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Review article

Climate-smart agriculture in India: Greenhouse gas mitigation strategies

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ABSTRACT

This review paper examines Climate-Smart Agriculture (CSA) as a crucial approach to mitigate greenhouse gas emissions from India's agriculture sector. It analyzes various CSA practices implemented in India, focusing on their effectiveness in reducing emissions while enhancing food security and farmer livelihoods. The paper explores crop management techniques like improved varieties, nutrient management, and water management, alongside soil management practices such as conservation agriculture and agroforestry. Additionally, it delves into livestock management strategies, including improved feeding practices and manure management. The review highlights the role of government policies and programs in promoting CSA adoption, such as the National Mission for Sustainable Agriculture and the Parampara at Krishi Vikas Yojana. Challenges hindering wider CSA adoption, including financial constraints, lack of awareness, and data gaps, are discussed. The paper concludes by emphasizing the need to address these challenges and leverage opportunities like strengthening extension services, promoting farmer-to-farmer learning, and utilizing technology to unlock the full potential of CSA in India.

Keywords: Climate-Smart Agriculture, Greenhouse Gas Mitigation, Sustainable Agriculture, Food Security, Climate Change.

There is a global perception that weather is unpredictable beyond typical patterns, and high-resolution, model-based climate forecasts suggest more severe changes in future climate (Pradipa *et al.,* 2022). The agricultural landscape faces an unprecedented challenge: feeding a growing global population while grappling with the escalating impacts of climate change (Aryal *et al.,* 2020a). This dual burden necessitates a paradigm shift in agricultural practices, moving away from conventional, resource-intensive methods towards sustainable and climate-resilient approaches. Climate-smart agriculture emerges as a beacon of hope, offering a holistic framework to address the intertwined challenges of food security, climate change mitigation, and rural development (Abegunde and Obi, 2022). The keel curve technique of CO2 enrichment, whose yield increased steadily until the end of the century, was proven to have a greater negative impact on temperature rise than any other approach. This could be due to increasing CO2 concentrations; Black gram came to similar results (Pradipa *et al.,* 2022).

The foundation of India's economy is agriculture, which largely provides food and livelihoods. Extreme weather events such as heat waves, droughts, cyclones and floods are caused by climate change and its variability and have serious negative impacts on people's health, livelihoods and crops (Panda *et al.,* 2023). Agriculture, while fundamental to human sustenance, is a significant contributor to greenhouse gas emissions, accounting for approximately 10-12% of global anthropogenic emissions (Smith and Gregory, 2013). These emissions primarily stem from activities such as deforestation for agricultural expansion, methane emissions from livestock and rice cultivation, and nitrous oxide emissions from fertilizer application. The urgency to mitigate these emissions is underscored by the alarming rate of climate change, with rising temperatures, erratic rainfall patterns, and increased frequency of extreme weather events posing significant threats to agricultural productivity and global food security (Campbell *et al.,* 2018).

India, with its vast and diverse agricultural sector, faces a particularly acute challenge. As the world's second-largest producer of rice, wheat, and fruits and vegetables, agriculture forms the backbone of the Indian economy, contributing significantly to its GDP and providing livelihoods for a substantial portion of its population (Prabhu, 2021). However, Indian agriculture is highly vulnerable to climate change impacts, with droughts, floods, and heatwaves increasingly jeopardizing crop yields and farmer incomes (Aryal *et al.,* 2020b).

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Table 1: Major sources of greenhouse gas emissions in Indian agricultural systems

Source	Description	Percentage contribution
Enteric fermentation	Methane released while ruminant animals, like cattle and buffaloes, digest their food.	54%
Rice cultivation	Methane emissions in flooded paddy fields due to anaerobic decomposition of organic matter.	17%
Agricultural soils	Emissions of nitrous oxide resulting from the handling of manure and the application of both organic and synthetic fertilizers.	19%
Manure management	Emissions of nitrous oxide and methane from the handling and storage of animal manure.	7%
Crop residue burning	Emissions of nitrous oxide, carbon dioxide, and methane from the post-harvest open burning of agricultural waste.	3%

Source: Ministry of Environment, Forest and Climate Change, Government of India (Ministry of Environment, Forest and Climate Change (moef.gov.in)

