



Climate-Smart Agriculture in India: Pathways to Resilient and Sustainable Agricultural Development

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Climate change is increasingly threatening agricultural sustainability in India through rising temperatures, erratic rainfall, extreme weather events, soil degradation, groundwater depletion, and biodiversity loss, underscoring the need for resilient farming systems. Climate-Smart Agriculture (CSA) offers an integrated approach that enhances productivity, strengthens climate resilience, and reduces greenhouse gas emissions while promoting sustainable resource management. This article synthesizes the principles, major practices, policy initiatives, benefits, and implementation challenges of CSA in the Indian context. It highlights key interventions, including conservation agriculture, climate-resilient crop varieties, precision farming, integrated farming systems, agroforestry, efficient water and nutrient management, carbon farming, and digital technologies such as artificial intelligence, remote sensing, GIS, drones, and the Internet of Things. The article also reviews major national initiatives supporting CSA and identifies barriers to adoption. It concludes that location-specific strategies, stronger policy support, climate finance, digital innovation, and multi-stakeholder collaboration are essential for scaling climate-smart agriculture and ensuring sustainable food security in India.

Keywords: Climate-Smart Agriculture (CSA), Climate Resilience, Sustainable Agriculture, Precision Agriculture, Food Security

Introduction

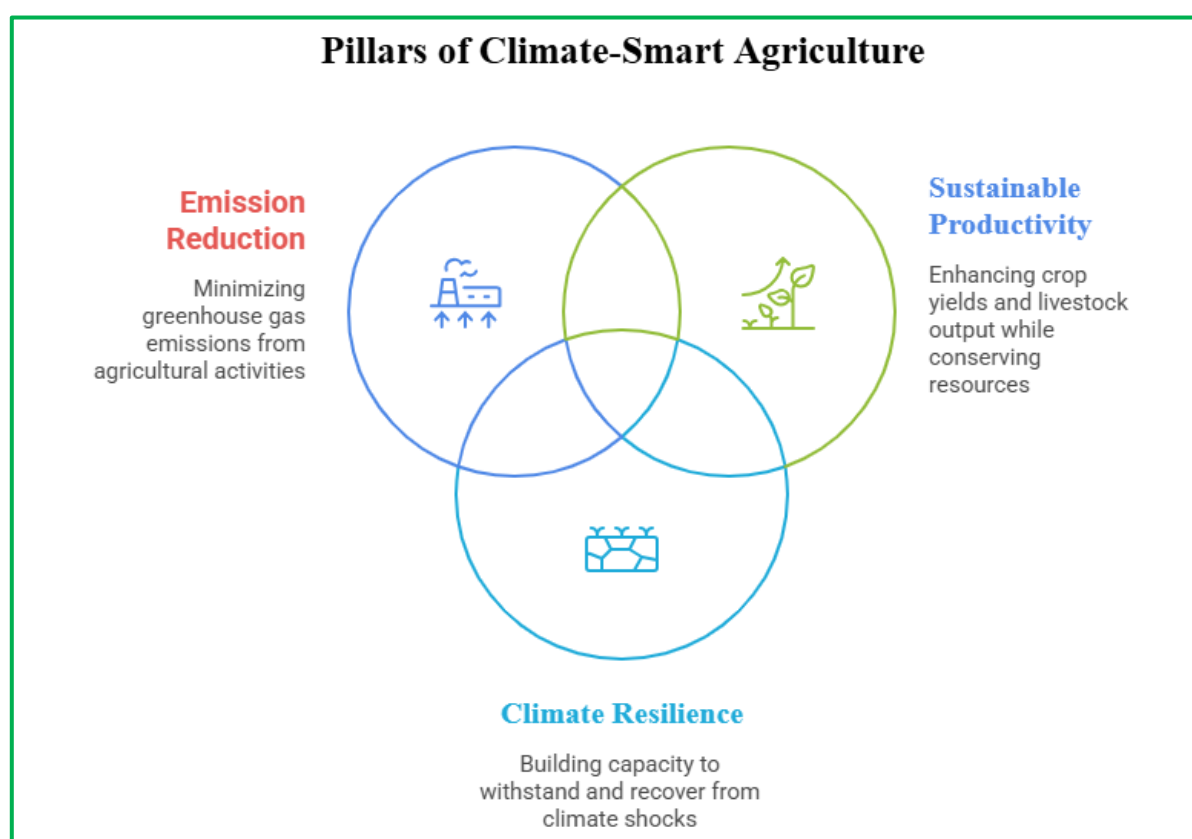
Agriculture forms the cornerstone of India's economy, livelihoods, and food security, supporting nearly half of the country's workforce while contributing significantly to national income and rural development. Beyond its economic importance, the agricultural sector plays a critical role in ensuring nutritional security, sustaining ecosystem services, and maintaining the socio-cultural fabric of rural communities (Lal et al., 2025). However, Indian agriculture is increasingly confronted with unprecedented challenges arising from climate change, natural resource degradation, and growing pressure to meet the food demands of a rapidly expanding population (Sarkar et al., 2023). Scientific evidence indicates that global temperatures have risen markedly since the pre-industrial era, leading to profound alterations in precipitation patterns, increasing frequency and intensity of droughts, floods, heat waves, cyclones, and other extreme weather events. These climatic disturbances have direct and indirect impacts on agricultural production by reducing water availability, accelerating soil degradation, increasing pest and disease outbreaks, and adversely affecting crop productivity and quality. Rising temperatures, erratic monsoons, groundwater depletion, declining soil

