



Climate-Smart Agriculture in India: Strategies, Challenges and Future Directions

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Abstract— Agriculture is intrinsically linked to climate variability, and India, with its vast agrarian base and climate-sensitive agricultural practices depending mostly on seasonal rains, is among the most vulnerable countries globally. Rising temperatures, shifting rainfall patterns, increased frequency of extreme weather fluctuations, and soil and groundwater depletion pose serious threats to agricultural productivity, farmer livelihoods, and national food security. Climate-Smart Agriculture (CSA) has emerged as an integrated approach to simultaneously address these complex challenges by enhancing productivity, building resilience, and mitigating greenhouse gas emissions wherever feasible. In India, CSA involves a combination of traditional knowledge and modern scientific innovations tailored to the diverse agro-climatic regions. Practices such as conservation agriculture, agroforestry, climate-resilient crop varieties, integrated farming systems, and efficient water management techniques are gaining increasing popularity. Initiatives like the National Innovations on Climate Resilient Agriculture (NICRA), the National Mission for Sustainable Agriculture (NMSA), and state-led programs underscore India's strategic focus on climate-resilient farming. However, despite proactive policies, the transition towards CSA faces significant hurdles. Socio-economic constraints, small landholdings, limited access to finance, technological gaps, and gender disparities continue to impede widespread adoption, particularly among smallholder and marginal farmers who form the backbone of Indian agriculture. A concerted effort across government, academia, private sector, and farming communities will be pivotal to realizing the full potential of Climate-Smart Agriculture in India.

Keywords— Climate-Smart Agriculture, climate resilience, sustainable agriculture, India, food security, adaptation, mitigation.

I. INTRODUCTION

Agriculture is the backbone of the Indian economy, employing more than 40% of the country's workforce and contributing around 18% to its GDP (Ministry of Agriculture & Farmers Welfare, 2023). Despite its critical importance, Indian agriculture remains highly vulnerable to climatic vagaries. The majority of farming in India is rainfed, depending on seasonal monsoons, making it susceptible to monsoon irregularities, droughts, floods, and other extreme weather events exacerbated by climate change. According to the Intergovernmental Panel on Climate Change (IPCC, 2022), South Asia, particularly India, is already experiencing temperature rises higher than the global average, leading to significant agrarian distress.

Historically, Indian farmers have demonstrated remarkable resilience and adaptive capacity. However, the current pace and magnitude of climatic changes, coupled with socio-economic pressures such as land fragmentation, resource degradation, groundwater depletion, and market volatility, necessitate a more structured and forward-looking approach. In this context, Climate-Smart Agriculture (CSA) provides a holistic framework that addresses the intertwined challenges of productivity, adaptation, and mitigation.

The Food and Agriculture Organization (FAO, 2013) defines Climate-Smart Agriculture as "agriculture that sustainably increases productivity, enhances resilience (adaptation), reduces/removes greenhouse gases (mitigation) where possible, and enhances achievement of national food security and development goals." This multi-pronged approach is particularly relevant

for India, where achieving food security for a population projected to reach 1.5 billion by 2030 must be balanced with environmental sustainability.

Recognizing the critical role of agriculture in climate change adaptation and mitigation, the Government of India has mainstreamed climate-resilient agriculture within its broader development agenda. Key initiatives include the National Action Plan on Climate Change (NAPCC, 2008) and its sub-mission, the National Mission for Sustainable Agriculture (NMSA), which focuses explicitly on promoting climate-adaptive farming practices. Complementing national efforts are numerous state-level schemes, private sector innovations, and community-driven adaptations that showcase India's diverse and dynamic responses to climate risk in agriculture.

Moreover, India's Intended Nationally Determined Contribution (INDC) under the Paris Agreement highlights sustainable agriculture as a priority for achieving climate goals. Innovations such as drought-tolerant crop varieties, zero-tillage practices, micro-irrigation technologies, innovative water harvesting technologies, and integrated farming systems are gaining prominence across agro-climatic regions.