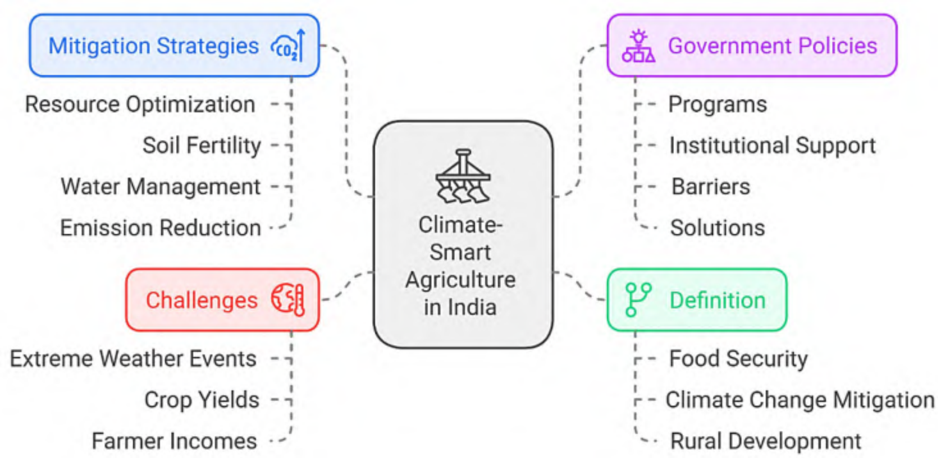

Fig. 1: Climate smart agriculture in India

Recognizing the critical need to address these challenges, the concept of Climate-Smart Agriculture has gained significant traction in India (Table 1). CSA, as defined by the Food and Agriculture Organization of the United Nations, is an approach that helps guide actions needed to transform and reorient agricultural systems to effectively support development and ensure food security in a changing climate (Sahu *et al.,* 2020).

CSA strives to enhance crop yields and livestock productivity, ensuring food security for a growing population while improving farmer incomes and livelihoods. This involves adopting practices that optimize resource use, enhance soil fertility, and improve water management. CSA emphasizes building the resilience of agricultural systems to withstand and recover from climate shocks and stresses. This includes promoting drought-tolerant and flood-resistant crop varieties, implementing water-efficient irrigation techniques, and adopting climate-resilient livestock management practices. CSA aims to minimize the environmental footprint of agriculture by reducing GHG emissions and sequestering carbon in soils and biomass. This involves promoting practices such as conservation agriculture, agroforestry, efficient fertilizer management, and renewable energy use in agriculture (Fig. 1).

The implementation of CSA practices in India holds immense potential to transform its agricultural sector into a more sustainable and climate-resilient system. By adopting practices that optimize resource use, enhance productivity, and reduce emissions, India can ensure food security for its burgeoning population while contributing to global efforts to combat climate change. This review paper delves into the multifaceted landscape of Climate-Smart Agriculture in India, examining the various GHG mitigation strategies employed across different agricultural systems. It analyzes the effectiveness of these practices in reducing emissions while enhancing productivity and building resilience to climate change. The paper further explores the role of government policies, programs, and institutional support in promoting CSA adoption among Indian farmers. Additionally, it identifies the challenges hindering wider CSA adoption and proposes potential solutions to overcome these barriers. By providing a comprehensive overview of Climate-Smart Agriculture in India, this review aims to contribute to the growing body of knowledge on sustainable agricultural practices and inform policy decisions aimed at building a more resilient and climate-friendly agricultural sector in India (Fig. 2).