fertility, and biodiversity loss have collectively intensified production risks, thereby threatening farmers' livelihoods and national food security. Simultaneously, conventional agricultural practices characterized by intensive tillage, excessive dependence on chemical fertilizers and pesticides, continuous monocropping, residue burning, and inefficient irrigation have accelerated the depletion of soil organic matter, increased greenhouse gas (GHG) emissions, deteriorated soil health, and reduced the resilience of farming systems to climatic stresses (Sarkar et al., 2025a). Agriculture itself contributes substantially to anthropogenic greenhouse gas emissions through methane emissions from flooded rice cultivation, nitrous oxide emissions from nitrogen fertilizer application, and carbon dioxide emissions associated with land-use change and fossil fuel consumption. Consequently, there is an urgent need to transform agricultural systems from resource-intensive production models towards sustainable, resilient, and climate-responsive approaches that simultaneously enhance productivity, conserve natural resources, and contribute to climate change mitigation (Sarkar and Sarkar, 2025a). In this context, Climate-Smart Agriculture (CSA) has emerged as an integrated and holistic framework capable of addressing the interconnected challenges of food security, climate adaptation, and environmental sustainability (Begna and Wakweya, 2025). CSA is defined as an approach that sustainably increases agricultural productivity and farmers' incomes, strengthens resilience and adaptive capacity to climate change, reduces or removes greenhouse gas emissions wherever feasible, and supports the achievement of national food security and sustainable development goals (FAO, 2013). Unlike conventional agricultural intensification strategies that primarily focus on maximizing yields, Climate-Smart Agriculture seeks to optimize productivity while enhancing ecosystem functions, improving resource-use efficiency, conserving biodiversity, restoring soil health, and strengthening the adaptive capacity of farming communities. The approach recognizes that agricultural systems differ across agro-ecological regions and therefore advocates location-specific, knowledge-intensive, and science-based interventions tailored to local climatic, socio-economic, and environmental conditions. Climate-Smart Agriculture integrates a wide range of sustainable management practices, including conservation agriculture, precision nutrient management, efficient water management, climate-resilient crop varieties, integrated farming systems, agroforestry, crop diversification, integrated pest management, digital agriculture, and carbon-smart land management. These interventions not only improve farm productivity and profitability but also enhance soil organic carbon sequestration, improve water-use efficiency, reduce production risks, and lower greenhouse gas emissions, thereby contributing to both climate adaptation and mitigation objectives (Sarkar and Sarkar, 2025b). Recent advances in remote sensing, geographic information systems (GIS), artificial intelligence, Internet of Things (IoT)-based sensors, drones, precision agriculture, and digital monitoring, reporting, and verification (dMRV) systems have further strengthened the implementation and monitoring of Climate-Smart Agriculture by enabling data-driven decision-making, efficient resource management, and transparent assessment of environmental outcomes (Sarkar et al., 2026a). Moreover, the increasing emphasis on regenerative agriculture, ecosystem restoration, nature-based solutions, and carbon markets has expanded the scope of CSA beyond farm-level productivity towards long-term environmental sustainability and rural prosperity. In India, several government initiatives, including the National Mission for Sustainable Agriculture, National Innovations on Climate Resilient Agriculture, Pradhan Mantri Krishi Sinchayee Yojana, Soil Health Card Scheme, and Digital Agriculture Mission, have laid a strong institutional foundation for promoting climate-resilient farming practices. Nevertheless, large-scale adoption of CSA continues to face multiple constraints, including limited awareness, inadequate access to climate information, financial barriers, fragmented landholdings, insufficient extension services, technological limitations, and policy and institutional challenges. As climate change continues to reshape global agriculture, the adoption of Climate-Smart Agriculture offers a transformative pathway towards sustainable intensification, enhanced resilience, improved natural resource management, reduced environmental footprints, and greater economic