However, the transition toward Climate-Smart Agriculture is neither automatic nor uniform across India's vast heterogeneous landscape and micro-economics of the region. Barriers such as knowledge dissemination gaps, lack of access to finance, socio-economic inequalities, and infrastructural constraints limit the widespread adoption of CSA practices. Further, smallholder farmers, who constitute about 85% of India's farming community, often lack the resources to independently invest in climate-resilient technologies.

Against this backdrop, this article aims to synthesize current knowledge on CSA from an Indian perspective, analyzing its principles, practices, policy frameworks, barriers, success stories, and future directions. By doing so, it seeks to provide actionable insights for researchers, policymakers, practitioners, and farmers in building a climate-resilient agricultural sector that is productive, equitable, and sustainable.

II. PRINCIPLES AND PILLARS OF CLIMATE-SMART AGRICULTURE

Climate-Smart Agriculture (CSA) rests on three foundational pillars:

1. Sustainably increasing agricultural productivity and incomes
2. Adapting and building resilience to climate change
3. Reducing or removing greenhouse gas emissions wherever possible (FAO, 2013)

These pillars provide an integrated framework to transform and reorient agricultural systems to effectively support development and ensure food security under a changing climate (Lipper et al., 2014). In India, operationalizing these pillars involves a complex balancing act between traditional farming practices, emerging technological innovations, socio-economic realities, and environmental sustainability imperatives.

2.1 Sustainable Productivity Enhancement

Ensuring higher agricultural productivity remains a key national objective in India, given the dependence of over 40% of the population on agriculture for their livelihood (Ministry of Agriculture & Farmers Welfare, 2023). CSA promotes sustainable intensification techniques that improve yield without degrading natural resources.

Important Indian examples include:

- **System of Rice Intensification (SRI):** Adoption of SRI in Tamil Nadu and Odisha has shown 25–50% yield increases while using 30–40% less water.
- **Precision Nutrient Management:** The Soil Health Card Scheme and site-specific nutrient management have improved fertilizer use efficiency across states like Punjab and Madhya Pradesh.
- **Stress-tolerant Crop Varieties:** Drought- and flood-tolerant rice varieties (e.g., Swarna-Sub1, Sahbhagi Dhan) released by ICAR have been widely adopted in Eastern India.

India's agro-climatic diversity demands localized climate-smart agricultural interventions. Various states have pioneered context-specific strategies to address climate vulnerabilities while enhancing agricultural productivity and sustainability. **Table**

1 presents a concise overview of key CSA practices adopted across different Indian states, illustrating the rich tapestry of innovations suited to diverse agro-ecological zones.

TABLE 1
CLIMATE-SMART AGRICULTURE PRACTICES IN DIFFERENT STATES OF INDIA

State	Climate-Smart Practice	Description	Impact/Outcome
Punjab	Zero Tillage (ZT)	Adoption of zero tillage to conserve soil moisture and reduce fuel consumption	Reduced water usage, enhanced soil health, and increased crop yield
Rajasthan	Micro-irrigation (Drip & Sprinkler Systems)	Use of micro-irrigation systems to enhance water use efficiency	Better water management, increased crop productivity in arid areas
Uttarakhand	Agroforestry and Multicropping	Integrating trees with crops to enhance biodiversity and soil health	Improved resilience to landslides and enhanced soil fertility
Madhya Pradesh	Conservation Agriculture (CA)	Practices like mulching, crop rotation, and minimum tillage	Improved water retention and soil structure
Tamil Nadu	Integrated Pest Management (IPM)	Managing pests with biological, physical, and cultural control methods	Reduced pesticide use and increased pest control efficiency
Kerala	Organic Farming and Integrated Nutrient Management (INM)	Adoption of organic farming with proper nutrient management	Improved soil health, reduced chemical usage, and enhanced biodiversity
Andhra Pradesh	SRI (System of Rice Intensification)	Adoption of SRI method for rice cultivation to increase yield with less water	Higher yield per unit of water and improved water efficiency
Maharashtra	Water-Saving Techniques (Rainwater Harvesting)	Use of rainwater harvesting to conserve water for irrigation	Improved water availability during dry seasons and reduced water stress
West Bengal	Salinity Tolerant Crop Varieties	Growing rice and other crops resistant to salinity in coastal areas	Increased crop resilience in saline-prone coastal regions
Odisha	Climate-Resilient Crop Varieties and Early Warning Systems	Adoption of drought and flood-tolerant crop varieties with early warning systems	Reduced crop failure due to extreme weather events

These practices not only highlight the adaptability of Indian farmers but also the critical role of policy, research, and community-level interventions in scaling up CSA initiatives across the country.