CLIMATE-SMART AGRICULTURE: A HOLISTIC APPROACH

Climate-Smart Agriculture is not merely a set of

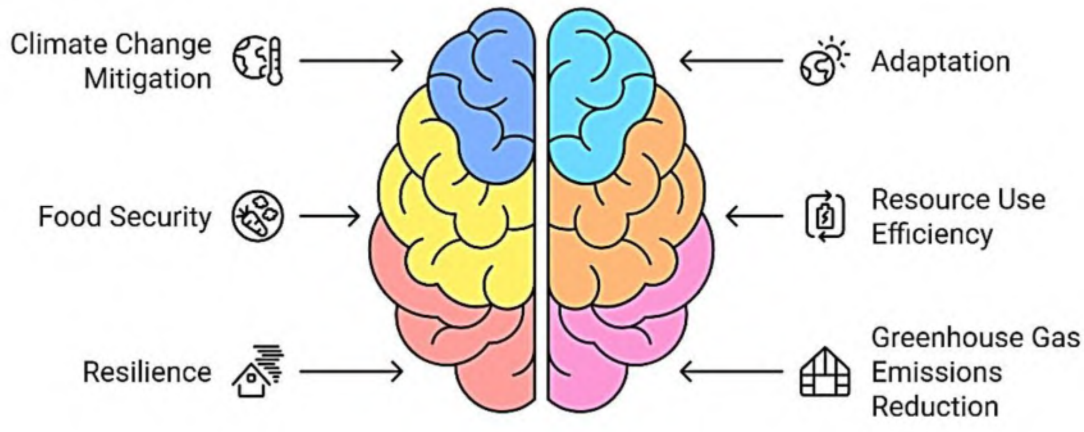

Fig. 2: Components of climate smart agriculture

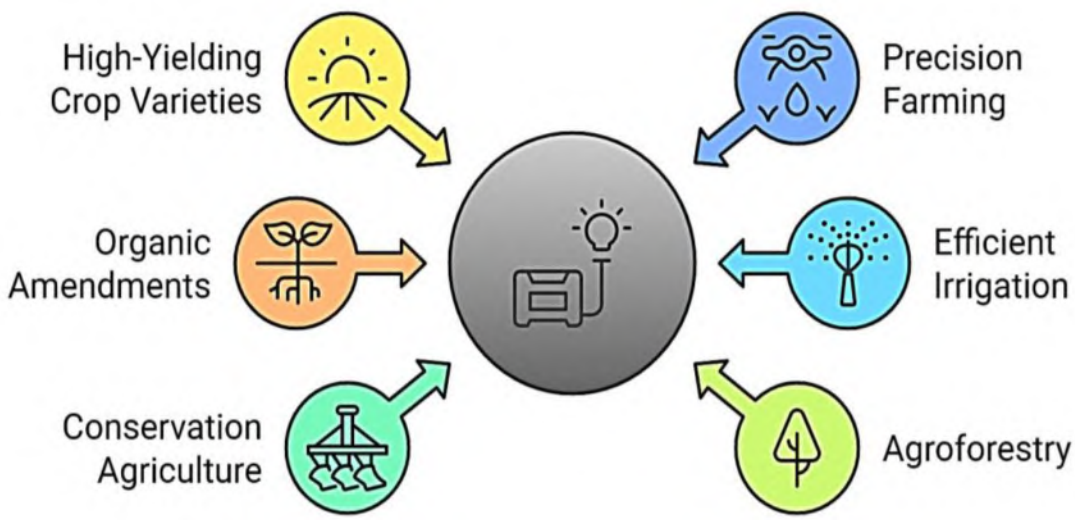

Fig. 3: Greenhouse gas mitigation strategies in Indian agriculture

practices but a holistic approach to agricultural development that integrates the imperatives of climate change mitigation, adaptation, and food security (Chinnasamy *et al.,* 2023). It recognizes the interconnectedness of these challenges and seeks to create synergies that benefit both people and the planet. CSA moves beyond simply increasing yields; it prioritizes the long-term sustainability of agricultural systems by enhancing resource use efficiency, building resilience to climate shocks, and reducing greenhouse gas emissions (Sahu *et al.,* 2020). This approach acknowledges that there is no one-size-fits-all solution and emphasizes context-specific interventions tailored to local agro-ecological conditions, socioeconomic factors, and farmer needs. By promoting a paradigm shift towards sustainable and climate-resilient agriculture, CSA paves the way for a future where food security is ensured without compromising the integrity of our planet.

