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Climate-smart agronomic practices for enhancing crop productivity and resilience in Indian agriculture: A review

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Abstract

Climate-Smart Agriculture (CSA) is a holistic strategy to increase agricultural production, improve climate resilience and reduce GHGs. Nearly 20–24% of global emissions are due to agriculture, indicating the importance of sustainable agriculture. This review looks at some of the most important elements of CSA like conservation agriculture, precision farming, integrated nutrient and water management and varieties that are climate-smart. However, the adoption of CSA is relatively low, especially by smallholder farmers, as a result of the economic, institutional, and knowledge barriers. The opportunities to further speed up adoption lie in emerging technologies like artificial intelligence (AI), Internet of Things (IoT) and remote sensing, as well as in crop breeding advancements. Building institutional capacity, improving the availability of climate finance, and the strengthening of extension services are crucial to scaling up CSA. In conclusion, CSA offers a strategic approach that can help enhance food security, sustainability, and climate resilience, especially in developing nations such as India.

Keywords: Climate-smart agriculture, sustainability, food security, adaptation, mitigation

1. Introduction

Climatic variability is a significant challenge for agriculture, as crop growth and yield is climate-dependent. Climate change has become a serious concern around the world, not only for agricultural systems and food security, but also for livelihoods. The Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2021) ^[10] indicates that extreme events like droughts, floods and heatwaves are becoming more frequent and intense, affecting production and sustainability, especially in tropical and subtropical areas. The Indian agriculture is very vulnerable because it is monsoonal and smallholder dominated with large rain fed agriculture areas. A significant number of districts are classified as being in moderate to very high vulnerability, meaning that they are at high risk of climatic impacts and have low adaptive capacity (ICAR 2024). This vulnerability is compounded by socio-economic factors and access to climate resilient technologies. The effects of climate change are already affecting crop productivity in India. Increased temperatures, changed precipitation and extreme events have a negative impact on key crops, including rice, wheat and oilseeds. Rice yields are affected by temperature and rainfall variability, and wheat yield potential is lowered by terminal heat stress affected especially in the Indo-Gangetic Plains (Galle *et al.*, 2025) ^[8]. Climate change also puts greater strain on the natural resources, due to increased soil erosion, depletion of groundwater, and decreased input-use efficiency (Lal, 2020) ^[12].

Climate-smart agriculture (CSA) is an integrated approach to mitigate the impacts of climate change and food security, such as improving productivity, resilience and emission reduction (FAO 2013) ^[7].

Climate-smart agronomic practices such as diversification, conservation agriculture, integrated nutrient management, efficient water management, climate-resilient varieties, agroforestry, and precision agriculture improve productivity, stabilize yields, and reduce production risks (Samuel *et al.*, 2024) ^[18]. Despite growing research, a comprehensive synthesis of climate-smart

agronomic practices and their effectiveness in Indian agriculture remains limited. This review aims to examine climate-smart agronomic practices and their role in enhancing productivity, resource-use efficiency, and resilience under climate variability.

2. Climate Change and Indian Agriculture

Indian agriculture is highly sensitive to climatic variability due to its dependence on monsoon rainfall, temperature, and natural resources. The dominance of small and marginal farmers further heightens. Climate change is already affecting productivity through rising temperatures, altered precipitation, and increased extreme events (BIRTHAL *et al.*, 2023) [4]. Rising temperature adversely affects crop productivity by disrupting key physiological processes such as flowering and grain filling. Climate warming, causes yield losses in the major cereal systems, especially in the Indo-Gangetic Plains where crop production is already constrained by thermal limits (ARYAL *et al.*, 2022) [2]. Variability of rainfall makes people more vulnerable, the onset, distribution and intensity of the monsoon has become unpredictable. This interferes with sowing, crop establishment in rainfed systems (CHAND *et al.*, 2022) [5].

Heatwaves, unseasonal rainfall, floods, cyclones and other such extreme events damage crops in an instant, resulting in loss of crop output and economic instability. The events increase production risk and uncertainty (MALHI *et al.*, 2023) [14]. Climate change aggravates resource constraints by accelerating soil degradation, groundwater depletion, and inefficient input use. These factors reduce the resilience of farming systems, particularly in intensively cultivated regions (MUKHERJEE *et al.*, 2023) [16]. Climate impacts vary across agro-ecological and socio-economic contexts. Rainfed, semi-arid, and resource-poor regions are more vulnerable due to limited access to irrigation and climate-resilient technologies. Spatial variability in vulnerability highlights the need for region-specific adaptation strategies (KUMAR *et al.*, 2024). Climate change poses a multidimensional challenge to Indian agriculture, affecting productivity, resource sustainability, and livelihoods. Increasing climatic uncertainty necessitates resilient and resource-efficient systems. In this context, climate-smart agriculture offers a scientifically grounded approach integrating productivity, adaptation, and mitigation, as discussed in the next section.

