IMPACT OF CLIMATE SMART AGRICULTURAL PRACTICES ON INDIAN AGRICULTURE: PROSPECTS, CHALLENGES AND FUTURE DIRECTIONS

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Abstract. India's agricultural sector faces mounting challenges due to climate change coupled with population growth. Impact of climate change is highly pronounced in rice-wheat cropping system, which, being the staple food of the country will jeopardize its long-term food security. While agriculture is vulnerable to climate change, it also contributes to greenhouse gas (GHG) emissions, with carbon dioxide (CO_2) from pre and post agricultural activities projected to reach 207 Mega tons (Mt) by 2030 and 231 Mt by 2035. Ensuring food security while simultaneously reducing the GHG emission is the greatest challenge of this century and Climate Smart Agriculture (CSA) has emerged as a promising solution. Still, significant knowledge gaps persist regarding its implementation and effectiveness. This paper presents a critical assessment of CSA in India, analyzing current challenges, opportunities and providing strategic directions for key stakeholders, using the PRISMA 2020 criteria for a systematic review. The findings reveal that lack of expertise, insufficient policy frameworks, limited technology access, inadequate funding, low awareness and absence of site-specific practices are the major challenges. A comprehensive strategy encompassing awareness campaigns, capacity-building initiatives, financial and technical assistance (including subsidies, carbon credits by industries, access to credit, index-based insurance), inclusive participation of stakeholders and gender-sensitive policies is proposed for effective adoption of CSA. The study concludes that coordinated efforts spanning from global to local domains are crucial for promoting CSA practices among farmers, enabling India to enhance agricultural resilience, ensure food security and progress towards achieving the Sustainable Development Goals.
Keywords: *climate change, agriculture, food security, climate smart approaches, greenhouse gas emissions, sustainable development goals*

Introduction

Climate change and food security have emerged as the most pressing challenges facing humanity in the 21st century. The Intergovernmental Panel on Climate Change (IPCC) has highlighted climate change as an incremental threat to the global agricultural production, affecting both food and livelihood securities worldwide. The impact of climate change on agriculture is severe (Long et al., 2016; Mugambiwa and

Makhubele, 2021; Jayadas and Ambujam, 2021) as the projections indicate a 50% drop in rain-fed crop yields and complete crop failure if global temperatures exceed 1.5°C (Schleussner et al., 2016; Nkemelang et al., 2018). India, as a developing economy with a significant workforce in the primary sector, faces high vulnerability. The 2021 Global Climate Risk Index ranks India 7th, underscoring the country's susceptibility to climate-related challenges (Eckstein et al., 2021).

These challenges are further complicated by the projected growth in global food demand. The Food and Agriculture Organization of the United Nations (FAO) estimated that farmers will need to produce 70% more food by 2050 to feed the world's anticipated population of 9.1 billion. However, this necessary increase in production must occur within the context of a changing climate that is expected to persist for the foreseeable future (Long et al., 2016; Vetter et al., 2017). The situation is further exacerbated by demographic trends and shifting dietary patterns. A projected one-third increase in human population by 2050 coupled with dietary shifts, is intensifying the food demand (Vetter et al., 2017). Despite these alarming trends, public prioritization of climate change remains low compared to other societal issues (Capstick et al., 2015). These interlinked challenges present a complex scenario for the global agriculture, necessitating innovative and sustainable approaches to ensure food security in the face of climate change (Barooah et al., 2023).

To address these multifaceted challenges, Climate Smart Agriculture (CSA) has emerged as a promising solution (Rao, 2017; Rao et al., 2024), particularly for developing nations (Long et al., 2016; Ahmad et al., 2020; Jamil et al., 2021). Introduced by the FAO in 2010, CSA is an innovative and cleaner production alternative to conventional farming. It aims to transform agriculture towards climate-resilient practices, thereby strengthening food systems. CSA's objectives are threefold: (i) increasing agricultural productivity and farmer income, (ii) enhancing resilience and adaptation to climate change, and (iii) reducing greenhouse gas (GHG) emissions to mitigate climate change (Anuga and Gordon, 2016; Joshi et al., 2019; Nongmaithem et al., 2019; Raihan, 2024)

By adopting CSA, nations can work towards achieving multiple Sustainable Development Goals, including SDG 1 (no poverty), SDG 2 (Zero hunger), SDG 7 (Affordable and clean energy) and SDG 13 (Climate action) (Okolie et al., 2022; Patra and Babu, 2023). However, despite its potential, the adoption of CSA practices remains uneven across regions and crops. This paper critically explores the current landscape of CSA in India, identifying key challenges, assessing future prospects and offering strategic insights to enhance sustainable practices in response to climate change.