GHG MITIGATION STRATEGIES IN INDIAN AGRICULTURE

India has witnessed the implementation of various Climate-Smart Agriculture practices aimed at reducing greenhouse gas emissions from its diverse agricultural systems (Table 2). These practices target key emission sources across crop cultivation, livestock rearing, and soil management (Fig. 3). Here's a closer look at some of the prominent GHG mitigation strategies employed in Indian agriculture:

Crop management practices

Pesticides are harmful to nature and are therefore considered poisonous to the environment (Murugesan *et al.,* 2021a). Chemical pesticides, which include herbicides, fungicides, rodenticides, and insecticides, pose a serious threat to biodiversity and the environment, contributing to air and water pollution (Murugesan *et al.,* 2023). Many are returning to natural options over synthetics in search of safety and stability (Murugesan *et al.,* 2021b). Traditional medicine is also an essential source of potentially valuable compounds for the development of therapeutic agents (Kaleeswaran *et al.,* 2019). Plant extracts and secondary metabolites have emerged as promising alternatives to synthetic pesticides (Rengarajan *et al*., 2024), offering potential solutions for sustainable pest management strategies (Murugesan *et al.,* 2024).

Table 2: Greenhouse gas mitigation strategies in Indian agriculture

Strategy	Description	GHG reduction potential	Benefits	Challenges
System of rice intensification (SRI)	A technique for managing plants, soil, water, and nutrients differently in order to increase rice yield	Reduces methane emissions (40%)	Reduces water usage by 25-50%. Enhances soil health	Initial reluctance from farmers due to change in traditional practices
Integrated nutrient management	Utilizing both organic and inorganic fertilizers in tandem to minimize overapplication and maximize nutrient availability.	Reduces nitrous oxide emissions by 20-30%.	Improves soil fertility and structure. Enhances crop yields sustainably	Limited availability of organic fertilizers
Conservation agriculture	Techniques to enhance soil health and lower emissions, such as crop rotation, zero tillage, and residue retention	Reduces CO_2 emissions by up to 50%	Enhances soil moisture retention	Requires access to specific machinery (e.g., zero-till seed drills)
Agroforestry systems	Including shrubs and trees in livestock and agricultural systems to increase ecosystem services and sequester carbon	Sequesters 2-4 tons of CO_2 per hectare/year	Improves biodiversity	Longer time to see financial gains from tree parts
Improved livestock management	Improved feeding techniques, efficient breeding methods, and health management are some of the strategies to lower enteric fermentation and manure emissions	Reduces methane emissions by 15-25%	Enhances quality of dairy and meat products	Effective breeds of livestock may not be adopted because of cultural preferences for particular breeds
Biogas production from manure	Methane emissions from open manure storage are decreased by the anaerobic digestion of animal manure, which yields digestate for fertilizer and biogas for energy	Captures up to 60% of potential methane	Reduces reliance on firewood and fossil fuels	Needs a steady supply of feedstock and technical upkeep
Precision farming techniques	Utilization of technology (e.g., GPS, sensors) to apply inputs like water and fertilizers accurately and efficiently based on crop needs and soil conditions	Reduces GHG emissions by 10-20%	Minimizes environmental contamination	Hefty upfront tech costs
Alternate wetting and drying (AWD)	Rice fields are routinely drained rather than continuously flooded as part of a water management strategy that lowers the anaerobic conditions that lead to the production of methane	Reduces methane emissions by 30-50%	Saves up to 30% of irrigation water	Needs sturdy water control systems
Use of nitrification inhibitors	Substances that are added to soil to slow down the ammonium to nitrate conversion, which lowers nitrous oxide emissions and increases the efficiency of nitrogen use	Lowers emissions of nitrous oxide by 30–40%.	Improves crop yields	Limited awareness and availability in farming communities.
Crop diversification	Incorporating a range of crops into intercropping or rotation systems to increase resilience and carbon sequestration, strengthen soil health, and lessen reliance on a single crop	Greatly increases the amount of carbon stored in soil	Lowers the prevalence of disease and pests. increases the security of food and income	Requires familiarity with a variety of cropping systems and management techniques.

