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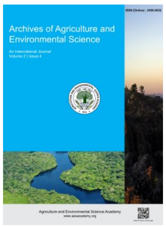

REVIEW ARTICLE

Climate-smart agriculture: A review of sustainability, resilience, and food security

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ABSTRACT

This paper investigates Climate Smart Agriculture (CSA), a comprehensive strategy aimed at improving agricultural efficiency and sustainability while addressing the challenges of climate change. It examines the economic advantages of CSA for adopters compared to traditional farming methods and assesses CSA's role in mitigating climate change, adapting to its impacts, and enhancing food security. The study reviews essential CSA practices, including agroforestry, conservation agriculture, water-efficient irrigation technologies, crop diversification, improved livestock management, and soil carbon sequestration, as well as the barriers to adoption, such as limited funding, arable land, land tenure issues, and insufficient expertise. Agroforestry and crop rotation have shown encouraging results, with agroforestry serving as a cost-effective solution for food production and environmental preservation. Dairy companies boosted milk consumption from 529,000 to 3 million liters, while farmer profits grew from $0.2 to $0.3 per liter. Rice yields have increased, from 3-4 tons to 7.5 tons per hectare. In cotton farming, CSA adopters cut input costs compared to traditional methods, resulting in long-term economic gains. Crop rotation increased maize productivity by 5–10%, while new irrigation techniques improved water efficiency by 5–35%. However, regions without CSA methods experienced significant livestock losses, highlighting the importance of widespread adoption to ensure resilience. Despite CSA's advantages, its widespread adoption is hindered by financial and knowledge barriers. Future research should focus on optimizing multiple cropping systems, crop diversification, and no-till agriculture. CSA, particularly when integrated with technologies like the Internet of Things (IoT), offers a promising path toward more adaptive and resilient agricultural practices. Broader adoption will require investments in research and resources to effectively scale CSA innovations.

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INTRODUCTION

Climate change poses a significant risk to global food security and the sustainability of agriculture. This situation calls for innovative farming methods that can boost resilience lower greenhouse gas emissions, and help food security goals. Climate Smart Agriculture (CSA) is recognized as a proactive approach to tackling issues related to climate change and food security by enhancing resilience, decreasing greenhouse gas emissions, and aiding the country's development and food security (Chandra *et al*., 2018). In 2010, the FAO released a report titled "Climate-Smart Agriculture: Policies, Practices, and Funding for Food Security, Adaptation, and Mitigation" to aid the Hague Conference on Agriculture, Food Security, and Climate Change that took place in October of that year (Lipper *et al*., 2014). The agricultural sector in developing countries must undergo significant changes to tackle the challenges posed by climate change and to secure food supplies. Projections indicate that, due to population growth and evolving food consumption patterns, agricultural output will need to increase by at least 70% by 2050 to meet demand. Emphasizing the development of climate-smart agriculture is essential for achieving future objectives related to food security and climate action (Dwivedi *et al.*, 2017). The three essential aims of Climate Smart Agriculture (CSA), which positively affect both farming and the environment, are: (1) sustainably enhancing agricultural productivity to improve farmer incomes, food security, and economic development; (2) adapting to and building resilience against climate change at both local and national levels; and (3) creating opportunities to reduce greenhouse gas emissions from agriculture compared to earlier trends. These aims are often referred to as the three "pillars" (or criteria) of CSA within agricultural science and development circles Since then, these three marks (briefly food security, adaptation, and mitigation) are denominated as the three "pillars" (or criteria) of CSA among the agricultural science and growth communities (Saj *et al.*, 2017).

Despite progress in applying CSA practices, there persists a considerable gap in understanding how these methods can be tailored and successfully executed across different agro-ecological environments. Numerous existing studies often concentrate on individual practices instead of viewing CSA as an interconnected and comprehensive strategy. Furthermore, distinct regional issues, such as socio-economic elements and specific climate conditions, technologies, and policies and institutional support have not been adequately investigated. This article discusses the concept of Climate Smart Agriculture (CSA) and its practical implications on agriculture and the environment in various countries worldwide. It emphasizes the core principles of CSA, alongside different farming practices. Furthermore, it assesses the potential advantages of CSA, highlighting both obstacles and opportunities. The primary goal of this paper is to outline upcoming trends and research necessities for the adoption of CSA practices across diverse terrains and scenarios.