Methods and materials

The review explores recent high-profile articles focused on the impacts of climate change on Indian agriculture and conducts an in-depth examination of mitigation strategies with particular emphasis on the transformative approach known as Climate-Smart Agriculture (CSA).

Search strategy

Multiple academic databases such as Web of Science, Semantic Scholar, Google Scholar, Scopus, JSTOR, Bielefeld Academic Search Engine (BASE) and Directory of Open Access Journal (DOAJ) were utilized to ensure comprehensive coverage of

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literature. The platforms were searched using targeted keywords related to climate change, sustainable agriculture, CSA and Indian agriculture.

Selection process

The PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) 2020 framework, an updated guideline for reporting systematic reviews was followed to ensure a proper workflow and the selection process consisted of the following stages.

Stage I (Identification): Initial search yielded 2,35,809 records across all databases.

Stage II (Screening): The screening process involved multiple steps to refine the selection. Firstly, the documents were filtered based on the type that includes research articles, review papers, working papers and book chapters, which resulted in 67,040 records. Then, these documents were further screened for relevance to the research topic and yielding 53,632 records. When limited to the publication date range to 2015-2024, the numbers were reduced to 3095 records. Finally, after screening based on abstracts and keywords relevance, 632 records were obtained.

Stage III (Inclusion): Based on full-text retrieval and availability, 92 articles were ultimately included in the study. *Figure 1* presents the flowchart outlining the identification and selection process of studies for the systematic review.

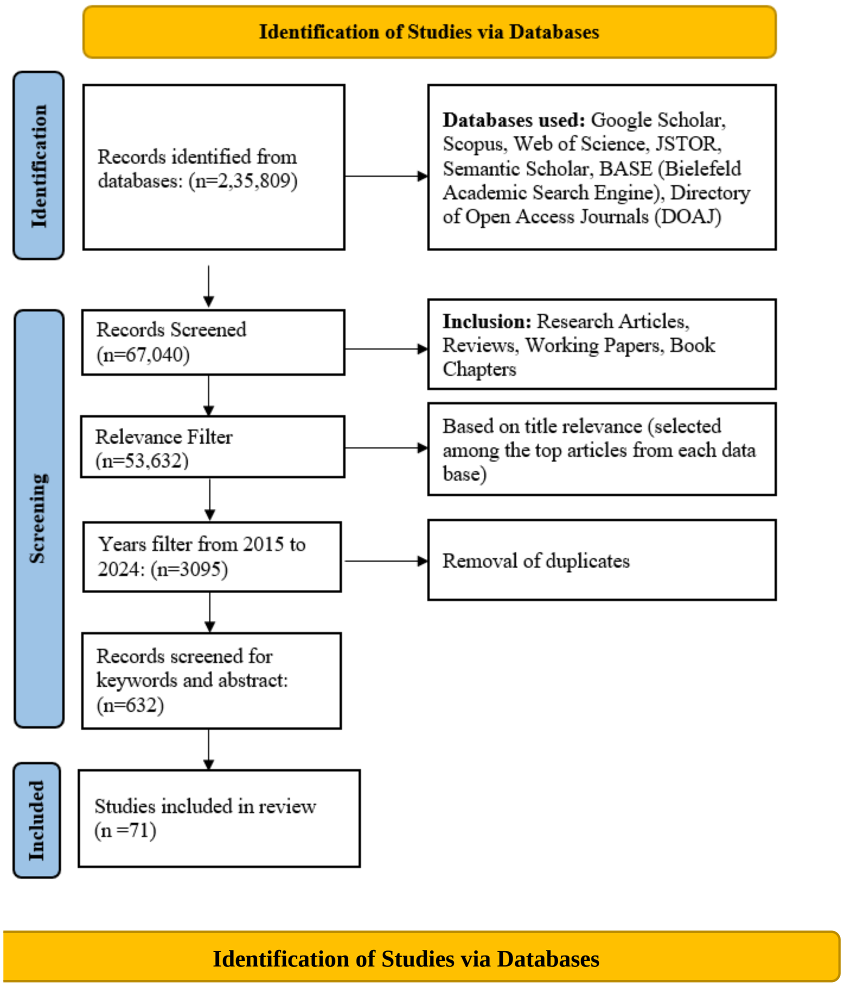

Figure 1. *Flowchart of identification and selection of studies for systematic review*