3. Climate - Smart Agriculture: Concept and Principles

Climate-smart agriculture (CSA) is an integrated approach that addresses food security and climate change simultaneously.

Promoted by the Food and Agriculture Organization, is based on three core objectives: -

- sustainable enhancement of agricultural productivity and farm income,
- strengthening resilience and adaptive capacity to climatic stresses,
- reducing greenhouse gas emissions and where possible (FAO 2013) [7].

CSA emphasizes resource-use efficiency, diversification, and risk management, unlike input intensive conventional approaches. It is a flexible framework integrating agronomic practices, improved crop varieties, and institutional support suited to agro-ecological conditions. CSA interventions can improve productivity and system stability by 15–30% under climate variability, particularly in smallholder systems (Zougmore *et al.*, 2023) [25]. The productivity pillar focuses on efficient use of water, nutrients, and energy while maintaining soil health. The adaptation pillar enhances resilience to drought, heat stress, and rainfall variability. The mitigation pillar aims to reduce emissions and enhance carbon sequestration through practices such as conservation agriculture and agroforestry. CSA is highly relevant in India due to monsoon dependence, diverse agro-ecologies, and smallholder dominance. Its contribution to yield stability, resource-use efficiency and resilience is exemplified in the initiatives like National Innovations on Climate Resilient Agriculture (NICRA). CSA is knowledge-intensive and location-specific and demands the integration of traditional knowledge, scientific innovations and policies.

Effective implementation depends on strong extension systems, climate information, and institutional support. Overall, CSA provides an integrated framework linking productivity, adaptation, and mitigation, forming the basis for climate smart agronomic practices discussed in the next section.

4. Climate - Smart Agronomic Practices

Agronomic management and strategic decision-making are central to improving crop productivity and resilience under climatic variability. These practices improve resource-use efficiency, maintain soil health, and reduce production risks through integrated, location specific approaches. Evidence from South Asia indicates that such interventions can increase farm productivity by 15–30% while reducing yield variability under climate stress (ARYAL *et al.*, 2022) [2].

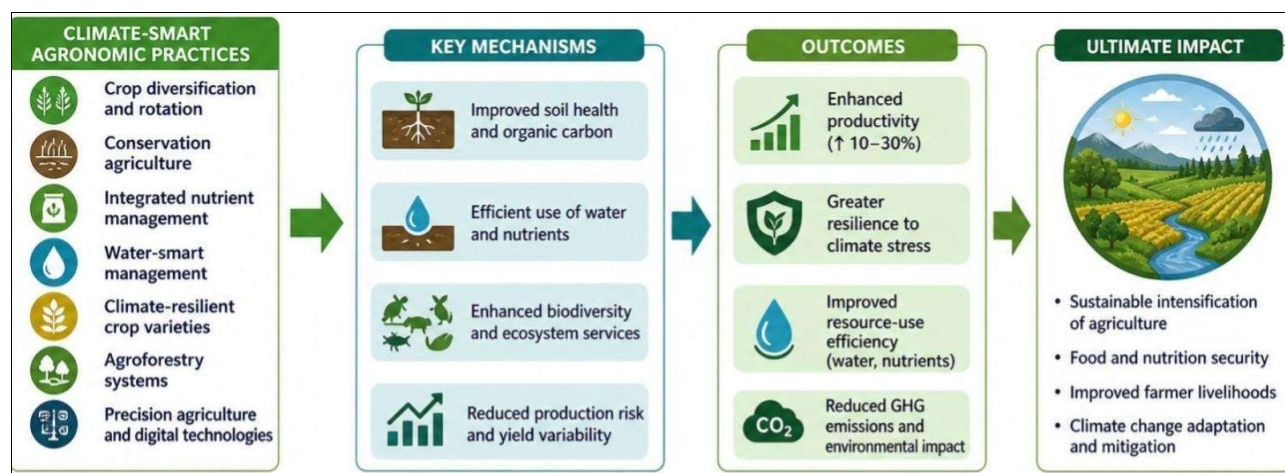


Fig 1: Climate - Smart Agronomic practices and their pathways to productivity and resilience

4.1. Crop Diversification and Cropping System Management

Crop diversification enhances resilience by reducing dependence on a single crop and enhances system stability. Practices such as crop rotation and intercropping promote nutrient cycling and reduce pest and disease pressure. Cereal–legume intercropping increases system productivity by 12–25% due to improved nitrogen-use efficiency and resource complementarity (Bithal *et al.*, 2023) ^[4]. Diversification towards pulses and oilseeds further improves income stability and reduces climate risk in rainfed systems.