2.2 Adaptation and Resilience Building

The second pillar of CSA focuses on enhancing the capacity of farming systems to cope with climate-related shocks and stresses. Adaptation measures in India involve:

- **Crop Diversification:** Shifting from water-intensive crops (e.g., paddy, sugarcane) to less water-demanding crops (e.g., millets, pulses) in states like Karnataka and Maharashtra
- **Agroforestry Systems:** Programs like the Sub-Mission on Agroforestry (SMAF) promote integrating trees on farms, improving microclimates, enhancing soil carbon, and providing alternative incomes
- **Climate-Smart Livestock Management:** Breed improvement programs and silvo-pastoral models in Rajasthan and Gujarat help livestock farmers adapt to changing temperatures and forage scarcity
- **Weather-based Crop Insurance:** The Pradhan Mantri Fasal Bima Yojana (PMFBY) enables financial adaptation by compensating for climate-induced crop losses

Community-based adaptation models such as participatory watershed management (e.g., Sukhomajri in Haryana) have demonstrated successful resilience outcomes by combining soil conservation, water harvesting, and sustainable agriculture.

2.3 Mitigation of Greenhouse Gas Emissions

Although India's per capita agricultural emissions are lower than global averages, its aggregate emissions are significant due to the large agricultural base. CSA encourages practices that mitigate emissions while maintaining productivity:

- **Zero Tillage and Conservation Agriculture:** Direct seeding of rice and zero tillage wheat in the Indo-Gangetic Plains reduces emissions from crop residue burning and lowers energy use
- **Alternate Wetting and Drying (AWD) in Rice Cultivation:** AWD reduces methane emissions by up to 30% compared to continuous flooding
- **Efficient Nitrogen Management:** Use of slow-release fertilizers like neem-coated urea minimizes nitrous oxide emissions
- **Renewable Energy in Agriculture:** Solar irrigation pumps, promoted under the PM-KUSUM scheme, help reduce dependence on diesel-based pumps

While mitigation is often a co-benefit of adaptation strategies in India, concerted efforts are needed to fully mainstream low-emission agricultural pathways.

2.4 Integrated Approach: Indian Perspective

Unlike siloed approaches, Indian CSA models increasingly adopt integrated farming system frameworks combining crops, livestock, fisheries, and agroforestry. This enhances resource recycling, risk-spreading, and sustainability. Climate-smart villages established under the NICRA project exemplify such integrated strategies.

Moreover, digital innovations—such as the use of mobile-based weather advisory services (e.g., Kisan Suvidha App) and climate information dissemination via farmer producer organizations (FPOs)—have accelerated knowledge transfer and decision-making support for climate-resilient farming.

In summary, India's CSA pathway aligns with global objectives but is uniquely characterized by diverse agro-climatic conditions, socio-economic constraints, and a rich heritage of traditional ecological knowledge.

III. CHALLENGES AND BARRIERS IN IMPLEMENTING CLIMATE-SMART AGRICULTURE IN INDIA

While Climate-Smart Agriculture (CSA) offers a promising approach to building resilience to climate change, its widespread adoption in India faces several challenges. These barriers include socio-economic constraints, inadequate infrastructure, limited access to resources, and institutional hurdles. Understanding these challenges is crucial for formulating effective strategies and policies to promote CSA across India.

3.1 Financial Constraints and Access to Credit

One of the primary barriers to the adoption of CSA practices in India is the financial constraint faced by smallholder farmers. Despite government schemes and subsidies, the initial investment required for many CSA practices, such as drip irrigation systems, greenhouses, and high-yielding seeds, is often beyond the reach of economically disadvantaged farmers. Furthermore, the lack of access to credit and financial services hinders farmers from investing in climate-resilient technologies. Financial institutions often perceive smallholder farmers as high-risk clients, and thus, credit availability for climate-smart farming practices remains limited.