Agriculture's dual role in climate change

Climate change poses a significant threat to the global agriculture, which is simultaneously acting as both a victim and a contributor to this environmental challenge (Velten et al., 2015). Agriculture's vulnerability to climate change is mainly due to its heavy reliance on temperature, precipitation and weather patterns (Rao et al., 2024). The changing climate is expected to intensify existing precipitation patterns, potentially causing more extreme weather events like heavy rain and droughts. These changes have far-reaching consequences.

Irregular precipitation and temperature fluctuations significantly affect crop sensitivity and productivity, particularly in rainfed crops, which constitute a substantial part of the global food production (Dube et al., 2021; Phiri et al., 2021). Globally the yield of cereals is projected to decline, with maize facing the largest potential decline at 60% followed by sorghum (50%), rice (35%), wheat (20%) and barley (13%), respectively (Porter et al., 2014; Alemu and Mengistu, 2019). Extreme temperatures cause water scarcity and soil depletion, while erratic rainfall leads to droughts and floods. As a result, the value of farmlands has been greatly affected by climate change (Laino and Iglesias, 2023). Climate change also alters the relationship between plants and pests. Rising temperatures affect weed growth, potentially altering competition between C_3 crops and invasive C_4 weeds (Simpson, 2017; Rao et al., 2024). These combined effects trigger pest and disease outbreaks, reducing crop yields and disrupting farming activities. The impacts extend to allied sectors like livestock through heat stress and changes in food and water availability (Rao et al., 2024).

The Intergovernmental Panel on Climate Change (IPCC) has emphasized the role of GHG emissions in disrupting the ecological equilibrium within ecosystems (Shamsuzzaman et al., 2016; Miah and Raihan, 2017; Rahman et al., 2017; Raihan, 2024). The agricultural ecosystem is directly responsible for 10%–12% of the global human GHG emissions (Long et al., 2016), making it the second-largest contributor (Isfat and Raihan, 2022). It also accounts for approximately 56% of total emissions not related to CO_2 (Raihan et al., 2024).

Agricultural GHG emissions stem from various sources and processes. CO_2 is primarily released through soil organic matter decomposition and burning of crop residues. Methane (CH_4) another significant GHG, is predominantly emitted from flooded rice fields, cattle digestion and decomposition of animal manure (Raihan et al., 2023; Lou et al., 2024). Developing countries are particularly vulnerable, as a larger portion of their national gross domestic product (GDP) is derived from agricultural and allied sectors (Long et al., 2016). On a broader scale, Maraseni and Qu (2016) projected that a consortium of seven nations viz., Argentina, Australia, Brazil, Canada, Chile, China, India and the United States would collectively contribute to approximately 50% of the global soil emissions and over 49% of the global agricultural emissions. Agricultural practices not only result in GHG emissions, but also contribute to nitrogen and water footprints (Maraseni and Qu, 2016; Arunrat et al., 2022).

Indian agriculture and climate change

In India a large rural population relies heavily on agriculture and allied activities, with over 80% of farmers being small-holders with limited resources (Dey et al., 2024; Wani, 2023). While the sector contributes about 16% to the nation's GDP, it simultaneously accounts for approximately 18% of the country's total GHG emissions

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(Lamb et al., 2021). Within agricultural emissions, livestock and rice production were found to be the main sources of GHG emissions with a country average of 5.65 kg CO_2eq kg^{-1} rice, 45.54 kg CO_2eq kg^{-1}mutton meat and 2.4 kg CO_2eq kg^{-1} milk (Vetter et al., 2017; MoEFCC, 2018; Tankha et al., 2020). From 1990 to 2016, the highest GHG emissions in agriculture came from enteric fermentation, followed by rice cultivation, use of synthetic fertilizers, manure management, crop residues and burning of agricultural waste (Ahmad et al., 2020).