METHODOLOGY

This review was performed by systematically assessing literature and reports associated with Climate Smart Agriculture (CSA) and its relevance to climate resilience, adaptation, and food security. A thorough search was conducted across academic databases like Google Scholar, utilizing keywords such as “Climate Smart Agriculture,” “CSA practices,” “Sustainable Agriculture,” “Climate Resilient Agriculture,” “Precision Agriculture,” and more. Chosen sources were examined for their relevance and reliability, with a focus on peer-reviewed articles and reports from respected organizations. This review specifically encompassed research on CSA practices including agroforestry, conservation agriculture, water-efficient irrigation technologies, crop diversification and rotation, enhanced livestock management, and soil carbon storage, alongside their possible advantages, challenges, and future suggestions. The collected data was categorized by key themes, and each source was critically evaluated to draw insights and pinpoint difficulties. Ultimately, the findings were integrated to showcase trends, gaps, and implications for forthcoming research, providing a thorough overview of CSA's contribution to tackling climate change.

PRINCIPLES OF CLIMATE SMART AGRICULTURE

Climate change mitigation: Climate change mitigation focuses on lowering CO_2 emissions using traditional strategies like decarbonization technologies, embracing renewable energy, shifting fuels, improving efficiency, utilizing nuclear power, and employing carbon capture and storage methods (Figure 1). There are also novel strategies in this field, such as enhanced weathering, direct air carbon capture and storage, biochar production, bioenergy carbon capture and storage, oceanization, boosting ocean alkalinity, storing carbon in soil, and creating or restoring wetlands (Fawzy *et al.*, 2020). Importantly, even with progress across various fields, the transportation sector continues to emerge as the quickest-growing contributor to greenhouse gas emissions, indicating a crucial area for focused mitigation initiatives (Wright & Fulton, 2005). While both conventional and cutting-edge methods for reducing CO_2 emissions are clearly outlined, real-world challenges such as financial limitations and technological preparedness obstruct broader implementation. Moreover, certain initiatives, particularly in the transportation sector, demand collaborative efforts among various parties to achieve effective execution and adherence.

Adaptation to climate change: Adaptation strategies consist of a set of actions designed to lessen vulnerability to climate change, which relies on the availability of necessary information and resources for successful execution (Boomiraj *et al.*, 2010). Effective measures for adaptation may involve increasing redundancy within reserve networks to strengthen resilience, as well as promoting proactive forest management techniques like selective thinning and shelter wood cutting to aid forest ecosystems in coping with heightened pest issues and wildfires (Figure 1). Furthermore, freshwater systems are anticipated to face alterations in temperature, flow dynamics, evaporation rates, water quality, and species distribution. Suggested management practices encompass channel redesign, modifications to dams, restoration of floodplains, flow regulation, and stabilization of riverbanks (Lawler, 2009; Kumar & Chopra, 2009). In the fields of climate research and policy, exploring the potential for synergy between climate change adaptation and mitigation has become a primary. There is an increasing need for studies that identify the most effective combinations of these strategies, underscoring the necessity for more research in this domain. (Vijayavenkataraman *et al.*, 2012). The success of adaptation strategies often relies on the specific ecological and socio-economic conditions of a locality, which can make implementation challenging. A failure to thoroughly assess these contextual factors may result in conflicts or unintended negative outcomes, ultimately jeopardizing the anticipated advantages of adaptation initiatives.