3.2 Lack of Knowledge and Awareness

The adoption of CSA practices requires a substantial amount of knowledge about new technologies, best practices, and climate-related risks. In many rural areas of India, farmers are either unaware of or misinformed about CSA options. Traditional farming methods still dominate, and there is a significant knowledge gap regarding climate-resilient technologies and their potential benefits. Furthermore, the extension services, which provide crucial support in disseminating knowledge, are often inadequate or lack the necessary resources to effectively reach remote farming communities.

3.3 Inadequate Infrastructure

The success of CSA depends on the availability of proper infrastructure, including irrigation systems, storage facilities, and access to markets. In rural India, there is often a lack of basic infrastructure such as functional irrigation systems, cold storage, and transportation networks. This limits farmers' ability to efficiently implement climate-smart practices like water-efficient

irrigation and post-harvest management. Additionally, inadequate market access prevents farmers from benefiting economically from their climate-resilient practices, as they are unable to sell their produce at competitive prices.

3.4 Institutional and Policy Barriers

While the Indian government has introduced various policies and schemes to promote CSA, there are still several institutional barriers to effective implementation. One of the main issues is the lack of coordination between various government departments and agencies involved in agriculture, climate change, and rural development. This leads to fragmented efforts and inefficient resource utilization. Moreover, policy frameworks often fail to address the specific needs of smallholder farmers or do not adequately incorporate CSA practices into mainstream agricultural policies. Despite the availability of schemes such as the Pradhan Mantri Fasal Bima Yojana (PMFBY) and the National Adaptation Fund for Climate Change (NAFCC), the implementation of these policies often faces bureaucratic delays and inefficient delivery mechanisms.

3.5 Land Tenure Issues

In India, land tenure issues present a significant challenge for the adoption of CSA practices. Many farmers, especially those working in landless or sharecropping systems, lack the legal rights to the land they cultivate. This insecurity discourages them from making long-term investments in sustainable farming practices like agroforestry, soil conservation, and irrigation systems. Without guaranteed access to land, farmers are less likely to adopt CSA practices that require significant time and financial commitment.

3.6 Climate Change Uncertainty

India's agricultural systems are highly vulnerable to climate change, but the unpredictability of future climate scenarios adds another layer of uncertainty for farmers. The uncertainty about climate change patterns, such as erratic rainfall, delayed monsoons, and extreme weather events, makes it difficult for farmers to plan and implement appropriate CSA practices. This uncertainty also complicates the task of developing region-specific CSA strategies, as the varying climatic conditions across India require tailored approaches.

3.7 Social and Cultural Barriers

Social and cultural factors also play a significant role in the adoption of CSA. In many rural communities, there is resistance to change due to traditional farming practices and cultural norms. Farmers are often hesitant to adopt new technologies or practices due to unfamiliarity or skepticism about their effectiveness. Moreover, the gender divide in agriculture, where women farmers have limited access to resources and decision-making power, further hinders the adoption of CSA practices in certain regions.

3.8 Short-term Focus and Risk Aversion

Farmers in India often prioritize short-term gains over long-term sustainability due to the financial pressures they face, especially in the context of small and marginal farming. The short-term focus on immediate yields and economic survival means that many farmers are reluctant to invest in CSA practices that require long-term commitment and may not yield immediate benefits. Additionally, risk aversion due to the unpredictability of climate impacts and limited knowledge about the benefits of CSA further limits adoption.

IV. POLICY AND INSTITUTIONAL SUPPORT FOR CLIMATE-SMART AGRICULTURE IN INDIA

The successful adoption of Climate-Smart Agriculture (CSA) in India requires strong policy support and effective institutional frameworks that encourage farmers to adopt sustainable and climate-resilient agricultural practices. While India has made significant strides in this area, gaps remain in terms of integration, implementation, and coordination. This section outlines the existing policies, institutional support systems, and areas that require improvement to foster CSA in the country.