prosperity for Indian farmers. By integrating productivity enhancement with climate adaptation and mitigation, CSA provides a comprehensive framework for achieving food security, ecological sustainability, and resilient agricultural development while supporting India's commitments to the Sustainable Development Goals (SDGs) and the Paris Agreement on climate change.

Principles of Climate-Smart Agriculture

Climate-Smart Agriculture (CSA) is an integrated and systems-based approach to transforming agricultural systems in response to the interconnected challenges of climate change, food security, and sustainable development. Promoted by the Food and Agriculture Organization (FAO), CSA is guided by three interrelated principles, commonly referred to as the three pillars of Climate-Smart Agriculture: sustainable productivity and income enhancement, climate adaptation and resilience, and greenhouse gas mitigation (FAO, 2013). These principles provide a framework for identifying context-specific agricultural interventions that can generate synergies among productivity, adaptation, and mitigation while minimizing potential trade-offs.



Sustainable Enhancement of Agricultural Productivity and Incomes

The first principle aims to sustainably increase agricultural productivity and improve farmers' incomes without compromising the natural resource base. CSA emphasizes producing more with efficient and responsible use of land, water, nutrients, energy, and other biological resources. The focus is therefore not merely on maximizing yields but on achieving sustainable intensification while maintaining soil health, ecosystem functions, and long-term productive capacity. Practices such as conservation agriculture, integrated nutrient management, precision agriculture, crop diversification, improved and climate-resilient crop varieties, integrated pest management, and efficient irrigation can improve resource-use efficiency and farm profitability. This principle is particularly important in India, where increasing food demand, shrinking landholdings, and growing pressure on natural resources necessitate higher productivity from existing agricultural land.

Strengthening Adaptation and Resilience to Climate Change

The second principle focuses on strengthening the capacity of agricultural systems, farmers, and rural communities to anticipate, withstand, recover from, and adapt to climate-related stresses and long-term environmental changes. Climate-resilient agricultural systems seek to reduce vulnerability to droughts, floods, heat waves, salinity, water scarcity, and climate-induced pest and disease outbreaks while maintaining stable production and livelihoods. Key approaches include crop and livelihood diversification, adoption of drought-, flood-, heat-, and salinity-tolerant varieties, efficient water management, soil moisture conservation, agroforestry, conservation agriculture, rainwater harvesting, and climate-informed weather and agricultural advisory services. Strengthening resilience also requires improved access to climate information, agricultural knowledge, technology, finance, extension services, and supportive institutions.

Reducing or Removing Greenhouse Gas Emissions

The third principle aims to reduce or remove greenhouse gas (GHG) emissions from agricultural systems wherever feasible, while ensuring that mitigation efforts do not compromise food security, productivity, or farmers' livelihoods. Agriculture contributes to climate change through methane emissions from flooded rice cultivation, nitrous oxide emissions associated with nitrogen fertilizer use, and carbon dioxide emissions related to land-use change, energy consumption, and intensive agricultural operations. CSA promotes mitigation practices such as improved nutrient management, precision fertilizer application, conservation agriculture, residue management, agroforestry, improved livestock management, renewable energy use, and water-saving irrigation practices. For example, Alternate Wetting and Drying (AWD) in rice cultivation can reduce methane emissions while conserving irrigation water, demonstrating the potential for adaptation and mitigation synergies. Similarly, conservation agriculture and agroforestry can contribute to soil and biomass carbon sequestration while improving soil health and ecosystem resilience.

