annual variability in crop production and heightened the vulnerability of small and marginal farmers. The impacts indicate that irrigated and rain-fed farming systems respond differently to climate stresses, underlining the need for climate-resilient crop planning, improved water management, and adaptive agronomic practices to reduce future production risks [11].

Table 2. Climate Shocks and Crop Loss Analysis (2014–2024)

Year	Major climate event	States/Regions Affected	Crop impacted
2014-15	Rainfall deficit 12% below LPA (IMD)	UP, Bihar, Maharashtra	Pulses, Coarse cereals
2015–16	Strong El Nino+ severe drought (IMD,CSE)	Bundelkhand	Pulses, Jowar
2016–17	Normal monsoon recovery (IMD)	All-India	Pulses, Rice
2018	Kerala floods+ NE Floods (IMD, NDMA)	Kerala, Assam	Rice
2019	Monsoon 10% above LPA (IMD)	MP, Maharashtra	Maize, Soybean
2020	Cyclone Amphan (IMD)	West Bengal, Odisha	Rice
2021	Unseasonal rains during wheat	Punjab, Haryana	Wheat
2022	Record March-April heatwave (IMD,ICAR)	Panjab, Haryana UP,MP	Wheat
2023	Weak monsoon (94% of LPA) heatwaves (IMD)	East India, NW India	Rice, Maize
2024	Extreme heat (>280 heatwave days) +	All-India	Rice, Wheat, Pulses

sources-Compiled from reports of the India Meteorological Department (IMD) (2014–2024), the National Disaster Management Authority (NDMA), the Indian Council of Agricultural Research (ICAR), and the Centre for Science and Environment (CSE) [11].

2.2 Crop-Specific Yield Trends (2014–2022) -

Yield per hectare provides a more precise indicator of crop productivity response to climate conditions than total production alone. Accordingly, crop yield trends are analysed to assess medium-term productivity changes under varying climatic conditions rather than short-term production fluctuations.

Table 3.Yield Trends of Major Foodgrains (kg/ha) (2014–2022)

Crop	2014-15 yield	2021-22 yield	% change
Rice	2,391	2,713	13.50%
Wheat	2,750	3,464	26.00%
Pulses (total)	728	892	22.50%
Nutri/ coarse cereals	1,032	1,195	15.80%
Total food grains	2,183	2,478	13.50%

Source- Compiled from reports of the Directorate of Economics & Statistics (DES), Ministry of Agriculture & Farmers Welfare, Government of India, as reported in Agricultural Statistics at a Glance and the Fourth Advance Estimates for the agricultural years 2014–15 and 2021–22. Percentage change values were calculated by comparing yield levels between these two years [12].

3 Environmental consequences of climate change on crop production in India -

Climate change presents a critical and escalating threat to the long-term sustainability of India's agricultural system. Rising temperatures, unpredictable rainfall patterns, shifting crop phenology, and the increasing frequency of extreme weather events- such as heat waves, floods, and droughts are affecting the nation's diverse agro-ecological zones [13]. Soil degradation and intensive nitrogen inputs contribute to the release of major greenhouse gases, including CO_2, CH_4, and N_2O, which exacerbate global warming. Excessive fertilizer application and declining soil organic carbon stocks weaken soil carbon sequestration capacity, leading to cascading effects such as pest infestations, ecological imbalance, and biophysical feedback mechanisms that further intensify climate risks [14].

Environmental processes and climate change are closely interconnected. Variations in temperature and precipitation influence soil formation, structure, microbial activity, and nutrient cycling, ultimately reducing soil fertility and agricultural productivity. Prolonged dry spells and intense rainfall events accelerate nutrient leaching, erosion, and salinization, thereby degrading soil quality. Likewise, the hydrological cycle has become increasingly unstable, threatening both the quantity and quality of irrigation water vital to India's agrarian economy due to erratic monsoon behavior and declining groundwater recharge. Furthermore, the delicate balance of biodiversity within agricultural landscapes and surroundings is being disrupted. The loss of biodiversity reduces ecosystem resilience, making crops more susceptible to pest outbreaks and climatic extremes. Changing temperature and humidity regimes facilitate the emergence and spread of new pests and diseases, altering their life cycles and geographic ranges. Consequently, conventional pest control methods are becoming less effective, promoting greater dependence on chemical pesticides which further degrade soil and water systems and create reinforcing feedback loops that amplify overall vulnerability. In this cyclical relationship, degraded environments contribute to further climatic imbalance, intensifying the long-term risk to crop productivity and environmental stability [15].