4.1 Existing Policies Supporting CSA

India has developed various policies aimed at addressing climate change and promoting sustainable agriculture. The National Action Plan on Climate Change (NAPCC), introduced in 2008, is the overarching framework that outlines the country's response to climate change, including strategies for agriculture. The NAPCC includes the National Mission for Sustainable Agriculture (NMSA), which aims to promote sustainable agricultural practices that are more resilient to climate change and improve productivity in a sustainable manner. Through the NMSA, the government promotes practices such as conservation agriculture, agroforestry, and organic farming.

In addition, the Pradhan Mantri Krishi Sinchayee Yojana (PMKSY), launched in 2015, is a flagship initiative aimed at improving irrigation facilities and water-use efficiency in agriculture, directly contributing to CSA by enhancing water availability and reducing dependency on rainfall. The National Adaptation Fund for Climate Change (NAFCC) was also established to provide financial assistance to states for implementing projects that promote climate resilience in agriculture, including CSA practices.

Another notable initiative is the Pradhan Mantri Fasal Bima Yojana (PMFBY), which provides crop insurance to farmers against climate-induced risks, such as floods, droughts, and hailstorms. This initiative helps reduce the financial vulnerability of farmers in the face of climate variability.

4.2 Institutional Mechanisms for CSA Implementation

Several government bodies are involved in the implementation of CSA practices at the national and state levels. The Ministry of Agriculture and Farmers' Welfare (MoA&FW) plays a pivotal role in designing and implementing agricultural policies, while the Ministry of Environment, Forest, and Climate Change (MoEFCC) oversees climate-related initiatives. Additionally, the Indian Council of Agricultural Research (ICAR) and its regional agricultural universities conduct research on climate-resilient agriculture and provide technical guidance to farmers.

The National Bank for Agriculture and Rural Development (NABARD) plays a crucial role in providing financial support for CSA projects, facilitating the implementation of climate-resilient practices in rural areas. State-level agriculture departments, along with extension services, assist in disseminating knowledge and promoting CSA practices in rural areas.

However, the effectiveness of these institutions has been limited by factors such as insufficient coordination, lack of resources, and slow implementation of climate adaptation programs. There is a need for a more integrated approach involving multi-stakeholder collaboration to address the challenges of CSA adoption.

4.3 Role of Private Sector and NGOs

In addition to government initiatives, the private sector and non-governmental organizations (NGOs) play a crucial role in promoting CSA in India. Several private companies are involved in the development and dissemination of climate-resilient technologies, including drought-resistant seeds, precision irrigation systems, and agro-chemicals tailored to climate-smart practices. These innovations have the potential to enhance the adoption of CSA, particularly in commercial farming systems.

NGOs have been instrumental in educating farmers about climate change and promoting CSA practices at the grassroots level. Many NGOs focus on capacity-building and awareness creation, helping farmers understand the risks posed by climate change and the benefits of CSA. Furthermore, NGOs often bridge the gap between farmers and government policies by assisting with the implementation of climate adaptation projects in rural areas.

4.4 Policy Gaps and Challenges

While the Indian government has introduced several policies that support CSA, there are still significant gaps that need to be addressed. One of the major challenges is the lack of integration between climate change policies and agricultural development programs. Climate-resilient practices are often implemented as standalone projects, without sufficient integration into broader agricultural policies or frameworks. This leads to fragmentation and inefficiencies in the delivery of CSA initiatives.

Moreover, while policies such as PMKSY and NMSA have made substantial contributions to climate adaptation, their reach is often limited to specific regions or sectors, leaving many vulnerable communities and farming systems unaddressed. There is also a lack of region-specific policy frameworks, as the diverse agro-climatic conditions across India necessitate tailored solutions for different areas. Additionally, delays in policy implementation and the lack of adequate funding for CSA projects hinder progress.

Another key issue is the insufficient attention to gender in agricultural policies. Women, who constitute a significant proportion of India's farming workforce, are often excluded from policy design and decision-making processes, limiting the effectiveness of CSA initiatives. Policies must ensure that women farmers have equal access to resources, training, and decision-making roles to facilitate CSA adoption.