Paradoxically, the agricultural sector is increasingly vulnerable to the effects of climate change. India faces recurring natural disasters, mainly droughts and floods (Tankha et al., 2020; Rao et al., 2024), with conservative estimates placing average annual losses from natural disaster at about 0.5% of GDP (Tankha et al., 2020). The impact is primarily severe for small-scale and subsistence farmers, who face challenges of unprofitability coupled with rising temperature, shifting rainfall patterns and escalating extreme weather events (Wani, 2023; Rao et al., 2024). Research indicates that even moderate temperature increases will significantly affect the yield of major cereals (rice, wheat and maize) in India (Aryal et al., 2020; Daloz et al., 2021). Saravanakumar (2015) projected a decline of 283 and 88 kg per hectare per decade for rice and sorghum by 2100, respectively, representing a 10% decrease in rice productivity and a 9% reduction in sorghum yield.

Not just the farming activities, but both pre- and post-production activities also play a crucial role in emission of GHG. Over the past three decades (1990-2021), a consistent upward trajectory in GHG emissions from the pre and post agricultural production activities is observed. This trend aligns with India's rapid economic growth, increased industrialization, and evolving agricultural practices during this period (*Graph 1*). Based on calculations using a regression equation, CO_2 emissions are projected to reach 207 Mega tons (Mt) by 2030 and further increase to 231 Mt by 2035. CO_2 has accounted for the highest share of GHG emissions at 83% (*Graph 2*), with household food consumption, fertilizer manufacturing, food transport, food retail and food processing as the major contributors (*Graph 3*). This highlights the significant role of carbon dioxide in the country's agricultural GHG profile and underscores its impact on the overall carbon footprint. While CO_2 remains the primary concern, it is important to note the significant increase in fluorinated gas emissions during the second decade (2000-2010) of the study period (*Graph 1*). This spike can be attributed largely to technological advancements in the food retail sector, particularly the widespread adoption of refrigeration systems (*Graph 3*).

To address these challenges India has implemented several programs National Adaptation Fund for Climate Change (NAFCC), National Innovation on Climate Resilient Agriculture (NICRA) and Pradhan Mantri Krishi Sinchayee Yojana (PMKSY) reflecting upon its commitment to CSA (Dey et al., 2024).

Climate-smart agriculture–a systemic solution

A significant criticism of CSA lies in its often-unclear differentiation from existing sustainable agriculture practices, leading to debates about its unique contribution to agricultural development (CSA Guide, n.d.). Sustainable agriculture has traditionally focused on practices that ensure long-term productivity and environmental health. Building upon this foundation, Climate-Smart Agriculture (CSA) emerges as a participatory, bottom-up approach that explicitly addresses the challenges posed by climate change (Lipper and Zilberman, 2018). While both approaches share