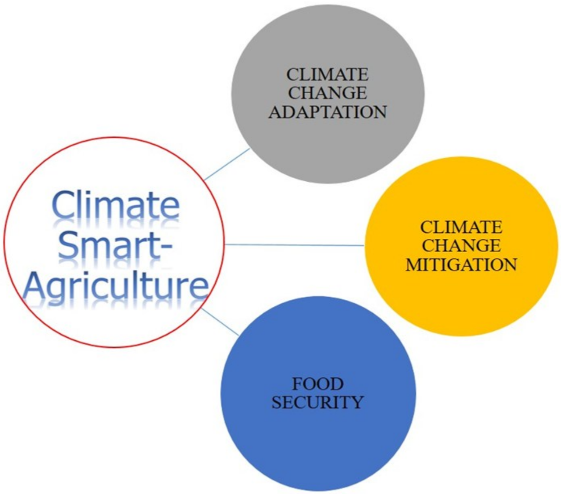

Figure 1. *Three components of climate smart agriculture.*

Food security: Ensuring food security is vital for guaranteeing that everyone has access to adequate, safe, and nutritious food that supports everyday activities and promotes overall health. Food security can be achieved through local production or by obtaining surplus food from other areas (Ehrlich *et al*., 1993). It comprises four essential dimensions: availability, access, food utilization, and stability (Figure 1).

- Availability relates to the amount of food accessible within a country or region, including local production, imports, food reserves, and aid.
- Access refers to the physical, economic, and social means available to obtain food.
- Food Utilization involves consuming safe and nutritious food that satisfies dietary needs.
- Stability signifies the continual availability, access, and proper use of food over time (Simon, 2012).

While these four dimensions of food security present a useful framework, they often fail to account for how socio-political factors affect food distribution and access. Moreover, climate change presents considerable threats to all four dimensions, highlighting the need for integrated strategies that foster resilience and adaptability within food systems.

CLIMATE SMART AGRICULTURE PRACTICES

There are various strategies for climate-smart agriculture (CSA) that aim to boost resilience, decrease greenhouse gas emissions, and enhance productivity. Below are some essential practices:

Agroforestry: Agroforestry combines trees and shrubs with crops and livestock for improved ecological and economic outcomes. This approach operates on the premise that diverse systems leveraging a blend of trees and crops can more effectively utilize resources like nutrients, light, and water than monoculture practices (Nair *et al*., 2009). Additionally, agroforestry supports better nutrient cycling and soil health. Recent efforts have broadened agroforestry to include integrating trees into farming alongside crops and livestock, initiating small-scale forestry on farms, rehabilitating degraded lands, and implementing practices in regions with poor soil conditions. Although agroforestry presents a sustainable solution for boosting productivity and rehabilitating damaged lands, its success often hinges on local context. Expanding these systems necessitates investment in farmer education and tackling socio-economic obstacles, particularly in areas with limited infrastructure or motivation for adoption.

Conservational agriculture: Conservation agriculture (CA) focuses on minimal soil disruption (no-till), maintaining permanent soil cover (mulch), and employing crop rotations to promote soil health. Permanent organic cover protects the soil from environmental factors like sunlight, rainfall, and wind while supplying nutrients for soil organisms and enhancing biodiversity. CA supports water conservation, improves soil structure, and captures carbon in the soil, making agricultural practices more resilient to climate change (Hobbs *et al*., 2008; Lal, 2015). While CA provides clear advantages for soil health and water preservation, the widespread implementation of no-till farming frequently faces challenges due to cultural habits, gaps in technical knowledge, and the initial costs associated with transitioning. Increased research is needed to identify local-specific barriers and facilitate effective knowledge dissemination to farmers.

Water saving irrigation techniques: Irrigation methods like Deficit Irrigation (DI) and Partial Root Zone Drying (PRD) have been investigated to enhance water use efficiency. In areas struggling with water shortages, such as China, techniques like Alternate Wetting and Drying (AWD) have demonstrated positive outcomes in rice farming by lowering water consumption while sustaining productivity. Research indicates that AWD can enhance irrigation water efficiency by 5–35% in comparison to continuous flooding (El-abedin *et al*., 2017; Barker *et al*., 2001). These irrigation strategies have substantial potential to tackle water scarcity, particularly in regions dependent on crops like rice that consume large amounts of water. Nonetheless, ensuring the long-term viability of AWD and similar methods requires additional research to confirm they do not adversely affect crop yields or soil health over time.