4.5 Recommendations for Strengthening Policy and Institutional Support

To enhance the adoption of CSA in India, the following recommendations are proposed:

- **Policy Integration:** There is a need to integrate climate change considerations into mainstream agricultural policies to ensure that CSA is a core component of India's agricultural development agenda.
- **Regional and Sectoral Tailoring:** Policy frameworks should be tailored to the specific needs of different agro-climatic regions and farming systems to maximize their effectiveness.
- **Improved Financing Mechanisms:** Strengthening financing mechanisms such as NABARD and providing subsidies for CSA practices will help reduce financial barriers for farmers.
- **Capacity Building and Awareness:** There is a need for a comprehensive capacity-building program to educate farmers, extension agents, and local leaders on CSA practices and their benefits.
- **Gender Inclusion:** Policies must prioritize gender equality, ensuring that women farmers have equal access to CSA technologies and decision-making processes.
- **Multi-Stakeholder Collaboration:** A coordinated approach involving government agencies, private sector players, and NGOs is essential to scale up CSA practices across India.

V. CONCLUSION

Climate change poses an unprecedented threat to agriculture, jeopardizing food security, farmer livelihoods, and rural economies worldwide. In India, where over 50% of the population is directly or indirectly dependent on agriculture, the stakes are even higher. Climate-Smart Agriculture (CSA) emerges as a transformative approach that integrates adaptation, mitigation, and sustainable productivity enhancement to future-proof Indian agriculture against climatic shocks.

India's agro-ecological diversity demands context-specific solutions. The varied regional initiatives—from zero tillage in Punjab to agroforestry in Uttarakhand, rainwater harvesting in Maharashtra to saline-tolerant crops in West Bengal—showcase the capacity for local innovation and community-driven adaptation. These examples highlight that CSA is not a one-size-fits-all strategy but a dynamic framework requiring localized interventions backed by scientific research, policy support, and community participation.

A key realization from India's experience is that technological innovations alone are insufficient unless they are embedded within enabling socio-economic and institutional frameworks. Investments in rural infrastructure, farmer education, climate services (such as weather forecasting and advisories), and financial mechanisms like crop insurance and green credits are vital to mainstream CSA practices. Moreover, integrating traditional knowledge systems with modern technologies can offer synergistic benefits, especially in enhancing resilience in marginalized farming communities.

Importantly, CSA must be inclusive. Women, who form a significant proportion of the agricultural workforce in India, must be recognized not just as beneficiaries but as key agents of change. Similarly, smallholder and marginal farmers, who are disproportionately vulnerable to climate risks, must have access to CSA technologies, credit facilities, and capacity-building programs tailored to their needs.

On the policy front, India has demonstrated leadership through initiatives like the National Action Plan on Climate Change (NAPCC) and its National Mission for Sustainable Agriculture (NMSA), which emphasize climate resilience and sustainable agricultural practices. However, operationalizing CSA at scale will require further strengthening of policies, better convergence among ministries, and greater decentralization to empower local governance structures like Panchayati Raj Institutions.

Research and innovation ecosystems must also pivot towards CSA priorities. Public and private sectors need to collaborate on developing climate-resilient crops, resource-efficient farming systems, and smart extension services leveraging digital technologies. Linking farmers to markets, value chains, and climate-resilient agri-business models will be critical to incentivizing adoption at scale.

Finally, CSA implementation must be monitored with robust, science-based metrics that evaluate not just productivity but also resilience and carbon footprint reductions. Developing region-specific CSA indicators aligned with global frameworks like the FAO's CSA approach can help track progress effectively and enable corrective actions.

In conclusion, Climate-Smart Agriculture offers a promising pathway for India to achieve its food security goals while meeting its climate commitments under the Paris Agreement and Sustainable Development Goals (SDGs). A concerted, multi-stakeholder effort—involving farmers, scientists, policymakers, private sector actors, and civil society—is imperative to scale up CSA interventions. With its rich tradition of agricultural ingenuity and a growing policy emphasis on sustainability, India

is well-positioned to lead the global transition towards climate-resilient agriculture. Future efforts must prioritize inclusivity, regional specificity, and systemic integration of climate resilience across the agricultural value chain. If implemented thoughtfully and inclusively, CSA can transform Indian agriculture into a resilient, sustainable, and economically vibrant sector capable of withstanding the challenges of a changing climate.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this research paper.

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