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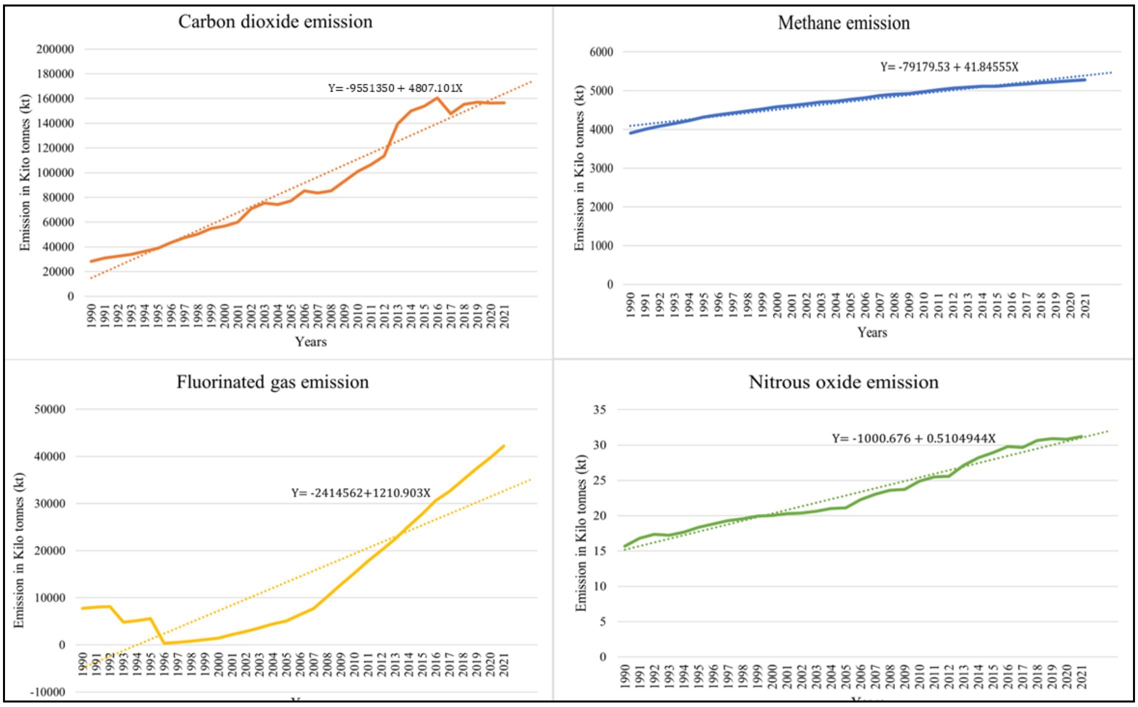
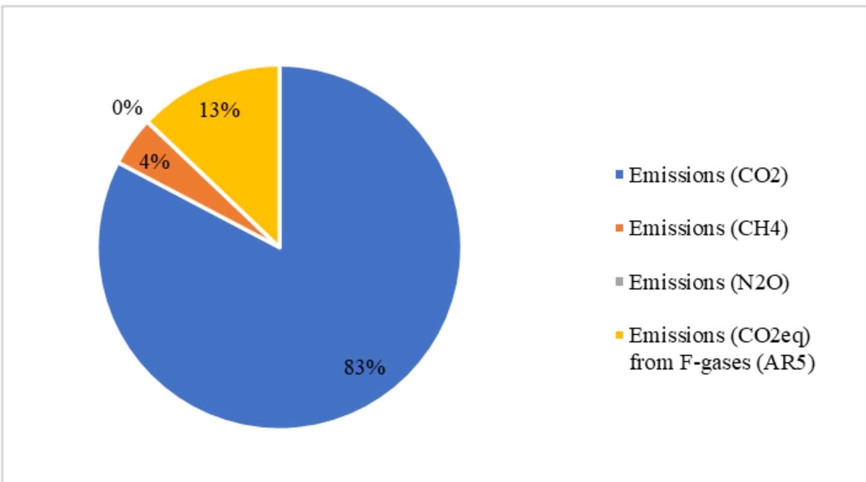
fundamental principles of enhancing productivity and sustainability, CSA distinguishes itself through its deliberate integration of climate change adaptation and mitigation strategies while prioritizing food security (CSA Guide, n.d.; Rosenstock et al., 2015). Rather than introducing entirely new sustainability principles, CSA strategically adapts existing agricultural development policies, programs and investments to incorporate climate-specific considerations (Lipper and Zilberman, 2018). In essence, CSA represents a strategic evolution of sustainable agriculture, maintaining its foundational principles while advancing a more targeted focus on climate resilience and greenhouse gas emission reduction (CSA Guide, n.d.).



Graph 1. *Trends in GHG emissions (kilo tons (kt)) from pre- and post-agricultural production activities in India (1990-2021). Data source: FAOSTAT, 2021*



Graph 2. *Distribution of GHG emissions from pre- and post-agricultural production activities in India. Data source: FAOSTAT, 2021*