Together, these three principles form the foundation of Climate-Smart Agriculture. Their implementation requires context-specific, location-specific, and participatory approaches because the potential for productivity gains, climate adaptation, and GHG mitigation varies across agro-ecological and socio-economic conditions. Effective CSA therefore depends on integrating scientific and indigenous knowledge with appropriate technologies, climate information, farmer-oriented extension services, financial mechanisms, institutional support, and enabling policies. The goal is to develop agricultural systems that are productive, economically viable, climate-resilient, resource-efficient, and environmentally sustainable, thereby contributing to long-term food security and sustainable agricultural development.

Why India Needs Climate-Smart Agriculture

India's agricultural sector faces the dual challenge of meeting rising food and nutritional demands while sustaining natural resources under increasing climate uncertainty. Rising temperatures, erratic monsoon patterns, droughts, floods, heat stress, groundwater depletion, soil degradation, and biodiversity loss are intensifying risks to agricultural productivity and rural livelihoods. These vulnerabilities are compounded by fragmented landholdings, declining farm profitability, and the high dependence of smallholder farmers on climate-sensitive agricultural systems. Climate-Smart Agriculture (CSA) therefore offers an integrated pathway to simultaneously improve productivity, strengthen climate resilience, and reduce greenhouse gas (GHG) emissions. CSA is essential for strengthening climate resilience. Indian agriculture remains highly exposed to monsoon variability and extreme weather events, which can disrupt crop growth, reduce yields, and destabilize farm incomes. CSA practices such as climate-resilient crop varieties, diversified cropping systems, improved water management, conservation agriculture, agroforestry, and climate-informed advisory services can reduce production risks and enhance farmers' adaptive capacity. CSA is critical for conserving India's increasingly degraded natural resource base. Intensive tillage, imbalanced fertilizer use, residue burning, and inefficient irrigation have contributed to soil degradation, declining soil organic carbon, nutrient imbalance, and groundwater depletion.

Resource-efficient approaches, including integrated nutrient management, precision agriculture, residue retention, soil carbon enhancement, and efficient irrigation, can improve soil health and water-use efficiency while sustaining long-term productivity. CSA can contribute to both food security and climate change mitigation. Sustainable intensification, crop diversification, and improved resource management can increase productivity without further expanding pressure on land and water resources. At the same time, practices such as Alternate Wetting and Drying (AWD) in rice, improved nitrogen management, conservation agriculture, agroforestry, and soil carbon sequestration can reduce agricultural GHG emissions and enhance carbon storage. Thus, CSA represents a strategic pathway for India to reconcile food security, farmer prosperity, climate resilience, and environmental sustainability under a changing climate.

Climate smart agricultural practices

Climate-Smart Agricultural (CSA) practices comprise a range of interventions that aim to simultaneously enhance agricultural productivity, strengthen resilience to climate change, and reduce or remove greenhouse gas (GHG) emissions wherever feasible. Key CSA practices include conservation agriculture, efficient water and nutrient management, crop diversification, climate-resilient varieties, integrated farming systems, agroforestry, integrated pest management, precision agriculture, regenerative practices, and digital agriculture. Together, these approaches promote efficient resource use, soil and water conservation, ecosystem health, and sustainable agricultural development.

Conservation Agriculture and Soil Health Management

Conservation Agriculture (CA) is a key component of Climate-Smart Agriculture (CSA) that enhances productivity while conserving natural resources and improving climate resilience (Sarkar and Sarkar, 2025b). Based on minimum soil disturbance, permanent soil cover, and diversified crop rotations (Sarkar et al., 2025c), CA improves soil health, increases soil organic carbon, reduces erosion, enhances water retention, and promotes resource-use efficiency. In India, particularly in the Indo-Gangetic Plains, practices such as zero tillage and residue retention have improved crop productivity while lowering production costs. Despite its benefits, wider adoption is constrained by limited mechanization, competing uses of crop residues, and inadequate extension support. Strengthening farmer training, mechanization, and policy incentives will be crucial for scaling CA and enhancing the sustainability and resilience of Indian agriculture.