Crop diversification and rotation: Crop diversification means increasing the variety of crops through practices like rotation, intercropping, or multiple cropping systems. This approach enhances ecosystem services, strengthens soil characteristics, and builds resilience against climate change. Studies indicate that crop rotations, such as switching between maize and soybeans, can boost yields by 5–10% while also improving soil water retention and microbial diversity (Hufnagel *et al*., 2020; Bowles *et al*., 2020). Although crop diversification presents both environmental and financial advantages, challenges such as the availability of market support for alternative crops and farmers' access to knowledge and resources remain. Improving market incentives and researching crop-specific benefits could aid in wider adoption.

Table 1. CSA adaptation in different countries.

Country	CSA Adaptation	References
Kenya, Rwanda, and Uganda	Increase in monthly milk intake by dairy businesses from 529,000 to 3 million liters between 2008 and 2014. Farmers also saw their earnings per liter of milk rise from $0.2 to $0.3 during this period.	Nyasimi (2014)
Rwanda	Rice yield rose from 3–4 tons per hectare to around 7.5 tons per hectare between 2006 and 2009.	Nyasimi (2014)
Pakistan	Compared to their CSA adapters in cotton farming, those who use conventional methods pay more for critical external inputs such as irrigation, fertilizers, and chemicals.	Imran *et al.* (2018)
North America	Farmers got 5-10% increment in maize yield in smile crop rotation than monoculture.	Bowles *et al.* (2020)
China	The efficiency of irrigation water use under AWD is reported to be 5–35% higher than that, under continuous flooding practices.	Barker *et al.* (2001)
India	50% of livestock losses followed by issues in reproduction and health due to lack of smart livestock practices.	Yadav *et al.* (2014)

Improved livestock management: Enhanced livestock management centers on optimizing techniques such as breeding, nutrition, healthcare, and integrated crop-livestock management practices (ICLMPs). These methods aim to boost productivity while ensuring animal welfare, reducing stress, and minimizing environmental effects. Implementing efficiency-enhancing technologies and sustainable practices can result in increased milk and meat production, benefiting both food security and the income of farmers (Yadav *et al.*, 2014; Orihuela, 2021). The effectiveness of improved livestock management largely relies on tailoring these methods to local circumstances. Existing gaps in addressing animal welfare issues and ensuring that small-scale farmers have access to new technologies persist, particularly in areas with limited resources.

Soil carbon sequestration: Soil carbon sequestration refers to the process of capturing atmospheric CO_2 and storing it as organic matter in the soil. This practice boosts soil organic carbon (SOC), enhances soil quality, and protects SOC from microbial breakdown through various mechanisms like stable microaggregates or recalcitrant carbon (Lal, 2004). The effectiveness of SOC sequestration is influenced by soil composition, environmental conditions, and microbial activity, with clay soils generally being more efficient at retaining carbon than sandy soils (Lal *et al.*, 2015). While soil carbon sequestration is a promising strategy for mitigation, its effectiveness is highly reliant on local soil types and climate. Further investigation is essential to refine sequestration methods across various ecosystems and to tackle challenges related to monitoring long-term carbon storage.

POTENTIAL BENEFITS

Increased agricultural productivity and food security: Climate-Smart Agriculture (CSA) has been crucial in boosting agricultural output while adapting to changing climate conditions and lowering emissions (Table 1). CSA emphasizes four primary areas of agricultural practices: conservation tillage, soil fertility management, improved nitrogen efficiency, and alternating wet and dry cycles. These methods have shown favorable impacts on crop yields and reductions in greenhouse gases across various scenarios; however, they require tailored adjustments and adaptations at the local level (De Pinto *et al.*, 2020). Climate change disrupts food markets, posing risks to the food supply of the entire population. By enhancing farmers' adaptability, strengthening resilience, and optimizing resource efficiency within agricultural systems, these threats can be diminished. The CSA encourages farmers, researchers, business sector players, non-profits, and policymakers to work together to advance climate-resilient initiatives. This collaboration focuses on four key areas: generating supportive evidence, strengthening the capacity of local institutions, fostering alignment between climate and agricultural policies, and bridging funding for climate and agriculture (Lipper *et al.*, 2014). The collaborative approach promoted by CSA is essential for tackling the challenges posed by climate change and food security. Nonetheless, putting these action areas into practice can be difficult due to differing priorities among stakeholders and the necessity for local adaptations. Creating supportive evidence involves comprehensive research and data collection, often requiring significant resources.