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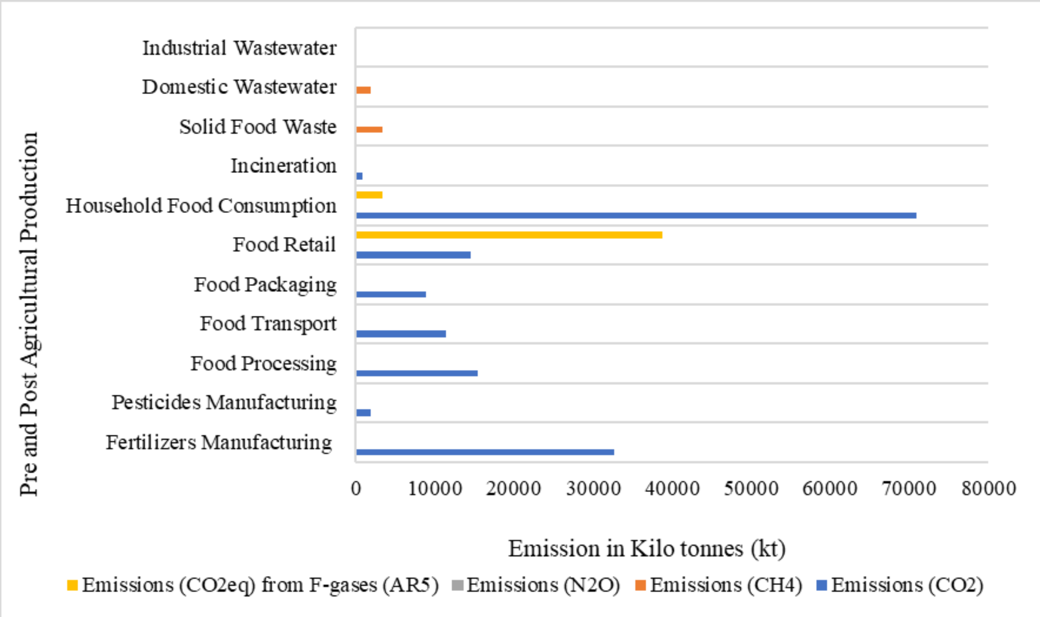

Graph 3. *Breakdown of GHG emissions (kt) from pre- and post-agricultural production activities in India (2021). Data source: FAOSTAT, 2021*

The scope of CSA encompasses a range of advanced techniques and practices including water-smart, energy-smart, carbon-smart, nutrient-smart, weather-smart and knowledge-smart strategies (Mrabet, 2023; Raihan et al., 2024). This adaptive approach emphasizes locally tailored solutions, enabling farmers to manage agricultural systems effectively under increasing climate pressures while simultaneously aiming to reduce GHG emissions and enhance food security (Kumari et al., 2019; Joshi et al., 2019; Nongmaithem et al., 2019). *Table 1* explores key technologies, practices and strategies within CSA.

Table 1. *Key technologies, practices and approaches in CSA*

CSA		Potential solution
Water smart strategies	•Laser land leveling •Raised bed planting •Watershed development •Rainwater harvesting •Contour ridging •Micro-irrigation (Drip and sprinkler irrigation) •Precision irrigation integrated with sensors, drones and satellite imaging •Conjunctive water use •Drainage management •Direct Seeded Rice (DSR) •Alternate Wetting and Drying (AWD) •Alternate cropping system •Crop diversification	•Maximize water use efficiency (WUE) •Reduced GHG emission •Enhances soil moisture levels •Monitors crop water requirements in real-time
Energy smart strategies	•Zero tillage (ZT) •Minimum tillage •Contour ridging •Direct seeding & DSR •Mulching •Application of farmyard manure (FYM) •Integrated soil fertility management •Residue management •Land consolidation	•Keep soil covered •Enhance soil fertility •Increased nutrient uptake •Reduced GHG emission •Reduced labor requirement