4.2. Conservation Agriculture

Conservation agriculture (CA), based on minimum soil disturbance, residue retention, and crop diversification, enhances soil moisture retention and carbon sequestration. In the Indo-Gangetic Plains, zero tillage increases yields by 4–10% and reduces irrigation demand by 15–20% (Jat *et al.*, 2023) ^[11]. Residue retention enhances soil organic carbon by 0.2–0.4 Mg ha⁻¹ yr⁻¹, improving water-use efficiency and drought tolerance (Powlson *et al.*, 2022) ^[17].

INM integrates inorganic fertilizers, organic manures, and biofertilizers to enhance soil fertility and nutrient-use efficiency. Studies across Indian agro-ecologies show yield increases of up to 20% along with increases in soil organic carbon and microbial activity compared to sole chemical fertilization (Mahajan *et al.*, 2023) ^[13]. In mustard systems, Sulphur and organic inputs improve yield, oil content, nutrient uptake, and soil moisture retention under stress.

4.3. Water-Smart Management Practices

Efficient water management is critical under climate variability.

Methods of water management like drip irrigation, mulching and rainwater harvesting bring better water-use efficiency and stability of production. Micro-irrigation contributes to 35-50% higher water productivity and 20-35% higher yield (Kumar *et al.*, 2023) and mulching helps in retaining moisture during dry conditions, which is 20-30% less evaporation loss.

4.4. Climate-Resilient Crop Varieties

Development of stress-tolerant crop varieties is crucial in preserving productivity under climatic stress. These varieties are more drought, heat and salt tolerant. Research has shown that they can improve yield stability in at-risk areas by reducing yield losses under stress conditions, which can be 10-25% (Cairns *et al.*, 2022).

4.5. Agroforestry Systems

Agroforestry makes it more resistant by enriching the soil, storing carbon and regulating the microclimate in combination with crops. Agroforestry systems can boost farm value by 20-40%, and store 0.5-2Mg ha⁻¹ yr⁻¹ of carbon, helping with adaptation and mitigation (Dhyani *et al.*, 2023) ^[6].

4.6. Precision Agriculture and Digital Technologies

Site-specific input management through tools like remote sensing and decision-support systems is facilitated by precision agriculture. The efficiency of input use is enhanced by 20-30% through precision nutrient management and by 8-15% through production improvement (Zhang *et al.*, 2023) ^[23]. Weather-based advisory systems also contribute to adaptive capacity by helping to inform timely decision-making.

Table 1: Climate-Smart Agronomic Practices and Quantified Benefits

Practice	Yield impact	Resource efficiency	Climate benefit
Crop diversification	Increases 12-25%	Better nutrient use	Risk reduction
Conservation agriculture	Increases 4-10%	Water saving 15-20%	SOC increases 0.2-0.4 Mg/yr
INM	Increases 10-20%	Improved NUE	Soil health
Water Management	Increases 20-35%	Water productivity increases 35-50%	Drought resilience
Improved varieties	Loss reduced 10-25%	Stable yield	Stress tolerance
Agroforestry	Income increases 20-40%	Resource recycling	Carbon sequestration
Precision farming	Increases 8-15%	Input efficiency increases 20-30%	Lower emissions

5. Impacts on Productivity And Resilience

Agronomic practices that are climate-smart improve resource-use efficiency, boost soil health, and make farming less vulnerable to climatic stresses, thereby increasing crop productivity and sustainability under climate change.

5.1 Influence on Crop Productivity

Climate smart practices help to enhance yield and system efficiency. Optimization of input use and improvement of the nutrient-use efficiency using integrated approaches to nutrient management, conservation agriculture and precision farming. Depending on the crop and environment, these interventions can boost crop yields by 10-30% (Aggarwal *et al.*, 2023) ^[3]. Conservation agriculture can help farmers boost productivity by 4-10%, while cutting production costs in the Indo-Gangetic Plains. The implementation of micro-irrigation yields better water productivity and increase yields by 20-35%. Precision nutrient management can boost the efficiency of fertilizer use by 20–30%, which can lead to increased productivity and reduced fertilizer input costs (Jat *et al.*, 2023) ^[11].