3.1 Impact of climate change on soil fertility -

Soil fertility forms the foundation of agricultural productivity, yet it is among the most climate-sensitive components of the agro ecosystem. The physical, chemical, and biological characteristics of Indian soils have changed due to rising temperatures and erratic precipitation, particularly through reductions in soil organic carbon content. Increased temperatures accelerate organic matter decomposition, reduce soil carbon sequestration capacity, and adversely affect long-term soil fertility and agricultural sustainability. Consequently, declining land productivity raises concerns regarding the long-term viability of agricultural systems. Maintaining soil organic carbon through appropriate land-use and soil management practices is therefore critical for sustaining soil health under changing climate conditions [16]. In addition to gradual climatic shifts, the increasing frequency of extreme rainfall events and flooding in India has adversely affected agricultural systems. Recurrent flooding and prolonged waterlogging disrupt crop growth, damage standing crops, and reduce overall productivity in vulnerable regions. Such hydrological disturbances increase the risk of soil degradation and agricultural losses in flood-prone areas of the country [17].

Climate change also influences soil health by altering its biological, chemical, and physical properties. Key processes such as nitrogen fixation, carbon cycling, and organic matter decomposition are disrupted by rising temperatures, erratic precipitation patterns, and increased carbon dioxide levels. These changes modify soil microbial community composition and functional diversity, creating feedback mechanisms that increase climate variability, reduce nutrient availability and weaken soil fertility [18].

Regional studies conducted in flood-affected areas, including Assam, demonstrate significant crop productivity losses associated with declining soil fertility under climate stress conditions [19]. Additionally, soil erosion and land degradation processes reduce soil organic carbon stocks and weaken the soil's capacity to retain nutrients, thereby diminishing long-term soil fertility [20]. The loss of soil carbon not only affects productivity but also disrupts the global carbon cycle, further linking soil degradation with broader climate change processes.

3.2 Impact on water resources-

Climate change has disrupted India's hydrological systems, resulting in uneven water distribution across river basins. Unpredictable rainfall patterns have increased the frequency of both droughts and floods, leading to alterations in river flow regimes, while rising temperatures enhance evapotranspiration and reduce groundwater recharge. The retreat of Himalayan glaciers further threatens perennial water sources, intensifying pressure on irrigation and freshwater availability across the country [21].

Irregular monsoon rainfall and changing precipitation patterns contribute to seasonal water scarcity in many parts of India by affecting surface water availability and groundwater recharge [22]. According to the Central Ground Water Board (2022), several regions of the country are experiencing declining groundwater levels due to over-extraction and inadequate recharge. Climate variability further increases the frequency and intensity of drought conditions, which disrupt hydrological cycles and reduce water availability for agriculture [23]. Prolonged drought can lead to hydrological drought, characterized by reduced streamflow, groundwater depletion, and soil moisture stress, thereby intensifying agricultural vulnerability in drought-prone regions.

3.3 Impact on Biodiversity and Ecosystem Services -

Biodiversity plays a crucial role in maintaining ecosystem balance by supporting essential ecological processes such as pollination, pest regulation, and nutrient cycling. High levels of biodiversity enhance the capacity of agricultural and natural ecosystems to adapt to environmental changes and climate stressors by improving soil fertility, crop productivity, and overall ecosystem resilience [24]. The ecosystems of Northeast India, though biologically rich, are highly fragile and increasingly vulnerable to climate change. Altered rainfall patterns, rising temperatures, and the increased frequency of extreme weather events contribute to habitat loss, species displacement, and reduced ecosystem resilience. These changes pose significant risks to both biodiversity and the ecosystem services upon which local communities depend, highlighting the urgent need for ecosystem conservation and climate-adaptive management strategies [25]. Climate change also influences ecosystem functioning by altering soil microbial communities, which play a critical role in greenhouse gas regulation, carbon sequestration, and nutrient cycling. Changes in microbial composition and activity can disrupt these processes, weakening soil fertility, water regulation, and crop productivity. As key mediators of climate-ecosystem feedbacks, soil microorganisms are essential for sustaining biodiversity and ecosystem resilience under changing climatic conditions [26]. More broadly, Climate change acts as a major stressor for biodiversity by modifying habitats, increasing extreme weather events such as floods, droughts, and disrupting ecological interactions. The loss of species or shifts in their geographic distribution reduce the capacity of ecosystems to deliver the vital- services, including pollination, nutrient cycling, soil formation, water regulation, and carbon storage, thereby threatening both ecological stability and human well-being [27].