	•Laser land leveling •Use of appropriate machinery	
Carbon smart strategies	•ZT •Mulching •AWD in rice production •Balanced fertilizer application •Use of micronutrients and biofertilizers •Improved storage mechanisms for manure •Reduced use of chemical •Improved nutrition and genetics of ruminant livestock •Integrated nutrient management •Agroforestry practices	•Improve nutrient accessibility •Increase the productivity of agricultural systems •Reduced wind and soil erosion •Increased water retention •Improved soil structure and aeration •Enhance soil quality •Reduce GHG emissions •Supply fuelwood and feed •Carbon sequestration and enhancing farmland carbon sink
Knowledge smart strategies	•Improved stress tolerant crop varieties •Crop diversification •Intercropping •Crop rotation •Altered planting timelines •Integrated Pest Management (IPM) •Improved crop residue management •Weather forecast •ICTs (Information and Communication Technologies) •Market information •Community based seed banks and cooperatives •Seed and fodder bank •Farmer-to-farmer learning •Gender empowerment •Capacity building •Off-farm research management in participatory way •Index based insurance •Gender equity	•Diversified revenue streams •Enhanced water retention •Improved soil structure and aeration •Counter anticipated rise in temperature and water stress during crop season •Cost effective •Minimal capital investment •Integration and use of Indigenous Traditional Knowledge (ITK)
Weather smart strategies	•ICT-based agro-meteorological services •Weather forecast and communication in right format •Index based insurance •Stress-tolerant crops and varieties •Seeds for needs (adapted varieties) •Crop diversification •Agroforestry •Transitioning cropping patterns to horticultural crops	•Safety against extreme weather events •Enhances farmers' ability to manage climate-related risks •Lead to more resilient agricultural systems •Improved soil health •Better pest and disease management •Carbon sequestration
Nutrient smart strategies	•Site-specific nutrient management (SSNM) •Precision nutrient management ➢Green Seeker ➢Leaf Color Chart (LCC) •Residue management •Legume integration ➢Legume catch-cropping ➢Alterations in cropping pattern and rotations •Brown manuring	•Optimized Nutrient Use Efficiency (NUE) •Reduced GHG emission •Enhanced nitrogen fixation •Improved soil health •Improved carbon sequestration

Source: Malhotra and Srivastava, 2015; Murray et al., 2016; Shrivastava, 2016; Srivastava et al., 2016; Imran et al., 2018; Shah, 2018; Sikka et al., 2018; Aryal et al., 2020; Barooah et al., 2023; Rao et al., 2024

Prospects of CSA in India

Several CSA practices and strategies have been successfully implemented in India, demonstrating positive impacts on the crop productivity, climate adaptation and mitigation. *Table 2* highlights various research studies conducted in India, showcasing potential benefits of adopting CSA in improving agricultural outcomes while addressing climate change challenges.

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Table 2. *Benefits of Implementing CSA practices in India*

Region	Cropping system	CSA practices	Prospects	Reference cited
Karnal [three Climate-Smart Villages (CSVs)]	Rice-wheat	•Laser land levelling •Zero Tillage (ZT) •Direct-Seeded Rice (DSR) •Site-specific nutrient management (SSNM) •Precision irrigation management	•Increased energy efficiency, biomass yield and farm profitability	Kakraliya et al., 2022
Punjab (Ludhiana) and Haryana (Karnal)	Rice-wheat	•ZT with residue retention using •Turbo Happy Seeder Super •Straw Management System	•Reduced on-site burning of paddy residues •Prevention of black carbon emission •Improved soil fertility •Reduced need for groundwater irrigation	Sidhu et al., 2015; Tallis et al., 2017
Punjab and Haryana	Rice-wheat	•Laser land levelling of field	•Reduced irrigation time by 47–69 h/ha/season in rice and 10–12 h/ha/season in wheat •Increased yield in rice (7%) and wheat fields (7%–9%) •Increased net profit of INR 9700/ha/year •Electricity needs for irrigation reduced by 754 kWh per year	Aryal et al., 2015
Maharashtra	Sugarcane	•Drip irrigation •Nutrient management (farmyard manure, vermicompost, straw residue incorporation)	•44%–55% less water use •25%–50% electricity savings •23% higher productivity	Sikka et al., 2018; Zhao et al., 2023
Indo-Gangetic plains of India	Rice-wheat	•Improved crop varieties •Laser land levelling •Zero tillage (ZT) •Residue management •Site-specific nutrient management (SSNM) •Crop diversification.	•Total production increased by •19% with improved seeds •6% with zero tillage •10% with laser land levelling •Yield increased by 1.03 tons/ha (Improved seeds) and 0.33 tons/ha (laser land levelling) boosting net returns	Khatri-Chhetri et al., 2016
Haryana	Rice	•Aerobic rice technology	•50%–60% less water use than flooded rice •32%–88% higher water productivity •Lower labor demand •Reduced CH_4 emissions	Dey et al., 2018
Bihar	Rice-wheat	•Zero tillage with partial residue retention	•4.66 MgC/ha increase in Soil organic carbon (SOC)	Sapkota et al., 2017; Aryal et al., 2020
Andhra Pradesh (Krishna River basin – Guntur district)	Rice	•DSR	•Improved crop yield (1–6 qt/ha) •Increased revenue •Intensification of rice cropped area (0.04%–64%) •Reduced fuel consumption and GHG emission (6788 metric tons of CO_2 emissions)	Kakumanu et al., 2019