Enhanced resilience to climate-related risks: CSA primarily aims to mitigate the impacts of extreme weather events and facilitate a quick recovery to normal operations. Key components of these strategies involve anticipating changes, building resilience and redundancy, adapting, and recovering swiftly (Marie *et al.*, 2019). In recent years, various innovations related to climate-smart agriculture have emerged, including drought-resistant crop varieties, climate information services, agricultural insurance, agroforestry, water collection techniques, and integrated soil fertility management. In the context of climate change, these innovations are seen as progressive means to sustainably improve farm productivity, enhance rural livelihoods, and increase farmers' capacity to adapt, while also contributing to mitigation efforts. Climate change policies and initiatives at regional, sub-regional, and national levels have been established to lessen the impacts of climate change and improve the adaptability of African populations, thereby facilitating the integration of climate-smart agriculture into agricultural development strategies. While the emphasis on adaptation and building resilience is praiseworthy, it's important to acknowledge the potential drawbacks and trade-offs that may arise from implementing climate-smart innovations. For example, while drought-resistant crops might yield better results in certain scenarios, they could also result in decreased genetic diversity and increased dependence on specific varieties. Additionally, the effectiveness of agricultural insurance and climate information services can differ based on farmers' access to needed information and financial resources, particularly in underserved communities. Therefore, promoting resilience must go hand in hand with inclusive strategies that take into account socio-economic disparities and empower all farmers.

Reduced greenhouse gas emissions and carbon sequestration: Soil organic carbon is vital in this process as it boosts soil biodiversity by providing energy to soil microorganisms. It enhances the formation of soil aggregates, which decreases vulnerability to erosion, and improves nutrient and water efficiency by reducing losses through drainage, evaporation, and volatilization. Furthermore, soil organic carbon serves as a buffer against rapid changes in soil pH brought about by agricultural chemicals and helps regulate soil temperature through its impact on soil color and albedo. This process also lowers sediment loads in waterways, acts as a filter for pollutants from agricultural chemicals, aids in breaking down contaminants, and helps mitigate greenhouse gas emissions from the soil into the atmosphere (Lal, 2004). The significance of soil carbon sequestration is increasingly acknowledged as a key strategy for combating climate change and enhancing ecosystem functions. However, achieving substantial carbon sequestration requires ongoing management practices and a long-term commitment from farmers. The challenges of measuring and verifying soil carbon levels can complicate efforts to incentivize practices that encourage carbon sequestration. Moreover, a potential conflict may arise between immediate agricultural productivity goals and the long-term advantages of carbon management, indicating a need for policies that promote sustainable practices while ensuring short-term food security.

CHALLENGES

Economic viability: Implementing Climate-Smart Agriculture (CSA) practices might be challenging for smallholder farmers due to economic hurdles. These limitations include a scarcity of farmland, concerns with land rights, little information about CSA, and a slow return on investment. Inadequate policy and execution methods, particularly those involving land tenure and financial assistance programs, are frequently viewed as unsuccessful. Many smallholder farmers struggle with fertilizer application and organic matter management, owing to the prohibitively expensive cost of fertilizers, which can result in unfavorable nutritional imbalances in their farmlands. As a result, crop yields on small-scale farms are much lower than their potential capacity, frequently falling below 50% of those achieved on experimental farms and research stations (Zerssa *et al*., 2021). Financial constraints also limit these farmers' capacity to invest in critical commodities such as land, machinery, and livestock. Although CSA can be more profitable in the long term than traditional farming practices, the initial investments may be prohibitively expensive or dangerous for small-scale farmers to make on their own. Vulnerable farmers, particularly those concerned about household food security, prefer to avoid risks, leaving little margin for error. In some agro-ecological settings, CSA methods may even necessitate substantial soil excavation to address soil crusts, raising early labor demands for site preparation (Kaptymer *et al*., 2019). Economic hurdles highlight the conflict between necessary investments and the urgent cash demands on smallholder farmers. To encourage CSA, targeted financial support and risk-sharing structures are critical, allowing farmers to invest in sustainable practices without risking their current incomes.