3.4 Impact on Pest and Disease Patterns

Climate change directly influences pest and disease dynamics in agricultural systems. Rising temperature facilitates the expansion of geographic ranges of many insect pests and accelerate their development, reproduction and survival rates [28]. As a result several economically important pest species have emerged or increased in prevalence in previously unaffected regions. For example, warmer climatic conditions have contributed to the spread and increased incidence of major crop pests such as Spodoptera litura and Helicoverpa armigera [29]. Globally, pests and diseases cause substantial crop yield losses across major food crops. Studies estimate average yield reductions of 21.5% (range 10.1–28.1%) for wheat, 30.0% (24.6– 40.9%) for rice, 22.5% (19.5– 41.1%) for maize, 17.25% (8.1–21.0%) for potatoes, and 21.4 % (11.0-32.4%) for soybeans [30]. Climate- induced pest outbreaks have also increased dependence on chemical pesticides, leading to secondary environmental consequences such as soil and water contamination, loss of beneficial insects, and disruption of ecosystem services.

Conventional pest management practices, particularly under changing climate conditions, may further exacerbate these challenges by reducing habitat complexity and weakening natural pest regulation mechanisms. Such practices can negatively affect biodiversity and ecosystem services, although knowledge gaps remain regarding their ecosystem-scale impacts. In contrast climate smart pest management (CSPM) aims to sustain these services by encouraging beneficial organisms, reducing chemical use, and promoting soil health [31].

3.5 Interactions between Soil, Water, changed and Biodiversity under climate-

Climate change strongly influences the interconnected dynamics of soil, water and biodiversity within agricultural systems. Declining soil fertility and reduced water availability often lead to decreased vegetation cover, which weakens soil structure and limits its capacity to store organic carbon. As soil organic carbon is lost, carbon previously sequestered in soils is released into the atmosphere as greenhouse gases, further intensifying global warming and creating a positive climate feedback loop [32]. Agricultural soils function as both sources and sinks of greenhouse gases, depending on land-use practices, soil degradation and land-use changes can enhance emissions of carbon dioxide, methane, and nitrous oxide. These emissions, in turn, negatively affect soil health, nutrient cycling, water regulation, and ecosystem service provision. Addressing these complex feedbacks requires integrated soil-water biodiversity management strategies aimed at improving soil carbon storage and reducing greenhouse gas emissions [33].

Building on these soil–climate feedback mechanisms, climate change also significantly influences soil–water interactions within agricultural systems. Alterations in temperature and precipitation patterns affect soil moisture availability, evapotranspiration rates, and groundwater recharge processes, thereby influencing crop productivity and ecosystem stability [34].

These interconnected interactions among soil degradation, water stress, biodiversity loss, and climate change show how climate related pressures can spread across agricultural system and reinforce one another. Understanding and addressing these connections are important for promoting climate resilient and sustainable agricultural practices [35].

4. Case Study: Climate Impacts in Maharashtra (Marathwada Region – Drought Stress)-

The Marathwada region of Maharashtra, one of the most drought-prone areas in India, has experienced severe and frequent water shortages, with prolonged dry spells and highly erratic and variable rainfall patterns that contribute to recurring drought conditions and agricultural stress [36]. As a result of increased evaporation caused by rising temperatures, soil moisture and groundwater levels have declined further) , exacerbating water scarcity in the region.

These climatic stresses have significantly affected the productivity of major food crops that depend on timely and adequate rainfall, including pulses, bajra (pearl millet), and jowar (sorghum). Studies indicate that rising temperatures and rainfall variability negatively influence crop yields across India, particularly in rainfed agricultural systems [37].

Prolonged water scarcity in drought-prone regions such as the Marathwada region can also contribute to soil degradation and declining land productivity, further threatening long-term agricultural sustainability. This case demonstrates how agricultural systems and farmer livelihoods in Maharashtra are increasingly vulnerable to climate variability and rising temperatures [36, 37].

5.Adaptation and Resilience Measures

Agricultural adaptation and mitigation cannot progress in isolation. Effective resilience-building in India calls for climate-resilient cropping systems, sustainable water and soil management, renewable-energy integration, and agro-ecological practices [38]. Recent assessments of Indian agriculture indicate that rising temperatures, increasing rainfall variability, and a greater frequency of extreme weather events are intensifying water stress and heat exposure across major cropping zones [39]. These projected climatic trends pose significant risks to agricultural productivity and long-term sustainability and are closely linked to broader climate change processes.