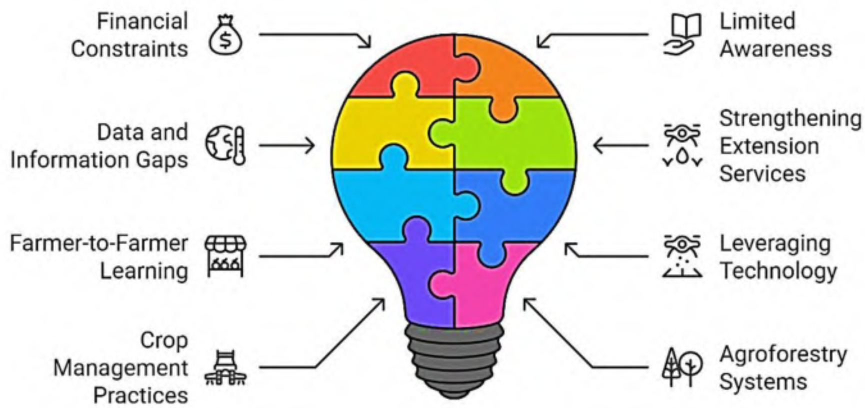

Fig. 4: Components of climate-smart agriculture in India

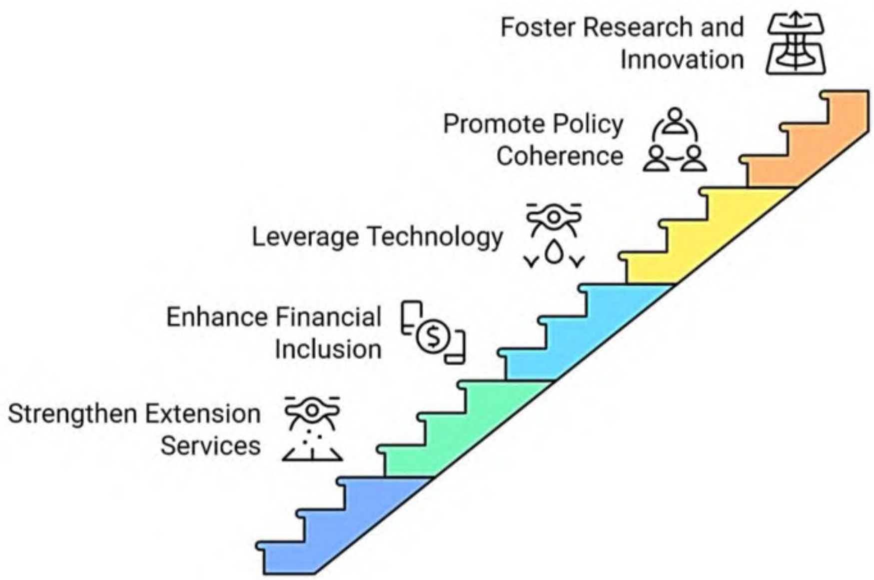

Fig. 5: Steps to enhance climate smart agriculture adoption in India

Utilizing high-yielding, drought-tolerant, and pest-resistant crop varieties is a cornerstone of CSA. These varieties require fewer inputs like water, fertilizers, and pesticides, thereby reducing the emissions associated with their production and application (De Pinto *et al.,* 2020). For instance, drought-tolerant rice varieties, like those developed by the International Rice Research Institute, can significantly reduce methane emissions from paddy fields by requiring shorter periods of flooding. Similarly, pest-resistant cotton varieties, like Bt cotton, minimize the need for pesticide applications, reducing emissions associated with their manufacture and use. Optimizing fertilizer application is crucial for mitigating nitrous oxide emissions, a potent greenhouse gas. Precision farming techniques, such as soil testing and GPS-guided fertilizer application, enable farmers to apply the right amount of nutrients at the right time and place, minimizing nitrogen losses to the environment (Kanter *et al.,* 2019). Additionally, promoting the use of organic amendments, like compost and manure, can improve soil health, enhance nutrient use efficiency, and reduce reliance on synthetic fertilizers.

Efficient irrigation methods, such as drip irrigation and sprinkler irrigation, deliver water directly to plant roots, minimizing water wastage and reducing methane emissions from rice paddies. Rainwater harvesting, another important water management strategy, involves collecting and storing rainwater for later use, reducing dependence on groundwater extraction and associated energy consumption (Oo *et al.,* 2018).