Climate-Smart Water Management

Climate-smart water management is essential for improving water-use efficiency and enhancing agricultural resilience under increasing water scarcity. Practices such as drip and sprinkler irrigation, rainwater harvesting, laser land levelling, farm ponds, precision irrigation, and Alternate Wetting and Drying (AWD) in rice reduce water use, production costs, and greenhouse gas emissions while maintaining crop productivity (Phoeurn et al., 2025). Soil moisture conservation through mulching, conservation tillage, and residue retention further strengthens drought resilience. Digital tools, including remote sensing, soil moisture sensors, automated weather stations, and IoT-based irrigation systems, enable precision water management and reduce groundwater depletion. Expanding micro-irrigation through initiatives such as the Pradhan Mantri Krishi Sinchayee Yojana (PMKSY) will further support sustainable water management in India's water-stressed agricultural regions.

Climate-Resilient Crops and Improved Varieties

Climate-resilient crop varieties are essential for sustaining agricultural productivity under changing climatic conditions. Improved tolerance to drought, floods, heat, salinity, and pests, along with short-duration cultivars, enhances yield stability, reduces production risks, and supports multiple cropping systems. Advances in genomics, molecular breeding, and precision phenotyping have accelerated the development of resilient cultivars, while quality seed systems and farmer awareness programmes promote their adoption. Overall, climate-resilient varieties represent a cost-effective strategy for strengthening food security and climate adaptation in agriculture.

Crop Diversification and Integrated Farming Systems

Crop diversification and integrated farming systems improve agricultural resilience, resource-use efficiency, and farm sustainability by integrating crops, livestock, fisheries, and agroforestry. Practices such as legume-based crop rotations, intercropping, and recycling of crop residues and livestock waste enhance soil fertility, nutrient cycling, biodiversity, and ecosystem stability while reducing dependence on external inputs. Diversified production systems also minimize climate and market risks, strengthen food and nutritional security, and generate multiple income sources, making them a key strategy for sustainable and climate-resilient agriculture.

Precision Agriculture and Digital Technologies

Precision agriculture employs advanced technologies such as GIS, GPS, remote sensing, drones, artificial intelligence (AI), IoT sensors, and decision-support systems to optimize the use of water, nutrients, and other agricultural inputs, thereby improving resource-use efficiency (Sarkar and Sarkar, 2025d). These technologies enable site-specific management, real-time crop monitoring, precision input application, climate-risk assessment, and digital monitoring of carbon sequestration (Sarkar et al., 2026a). Although adoption among smallholders remains constrained by financial and technical barriers, expanding digital advisory services and government-led digital agriculture initiatives are accelerating the adoption of precision farming in India.

Climate-Smart Nutrient Management

Climate-smart nutrient management enhances nutrient-use efficiency while reducing environmental impacts and greenhouse gas emissions. Practices such as soil test-based balanced fertilization, Integrated Nutrient Management (INM), Site-Specific Nutrient Management (SSNM), biofertilizers, organic manures, compost, green manuring, and crop residue recycling improve soil fertility, crop productivity, and soil organic carbon while minimizing nutrient losses (Sarkar and Sarkar, 2026b). Precision nutrient application and Soil Health Card-based recommendations further optimize fertilizer use, contributing to sustainable productivity, improved soil health, and climate change mitigation.

Integrated Pest and Disease Management

Integrated Pest Management (IPM) is a climate-smart approach that combines biological, cultural, mechanical, and need-based chemical methods to manage pests while reducing pesticide dependence. Practices such as resistant crop varieties, crop rotation, biological control, pheromone traps, and weather-based forecasting improve pest management, reduce crop losses, and minimize environmental pollution. By conserving biodiversity, lowering pesticide residues, and enhancing ecosystem resilience, IPM supports sustainable crop protection and complements conservation agriculture and precision farming within Climate-Smart Agriculture systems.