5.1. Adaptation Strategies (Drought-Resilient & Eco-Based Solutions) -

In response to these emerging challenges, the Indian Council of Agricultural Research (ICAR) implemented the National Innovations in Climate Resilient Agriculture (NICRA) initiative to enhance adaptive capacity at the local level. The program promotes location-specific technologies, climate-resilient crop varieties, improved water-use efficiency, and institutional capacity-building measures to strengthen farmers' resilience under changing climatic conditions [40].

•**Drought-tolerant and short-duration crops:** Climate adaptation strategies further integrate crop improvement with water-efficient management and institutional support mechanisms under national initiatives such as NICRA and the Pradhan Mantri Krishi Sinchayee Yojana (PMKSY) [41]. Promoting drought-resistant crops, particularly millets suited to arid and semi-arid regions due to their efficient water use and short growing cycles, reduces exposure to terminal heat stress and rainfall variability [42].

•**Water-use efficiency and micro-irrigation:** The diffusion of drip and sprinkler irrigation systems under the PMKSY "Per Drop – More Crop" initiative enhances water productivity and promotes efficient water management aligned with crop-specific requirements [43]. When combined with rainwater harvesting and on-farm storage structures, micro-irrigation reduces dependence on erratic rainfall and overexploited groundwater resources

•**Agroforestry and mixed-cropping:** Integrating trees and shrubs with crops through agroforestry moderates microclimates, enhances soil organic carbon, and improves water-holding capacity. These systems provide both adaptation benefits (shade, windbreak, moisture conservation) and multiple livelihood opportunities through fodder, fruit, and timber production [44].

• **Soil health and conservation agriculture:** Conservation tillage, cover crops, residue retention, and organic amendments improve soil structure and moisture retention, thereby reducing crop susceptibility to both drought and intense rainfall. NMSA emphasizes these integrated practices, particularly in rainfed regions, to stabilize agricultural production while conserving natural resources [45].

•**Implementation considerations-** Successful scaling of climate-resilient practices requires strengthened agricultural extension systems, improved access to localized climate information services, and increased public investment in climate adaptation strategies [46]. Farmer participatory breeding programs and targeted subsidies for micro-irrigation and agroforestry can further enhance adaptive capacity at the local level. While national programs provide proven technologies, persistent gaps remain in financing, training, and regionally tailored extension services to effectively reach smallholders [47].

6. Mitigation Strategies

Mitigation in the agricultural sector is critical because, while adaptation addresses vulnerability to climate impacts, mitigation targets the underlying contribution of agriculture to greenhouse gas (GHG) emissions and climate change. In India, the adoption of low-emission and carbon-sequestering agricultural practices provides multiple co-benefits, including enhanced productivity, resilience, and livelihood security. A major mitigation pathway involves reducing methane (CH_4) emissions from rice cultivation by transitioning from continuously flooded paddy fields to direct-seeded rice (DSR) or alternate wetting and drying (AWD) practices, which reduce anaerobic soil conditions and significantly lower methane emissions while also reducing irrigation water demand [48]. In the livestock sector, improving feed quality, promoting balanced ration formulation, and enhancing herd management practices can improve feed efficiency and contribute to lowering enteric methane emissions while sustaining productivity gains [49].

- **Soil carbon sequestration and agroforestry-** Soil carbon sequestration and agroforestry systems strengthen mitigation efforts by increasing carbon storage in above-ground biomass and soils, improving micro-climatic regulation, enhancing water retention, and diversifying farm income sources. Conservation agriculture practices such as minimal tillage, residue retention, and cover cropping further enhance soil organic carbon and function as carbon sinks in agricultural landscapes [50]. Reducing nitrogen-based emissions, particularly nitrous oxide (N_2O), through improved nutrient-use efficiency is also critical for lowering the emission intensity of agriculture. Practices such as precision fertilizer application, balanced nutrient management, and incorporation of organic amendments help maintain crop productivity while minimizing environmental impacts. In addition, enabling policy frameworks, institutional support, and economic incentives—including support for low-emission technologies and diversification away from water- and input-intensive rice–wheat systems toward millets, pulses, and oilseeds—are essential for advancing a low-carbon agricultural transition in the post-COP26 policy landscape [51].

7.Policy Framework Supporting Climate-Resilient Agriculture in India-

(i) National Action Plan on Climate Change (NAPCC) - Launched in 2008, the National Action Plan on Climate Change (NAPCC) serves as India's overarching framework to address climate change through eight core missions focusing on energy efficiency, sustainable agriculture, and green cover enhancement. It emphasizes a "co-benefit" approach —achieving economic growth while reducing greenhouse gas emissions. Under the NAPCC, the National Mission for Sustainable Agriculture (NMSA) directly addresses climate adaptation in farming systems by integrating productivity, resilience, and resource efficiency objectives [52].