5.2 Effect on Climate Resilience

Climate-smart practices enhance resilience through increasing

farming systems' resistance to climate variability. Better soil structure, more organic matter and improved moisture holding capacity increase water and nutrient supply. With mulching and conservation tillage, the moisture holding capacity of the soil is raised by 15–25%, and the incidence of dry spells is decreased (Thierfelder *et al.*, 2022) ^[20]. By diversifying crop production, crop diversification decreases the risk of crop production. Stress-tolerant varieties can save 10-25% production loss under Drought and heat stress conditions (Prasanna *et al.*, 2023) and agroforestry is helpful in providing extra income and regulating microclimate.

5.3 Integrated Impact on Productivity and Stability

Climate-smart agriculture does not only increase productivity, but also resilience. CSA is a long-term approach that encourages sustainability and stability, as opposed to short-term yield optimization. Farms using several of one or more CSA practices experience reduced yield variability and increased income stability compared to conventional farms (Thornton *et al.*, 2023) ^[21], particularly for smallholder farmers in India.

Table 2: Summary of Impacts

Practice	Productivity Impact	Resilience Impact
INM	Yield increases 10-20%	Soil health increases
Conservation agriculture	Yield increases 4-10%	Moisture retention increases
Water management	Yield increases 20-35%	Drought resistance increases
Crop diversification	Yield stability increases	Risk reduction
Improved varieties	Yield loss decreases 10-25%	Stress tolerance
Agroforestry	Income increases 20-40%	Climate buffering

6. Constraints and Future Prospects

6.1 Constraints

Climate-Smart Agriculture (CSA) has a high potential for improving the productivity, resilience of agricultural systems and climate change mitigation in developing countries like India but the implementation of CSA is restricted due to several interacting factors. One of the key challenges is the limited awareness and technical knowledge of farmers and limited access to extension services and climate information systems. As a result, small and marginal farmers still use traditional farming methods (Samuel *et al.*, 2024) ^[18]. Economic considerations also influence adoption, with some CSA interventions, like precision irrigation or climate-resilient crop varieties, and soil health management practices, for example, necessitating significant start-up costs. Financial and credit access is limited and disproportionately affects resource-poor farmers, thus limiting large-scale implementation (Villalba *et al.*, 2024) ^[22]. Agriculture extension system is also weak and this severely restricts effective dissemination. The efficiency of the technology uptake of CSA is limited by poor field demonstrations, low-capacity building initiatives, and poor farmer–scientist linkages.

Also, the agro-climatic diversity makes it difficult to scale up CSA practices, since their success in the various regions varies according to soil types, rainfall patterns, and cropping systems (Mohapatra *et al.*, 2023) ^[15]. Other institutional and policy gaps hinder adoption. Weak incentive mechanisms, limited access to carbon markets, low penetration of crop insurance, and inadequate support mechanisms mean that farmers' willingness to adopt CSA technologies is low (IPCC 2022). Most importantly, recent studies indicate that the CSA rollout in India is not uniform and complete across all regions, necessitating integrated frameworks, location-specific approaches, and scalable solutions (Ajatasatru *et al.*, 2024) ^[1].

6.2 Future Prospects

Carbon markets and Payment for Ecosystem Services (PES) are enabling payment incentives for farmers to reduce their emissions from agriculture, thus contributing to the speed of CSA uptake (Villalba *et al.*, 2024) ^[22]. Enhancing institutional and policy frameworks (e.g. climate-based crop insurance, targeted subsidies and promoting low carbon agricultural systems) will be crucial to boost the adoption and resilience. What's more, capacity-building and participatory extension methods such as farmer field schools, digital advisory systems, and mobile weather prediction systems are good enough to fill knowledge gaps at the grassroots level (Samuel *et al.*, 2024) ^[18]. The adoption of technological innovations alongside robust institutional engagement and geographical adaptation will be key to scaling up CSA effectively in India, from a strategic perspective. Overall, CSA is projected to be an important method to achieve food security, climate resilience, and GHG mitigation, especially in climate-vulnerable areas like South Asia, and will be vital to meet Sustainable Development Goals (SDGs 2 and 13).

Climate-Smart Agriculture (CSA) provides a holistic strategy to tackle the challenge of food security in order to build climate resilience and lower greenhouse gas emissions by the sustainable management of climatic resources. However, its widespread adoption is limited by lack of awareness, low extension services, financial constraints, agro-ecological diversity and lack of policy support, especially for smallholder farmers in less-developed countries such as India.

7. Conclusion

However, the opportunities to increase CSA adoption and effectiveness are high due to the development of digital agriculture technologies, climate resilient crop varieties and better agronomic practices. Actions to enhance institutional systems, increase climate financing, and strengthen extension systems will play a major role in scaling up the implementation of CSA. In sum, CSA offers a strategic approach to sustainable agricultural transformation and will play an important role in future food security, climate change resilience, and sustainability.

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