Technical constraints: Impoverished households frequently lack the necessary knowledge, expertise, and resources to apply new CSA practices. CSA encourages a variety of conservation farming techniques designed to improve soil fertility, avoid erosion, and conserve water. Contour ridging, manure application, compost production, low tillage, agroforestry, and the use of herbicides to save labor are some of these strategies. However, many poor farmers struggle to implement these methods due to a lack of critical skills and knowledge (Murray *et al*., 2016). Trustworthy technology enterprises are critical for the transition to a more sustainable future, especially in the context of CSA (Table 1). Delayed adoption and dissemination rates are frequently correlated with temporal limits imposed by relevant policy goals and climate change. As a result, a better understanding of the individual barriers to adoption is critical. This insight can help with the development and execution of initiatives targeted at reducing barriers. As a result, the efficient adoption and diffusion of CSA technical breakthroughs is a major issue that must be addressed at the policy, research, and practice levels (Long *et al*., 2015). Addressing technological obstacles is critical to CSA adoption (Table 1). Improving education and creating relationships with technical enterprises can provide farmers with the required skills and resources, closing the knowledge gap and supporting more resilient agricultural methods.

Social implications: Gendered institutional, informational, and knowledge-related hurdles frequently impede women's use of agricultural technology. The knowledge and expertise needed to operate irrigation equipment and manage conservation agriculture are not widely available. In Ethiopia, for example, women smallholders have limited access to extension services and training opportunities due to gender biases in agricultural organizations. Male farmers generally receive more agricultural extension assistance, whereas female-headed households frequently receive less supervision than their male counterparts. Furthermore, extension services typically fail to address female farmers' unique demands and chosen technology. The predominance of male extension agents exacerbates this difficulty, as cultural norms in some communities prohibit married women from engaging with external agents in front of their husbands (Tsige *et al*., 2020). The social hurdles to technology adoption highlight the need for inclusive policies. Empowering women through focused training and resources can boost productivity and improve gender parity, hence benefiting the agricultural sector as a whole.

Policy and institutional support: Government entities, such as authorities, ministries, departments, and municipal governments, are critical to policy development. However, the private sector's role in promoting CSA practices is frequently restricted, and government officials' competitive attitudes and a lack of resources at the lowest levels compound the problem. Conversations with district representatives revealed a lack of understanding how communities might impact the successful implementation of policies (Ampaire *et al*., 2015). These policy problems highlight the importance of comprehensive approaches that stress community involvement and flexibility. Collaboration among stakeholders can improve policy efficacy by ensuring that CSA practices are relevant and accessible to smallholder farmers.

FUTURE DIRECTION AND RESEARCH NEEDS

Enhancement of management approaches and cropping patterns: Examples of multiple cropping patterns, crop diversification techniques, and no-till agriculture that can boost agricultural productivity and lower greenhouse gas emissions include rice-wheat rotation and rice-potato-sesame cropping. Appropriate dry land crops can also be introduced to shorten the submergence period in the annual planting cycle. It is advised to use soil protection techniques such crop residue utilization, increased nitrogen use efficiency, and decreased planting in order to lower CO_2 emissions. Crop production can be increased by applying crop wastes because they boost soil organic carbon. These doable actions can reinforce the element cycle, enhance soil structure, further preserve water, boost agricultural productivity, and lower greenhouse gas emissions. Future CSA development will advance sustainable agriculture development and accomplish the triple bottom line of reducing greenhouse gas emissions, ensuring food security, and adapting to climate change (Table 1). Enhancing cropping strategies and management approaches helps make CSA a reality in the future (Zhao *et al*., 2023).