(ii) National Mission for Sustainable Agriculture (NMSA) -

The NMSA promotes the adoption of climate-resilient agricultural practices such as integrated nutrient management, micro-irrigation, rainwater harvesting, and soil health restoration. Its sub-programs like the Rainfed Area Development (RAD) and Soil Health Management (SHM) help reduce vulnerability in drought-prone and semi-arid regions. The mission also encourages the adoption of drought-tolerant and stress resilient crop varieties to sustain productivity under temperature and rainfall extremes [53].

(iii) **National Initiative on Climate Resilient Agriculture (NICRA)** -Implemented by the Indian Council of Agricultural Research in 2011, focuses on strengthening research and on-field demonstration of climate-resilient technologies. The programme has been implemented across 100 climatically vulnerable districts of India and supports the development of weather-based agro-advisories, integrated farming systems, and water management strategies. NICRA also enhances farmers' adaptive capacity through technology demonstration and institutional capacity-building initiatives [54].

(iv) Renewable Energy Integration in Agriculture (PM-KUSUM) - The Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahabhiyan (PM-KUSUM), launched by the Ministry of New and Renewable Energy in 2019, promotes the installation of solar-powered irrigation pumps and decentralized solar power plants on barren or agricultural lands. The scheme aims to reduce dependence on diesel-based irrigation, lower input costs for farmers, and enable income generation through the sale of surplus electricity to the grid. The initiative contributes to India's broader renewable energy expansion strategy [55].

(v)Institutional Coordination and Financial Mechanisms- Effective climate governance in Indian agriculture requires strong financial mechanisms and institutional coordination. The National Bank for Agriculture and Rural Development supports climate-resilient agriculture through dedicated funding windows, green financing instruments, and credit support mechanisms that enable farmers and rural institutions to adopt adaptive and low-emission technologies [56]. At the international level, technical and strategic support from the Food and Agriculture Organization and the World Bank has contributed to the promotion of climate-smart agriculture frameworks, investment planning, and capacity-building initiatives in India. These collaborations strengthen institutional capacity, improve access to climate finance, and support the integration of resilience-oriented practices into agricultural development strategies [57].

(vi) Challenges and Future Outlook -

Despite significant policy progress, several challenges persist. These include limited farmer awareness, fragmented climate and agricultural data systems, uneven institutional capacity across states, and inadequate last-mile extension services. Climate advisories often do not reach smallholder farmers in a timely and usable form, limiting effective adoption of adaptive practices. Strengthening digital extension systems and integrating climate information into agricultural planning are therefore critical for improving resilience outcomes [58].

8.Recommendations and Conclusion -

Recommendations -

(i) Enhance Climate-Resilient Crop Research: Greater investment in the development of drought-, flood-, and heat-tolerant crop varieties is essential for long-term adaptation. Strengthening national and state-level agricultural research systems, along with expanding participatory breeding and farmer-led trials, can improve local suitability and accelerate adoption among smallholder farmers.

(ii) Promote Nature-Based Solutions: Agroforestry, mixed cropping systems, conservation agriculture, and soil carbon restoration should be integrated into mainstream farming practices to improve ecosystem stability and farm incomes. Incentive-based mechanisms, such as ecosystem service payments and carbon-linked benefits, can further support sustainable land management.

(iii) Strengthen Institutional Coordination: Improved coordination among ministries, research institutions, extension services, and financial agencies is critical for effective policy implementation. Enhancing climate finance access and strengthening grassroots extension networks can ensure equitable and efficient delivery of adaptation measures**.**

(iv) Leverage Digital and Renewable Technologies: Scaling renewable energy solutions, particularly solar-powered irrigation, alongside mobile-based climate advisory services can promote low-emission and data-driven agricultural decision-making. Integrating localized weather forecasting with digital platforms will further reduce climate-related production risks.

Conclusion -

Climate resilience in Indian agriculture requires combining modern technology, traditional knowledge, and strong policy support. As highlighted in India's Long-Term Low Emissions Development Strategy (NITI Aayog, 2023), agricultural growth must align with climate adaptation and low-emission development pathways. This involves promoting climate-smart farming practices, efficient water and soil management, crop diversification, and greater use of renewable energy such as solar irrigation. Strengthening research–policy coordination and ensuring that benefits reach small and marginal farmers are equally important. With a community-based, inclusive, and data-driven approach, Indian agriculture can enhance food security and serve as a sustainable model for other climate-vulnerable regions in the Global South [59].

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