Challenges in implementation of CSA

Despite the promise of CSA practices to mitigate the adverse impacts of climate change, several conflicts and challenges hinder its global implementation, particularly in developing countries (Mizik, 2021). At the macro level, accurately predicting the future impacts of climate change on agriculture is highly uncertain. Lack of standardized and unified carbon monitoring and accounting methodologies in agriculture complicates the

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measurement of CSA's effectiveness leaving the potentials of GHG emission reduction and carbon storage in agriculture unclear (Dabesa et al., 2022; Lou et al., 2024). Although some CSA practices enhance productivity, they may also contribute to increased GHG emissions. For instance, the use of manure from livestock, a major source of missions within the agricultural sectors, can offset some of the environmental benefits (Vetter et al., 2017; Pivoto et al., 2018; Mizik, 2021). The wide spread adoption of CSA faces several other challenges, including lack of expertise, insufficient national policy frameworks, limited access to technology, inadequate climate related funding and support for smallholder empowerment (Chandra et al., 2016; Long et al., 2016; Rohila et al., 2018; Nyang'au et al., 2021). In developing regions, the primary barrier is lack of awareness and knowledge about CSA practices (Long et al., 2016). Identifying site-specific CSA practices that address the diverse needs of stakeholder further complicates the adoption efforts (Nyang'au et al., 2021).

At farm level, transitioning from traditional farming methods to CSA often entails significant costs, hazards and trade-offs (Chandra et al., 2016). Marginalized groups, especially women, often have face unequal access to resources and opportunities, which makes it harder for them to adopt CSA practices (Imran et al., 2018; Makate et al., 2019; Phiri et al., 2021). Addressing these challenges requires capacity building at the local level, equipping farmers and stakeholders with the necessary knowledge, tools that support in implementing CSA practices effectively. The agronomic, economic and environmental benefits of CSA underscore the urgency of scaling it up for agricultural sustainability in the face of climate change and dwindling natural resources (Aryal et al., 2020).

Conclusion

This paper reviews the current landscape of CSA in India, identifying key challenges. CSA practices implemented in India, demonstrating positive impacts on the crop productivity, climate adaptation and mitigation and their potential benefits in improving agricultural outcomes while addressing climate change challenges are detailly explained. By adopting suitable CSA practices, policies and investments, the agricultural sector can not only reduce poverty and food insecurity but also act as a long-term strategy to mitigate climate change's impact on food production**.** While CSA presents a robust framework for sustainable agriculture, its success hinges on overcoming economic and policy-related challenges to ensure widespread implementation and adaptation. Coordinated efforts spanning from the global to local domains, encompassing research, legislation and investments are crucial to address the complex nexus of food security and climate change. With the dual pressures of agricultural importance and climate fragility, the implementation of CSA in India is not just desirable but essential. This move helps India to enhance agricultural resilience, ensure food security and progress towards achieving the SDGs: eradicating poverty (SDG 1), ending hunger (SDG 2), Affordable and clean energy (SDG 7) and Climate action (SDG 13).

Policy suggestion

The successful implementation of CSA requires a multi-faceted approach that goes beyond technological solutions. This comprehensive strategy should address policy, collaboration, education and gender inclusion. Collaboration among researchers,

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policymakers and farmers is crucial. Effective extension services and local cooperatives strengthened through (Krishi Vigyan Kendra) KVKs and framers training centers are needed to serve as innovation and learning platforms for farmers, encouraging the widespread adoption of CSA practices and uptake at the grassroots level. Technical and financial support viz., subsidies such as carbon credits by industries, facilitating access to credit, index-based insurance and digital platforms are essential for implementing CSA technologies. Implementation of tailored fiscal-policy measures along with gender-sensitive and customized policies should be developed to support site-specific CSA strategies and overcome barriers faced by women. Addressing these challenges requires concrete, synergistic strategies from local to national levels. However, the institutional and governance aspects at the local level must be well-integrated, as they are crucial to the successful implementation of CSA.

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