Soil management practices

Conservation of agriculture approach encompasses a suite of practices, including no-till farming, crop rotation, and cover cropping, that aim to minimize soil disturbance, improve soil health, and enhance carbon sequestration. No-till farming involves planting crops directly into the residue of the previous crop without tilling the soil, reducing soil erosion and decomposition, thereby sequestering more carbon in the soil. Crop rotation, the practice of growing a series of different types of crops in the same area in sequenced seasons, helps break pest cycles, improve soil fertility, and enhance carbon storage. Cover cropping, involving growing specific crops primarily to cover and benefit the soil, further contributes to soil health, weed suppression, and carbon sequestration (Chapagain *et al.,* 2020)

Integrating trees into agricultural landscapes provides multiple benefits, including carbon sequestration, improved soil fertility, and enhanced biodiversity. Trees act as carbon sinks, absorbing carbon dioxide from the atmosphere and storing it in their biomass and soils. Agroforestry systems also improve soil health by adding organic matter, enhancing nutrient cycling, and reducing erosion. Additionally, they provide habitat for beneficial insects and pollinators, promoting biodiversity and ecosystem services (Hovis *et al.,* 2021).

Livestock management practices

Improved feeding practices providing livestock with balanced diets tailored to their nutritional needs can enhance feed conversion efficiency, leading to increased productivity and reduced methane emissions from enteric fermentation. Utilizing feed additives, such as methane inhibitors and enzyme supplements, can further reduce methane emissions from livestock. Implementing biogas digesters and composting systems can capture methane emissions from manure and convert them into valuable resources. Biogas digesters break down organic matter in manure anaerobically, producing biogas, a renewable energy source, and digestate, a nutrient-rich fertilizer. Composting, on the other hand, involves the aerobic decomposition of manure, producing compost, a valuable soil amendment (Rahmat *et al.,* 2019).

These GHG mitigation strategies, when adopted widely and integrated into existing farming systems, can significantly contribute to reducing the environmental footprint of Indian agriculture. However, successful implementation requires addressing various challenges, including financial constraints faced by farmers, limited access to information and technology, and the need for tailored solutions that suit diverse agro-ecological conditions and farming practices across India (Fig. 4).

CHALLENGES AND OPPORTUNITIES

Despite the significant potential of Climate-Smart Agriculture, several challenges hinder its widespread adoption in India. Financial constraints pose a significant barrier for smallholder farmers who often lack the capital required for upfront investments in new technologies or practices**.** Limited awareness about CSA practices and their benefits among farmers further impedes adoption. Additionally, data and information gaps, such as limited access to reliable climate information and best practices, hinder effective decision-making. However, addressing these challenges presents significant opportunities for scaling up CSA in India (Vincent and Balasubramani, 2021). Strengthening extension services to provide farmers with timely and relevant information on CSA practices is crucial. Promoting farmer-to-farmer learning, where farmers can exchange knowledge and experiences, can accelerate the adoption of successful practices (Makate, 2019). Leveraging technology, such as digital platforms and mobile applications, can enhance access to information, markets, and financial services, further empowering farmers to transition towards climate-smart agriculture (Fig. 5).

STRATEGIES TO IMPLEMENT CLIMATE-SMART PRACTICES IN INDIAN AGRICULTURE TO REDUCE GREENHOUSE GAS EMISSIONS

Climate change poses a major threat to India's agribusiness industry, whose economy and food security are heavily dependent on agriculture. Improving crop management practices is an important way to reduce greenhouse gas emissions from Indian agriculture. Crop diversification and rotation can improve soil health and increase carbon uptake, both of which are important for reducing emissions. For example, growing legumes as cover crops can increase soil nitrogen levels and reduce the need for synthetic fertilizers, which are a major source of nitrogen oxide emissions. Additionally, techniques such as conservation tillage, which minimizes soil disturbance, help maintain soil carbon stocks and reduce carbon dioxide emissions. Using these sustainable agricultural approaches can help farmers reduce greenhouse gas emissions while increasing their yield and resilience to climate unpredictability (Chachei, 2024).

Agroforestry systems

Another effective strategy is the introduction of agroforestry systems, which include planting trees and shrubs in agricultural settings. Agroforestry contributes to carbon sequestration and provides various benefits such as improved soil quality, increased biodiversity, and increased resilience to climate change. In India, planting trees alongside crops or livestock could significantly increase the amount of carbon stored in soil and biomass, leading to a reduction in greenhouse gas emissions. Agroforestry systems can help raise farmers' living standards and, ultimately, improve agriculture's sustainability by creating additional sources of income through the sale of fruits, wood, and other tree products (Datta and Behera, 2024).