Internet of Things (IoT): In order to give the best alternative for gathering and processing information while increasing net production, new technologies and solutions are being deployed in the agricultural sector. IoT integrates sensors and actuators with people, processes, devices, and technology. It is possible to pursue real-time decision-making thanks to the overall integration of IoT with humans in terms of communications, cooperation, and technological analytics.

Applications for agriculture based on IoT: System for managing irrigation Dairy observation Monitoring of water quality Greenhouse condition tracking Soil observation accuracy Agricultural Production Supply chain management is referred to as agricultural (Ray, 2017).

Improved water management technologies: Water efficient irrigation systems technologies ranging from basic syphon tubes for field water application to complex canal automation and telemetry are available for better operation, better administration, and more effective use of irrigation water. In rice farming, water-efficient irrigation systems include:

i) Alternating wetting and drying in addition to ii. Combining wetting and drying with shallow water layer irrigation systems.
ii) Semi-Dry Cultivation (SDC) (Kulkarni, 2017).

In-situ moisture conservation: Careful application of irrigation water on the farm can improve its efficiency. Crop productivity and water use efficiency are increased by on-farm water management techniques such as conserving moisture in-situ, reducing seepage loss through lining material, improving irrigation channel conveyance efficiency, applying water efficiently, scheduling irrigation, altering crop establishment, and using irrigation water for multiple purposes. To preserve in-situ moisture, a variety of materials were used as mulch including cowpea, lantana, daincha, paddy husk, paddy straw, grass, and black polythene. Research has shown that using mulch is a useful technique for preserving moisture in-situ and that it can assist reduce the amount of water crops need from external sources (Upadhyaya, 2015).

Weather index-based insurance: Weather Index Crop insurance provides access to financing, making it an essential component of financial inclusion, and it encourages/protects investments in improved inputs and technology that increase production. The various types of insurance also lower the government's financial exposure to agricultural risks. Crop insurance may encourage farmers to raise their input consumption, however indemnity-based crop insurance plans are plagued by market failures (Kajwang, 2022). IBRTPs (Index-Based Risk Transfer Products) serve as both a loss proxy and a means of transferring risk to insurance or capital markets. These products are intended to pay out when an independent physical measure of a loss event (such as extreme weather, area yields, or even complex process models that use satellite images) exceeds a threshold value of the index, indicating that catastrophic conditions are causing significant problems for clients (Skees, 2008).

Crop diversification planting: In order to increase ecosystem resilience and productivity, diverse cropping is defined as the deliberate incorporation of functional biodiversity at temporal and/or spatial scales. The most effective technique for establishing a resilient and sustainable agricultural system is to combine diverse farming with ecological weed management solutions. Farmers, on the other hand, are hesitant to implement a varied cropping system due to the need for different skill sets and a larger initial investment (Sharma *et al.*, 2021). Diversification in agricultural systems can benefit farmers from climate change by increasing structural diversity, increasing genetic diversity in monocultures, diversifying fields with non-crop vegetation, implementing crop rotations, polycultures, agroforestry, and mixed landscapes (Brenda, 2011).

Conclusion

Climate-Smart Agriculture (CSA) has proven its revolutionary power by considerably enhancing agricultural productivity and resilience. For example, dairy companies considerably improved milk production, resulting in higher revenues for farmers, while rice yields grew significantly. In cotton farming, CSA users outperformed traditional methods by lowering input expenses such as irrigation and herbicides, resulting in long-term economic benefits. Crop rotation and irrigation procedures have been improved in other regions, increasing water efficiency and yield. However, the lack of CSA methods in some places has resulted in significant losses, emphasizing the crucial need for widespread CSA implementation to maintain sustainability and resilience to climate concerns.

DECLARATIONS

Authors contribution

Conceptualization and design: S.R. and B.P.; Critical analysis and synthesis: S.R.; Writing and drafting: S.R. and B.P; Literature search and collection: S.R. and B.P; Editing and revising: S.R.

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