Agroforestry and Carbon Farming

Agroforestry and carbon farming are increasingly recognized as important components of Climate-Smart Agriculture because they simultaneously improve productivity, enhance ecosystem services, and mitigate climate change (Sarkar et al., 2026b). Agroforestry integrates trees with crops and livestock to diversify farm income while improving soil fertility, reducing erosion, conserving biodiversity, and regulating microclimates. Tree-based systems sequester significant quantities of atmospheric carbon in biomass and soils, thereby contributing to greenhouse gas mitigation. Carbon farming further promotes practices such as conservation agriculture, cover cropping, biochar application, residue retention, and restoration of degraded lands to increase soil organic carbon stocks (Sarkar et al., 2026c). These practices improve soil health, water retention, and nutrient cycling while creating opportunities for farmers to participate in emerging carbon markets. In India, integrating agroforestry with regenerative agriculture and digital carbon monitoring systems has considerable potential to support sustainable livelihoods, enhance climate resilience, and contribute to national climate commitments under the Paris Agreement.

Government Initiatives Supporting Climate-Smart Agriculture in India

India has introduced several policy initiatives to promote Climate-Smart Agriculture (CSA) by enhancing productivity, strengthening climate resilience, and improving resource-use efficiency. Key programmes include the National Mission for Sustainable Agriculture (NMSA), National Innovations on Climate Resilient Agriculture (NICRA), Pradhan Mantri Krishi Sinchayee Yojana (PMKSY), Soil Health Card Scheme, Pradhan Mantri Fasal Bima Yojana (PMFBY), and the Digital Agriculture Mission, which support sustainable resource management, climate-resilient technologies, precision agriculture, efficient irrigation, soil health, and risk management. Complementary initiatives such as Paramparagat Krishi Vikas Yojana (PKVY), Sub-Mission on Agricultural Mechanization (SMAM), National Agroforestry Policy, and Mission for Integrated Development of Horticulture (MIDH) further promote organic farming, mechanization, agroforestry, and diversified production systems. Despite these efforts, adoption remains limited by fragmented landholdings, inadequate extension services, financial constraints, and uneven technology access. Strengthening institutional support, digital advisory systems, climate finance, and farmer capacity building is essential for scaling CSA across India.

Benefits of Climate-Smart Agriculture

Climate-Smart Agriculture (CSA) offers multiple economic, environmental, and social benefits by simultaneously enhancing agricultural productivity, strengthening climate resilience, and reducing greenhouse gas emissions. Through practices such as conservation agriculture, climate-resilient crop varieties, efficient water and nutrient management, crop diversification, agroforestry, integrated farming systems, precision agriculture, and digital technologies, CSA improves resource-use efficiency, soil health, carbon sequestration, and water conservation while reducing production risks and environmental degradation. It enhances yield stability, farm profitability, food and nutritional security, and rural livelihoods by diversifying income sources and increasing resilience to climate-induced stresses. Emerging technologies, including remote sensing, GIS, artificial intelligence, drones, IoT, and digital monitoring systems, further support precision resource management, climate-risk assessment, and access to climate finance and carbon markets. Overall, CSA provides a sustainable pathway for achieving resilient, resource-efficient, low-emission, and economically viable agricultural development, particularly when supported by enabling policies, research, extension services, digital innovation, and institutional collaboration.

Conclusion

Climate change poses significant challenges to India's agricultural sustainability, necessitating a shift toward resilient and resource-efficient farming systems. Climate-Smart Agriculture (CSA) offers an integrated approach to enhance productivity, strengthen climate resilience, and reduce greenhouse gas emissions through practices such as conservation agriculture, efficient resource management, crop diversification, agroforestry, precision farming, and digital technologies. Despite its considerable potential, large-scale adoption is hindered by limited awareness, financial and technological constraints, fragmented landholdings, and weak extension support. Scaling CSA will require stronger policy support, climate finance, research and innovation, digital advisory services, and capacity building through coordinated efforts among policymakers, researchers, extension agencies, and farmers. Widespread adoption of CSA can significantly contribute to sustainable food security, improved rural livelihoods, natural resource conservation, and climate-resilient agricultural development in India.

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