Water management system

Water management is another crucial factor in reducing greenhouse gas emissions in Indian agriculture. Wet soils and water waste from traditional irrigation systems can lead to higher emissions. Efficient irrigation techniques, such as drip irrigation and rainwater harvesting, can reduce methane emissions from rice fields and conserve water. Furthermore, effective management of water resources could help farmers adapt to changing rainfall patterns caused by climate change. Implementing these water management techniques can ensure sustainable water use, increase agricultural productivity, and reduce greenhouse gas emissions. Enteric fermentation and manure management are the primary methods by which the Indian livestock sector significantly contributes to greenhouse gas emissions by releasing methane into the environment. To reduce these emissions, India is promoting a variety of programs to improve cattle farming. For example, adding more digestible feed and feed additives can improve feed quality by potentially reducing methane emissions during digestion. Additionally, better manure management practices, such as composting and anaerobic digestion, can collect methane for energy production and improve nutrient recycling in agriculture. Using these techniques, livestock producers can improve animal welfare and productivity while reducing emissions (Singh *et al.,* 2021).

Finally, India now has the opportunity to address climate change concerns, increase agricultural productivity, and ensure food security through climate-smart agriculture. By implementing a range of greenhouse gas reduction strategies, such as organic farming, improved livestock production, agroforestry, improved crop management, and efficient water management, India can significantly reduce its agricultural greenhouse gas emissions. However, to achieve these goals, farmers, policymakers, and other interested parties must work together to create conditions that promote sustainable agricultural practices, promote awareness, and enable education. India, a country currently grappling with the impacts of climate change, can reduce its emissions by adopting CSA while strengthening its agricultural industry and improving its ability to withstand future weather fluctuations. It may be possible to mitigate the effects of climate change and its extremes by using crop models to assess how climate change affects crop yield and adopt sustainable agricultural practices (Singh, 2023).

CONCLUSION AND FUTURE ASPECTS

Climate-Smart Agriculture emerges as a critical pathway for transforming Indian agriculture into a more sustainable, resilient, and low-emission sector. By adopting a holistic approach that integrates productivity enhancement, climate change adaptation, and GHG mitigation, CSA offers a win-win solution for both farmers and the environment. While significant strides have been made in implementing various CSA practices across India, widespread adoption necessitates addressing key challenges such as financial constraints, limited awareness, and information gaps.

Moving forward, several key aspects require attention to unlock the full potential of CSA in India:

- ***Strengthening extension services*:** Bridging the knowledge gap among farmers is crucial. Extension services need to be revamped to effectively disseminate information on CSA practices, tailored to local conditions and delivered through accessible channels, including digital platforms and farmer-to-farmer learning initiatives.
- ***Enhancing financial inclusion*:** Access to affordable credit is essential for farmers to adopt CSA practices, many of which require upfront investments. Innovative financial mechanisms, such as climate-smart agriculture credit lines and risk mitigation instruments, can incentivize adoption and de-risk investments in sustainable practices.
- ***Leveraging technology and data*:** Digital technologies, including mobile applications, remote sensing, and data analytics, offer immense potential to enhance CSA adoption. Providing farmers with real-time weather information, crop advisories, and market linkages can empower them to make informed decisions and optimize their practices for climate resilience.
- ***Promoting policy coherence*:** Mainstreaming CSA into national and regional agricultural policies is essential for creating an enabling environment for its adoption. This includes aligning policies across sectors, such as agriculture, water, energy, and climate change, to ensure synergy and avoid conflicting objectives.
- ***Fostering research and innovation*:** Continued research and development are crucial for developing and disseminating new climate-smart technologies and practices tailored to the evolving challenges posed by climate change. Investing in agricultural research and promoting public-private partnerships can accelerate innovation and knowledge transfer in the field of CSA.

By prioritizing these future aspects, India can harness the transformative potential of Climate-Smart Agriculture to ensure food security, enhance farmer livelihoods, and contribute to global efforts to combat climate change.

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