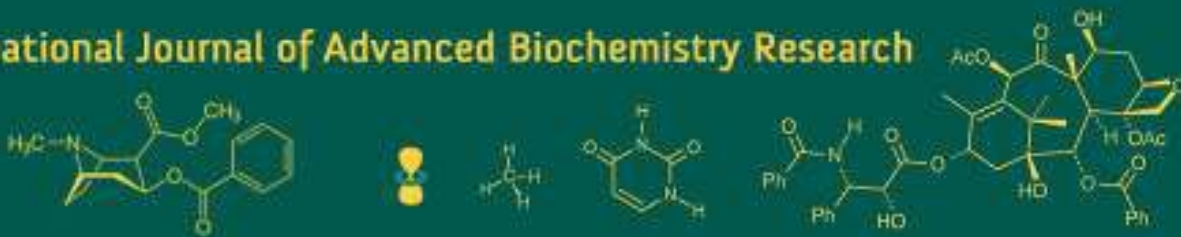


International Journal of Advanced Biochemistry Research



ISSN Print: 2617-4693
 ISSN Online: 2617-4707
 NAAS Rating (2026): 5.29
 IJABR 2026; SP-10(4): 46-52
www.biochemjournal.com
 Received: 22-01-2026
 Accepted: 25-02-2026

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Economics of climate-smart agriculture for sustainable farm income

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DOI: <https://www.doi.org/10.33545/26174693.2026.v10.i4Sa.8052>

Abstract

Climate-Smart Agriculture (CSA) has become a pivotal, integrative concept to solve the challenges of climate change and agricultural sustainability in many agro-ecological environments. CSA is gaining recognition for its potential to simultaneously increase productivity and resilience and reduce greenhouse gas emissions, thus supporting sustainable development goals. This review brings together recently published literature on economic aspects of CSA with attention to the potential for increasing farm income, enhancing resource-use efficiency and hedging production risks under climate variability. Empirical results indicate that CSA practices including conservation agriculture, agroforestry, diversification, efficient water use, and other related practices, among others, contribute to substantial improvement in yield stability and farm profitability. Moreover, by minimizing exposure to extreme climate events, CSA contributes to enhanced resilience and income stability for farmers. Nonetheless, adoption of CSA practices is subject to a number of economic and institutional barriers such as substantial upfront investment, lack of access to credit and extension services, and so on. The review underscores the significance of cost-benefit analysis, policy interventions, and institutional support in facilitating a wider adoption of CSA for sustainable income generation.

Keywords: Climate-smart agriculture, farm income, economic efficiency, resilience, cost-benefit analysis, sustainability

1. Introduction

Agriculture continues to be among the sectors most vulnerable to climate, particularly in the developing world where the livelihood of majority of the population is tied to rain-fed agriculture (FAO, 2023; World Bank, 2023; Raveloaritiana and Wanger, 2024; Mwikamba *et al.*, 2024) [43, 48]. Climate variability and change have dramatically influenced agricultural productivity by way of increasing temperatures, unpredictable rainfall patterns, and growing occurrence of extreme events such as droughts and floods (Hussein & Toru, 2024; Wekesa *et al.*, 2022; Tanti *et al.*, 2024) [22, 53]. These climatic shocks have caused declining crop yields and increasing production risk and farm income, posing food security and livelihoods of the rural poor at risk (Ma and Rahut 2024; Rahut *et al.*, 2024; Musafiri *et al.*, 2022) [41]. Against these challenges, Climate-Smart Agriculture (CSA) has been advocated as an integrated strategy to improve agriculture sustainability and resilience (FAO, 2023; Sang *et al.*, 2024; Villalba *et al.*, 2024) [51, 58].

CSA is founded on three interrelated pillars, which includes sustainably increasing productivity, adaptation to and resilience of the agricultural system to climate change, and mitigation of GHG emissions (FAO, 2023; Springer, 2024; Musafiri *et al.*, 2022) [41]. The synergistic combination of these pillars is vital in keeping agricultural systems economically sustainable, environmentally sound, and socially equitable (Bekuma, 2024; Raveloaritiana & Wanger, 2024; Bekuma, 2024) [8, 48]. CSA seeks to increase farm income in a sustainable manner through enhancing resource use efficiency and reducing resource use entropy, and through decreasing the risk for production associated with climate variability (Rahut *et al.*, 2024; Arslan *et al.*, 2018; Anjanappa, 2025) [3, 5]. Several panic studies have found that the usage of CSA practices is associated with substantial increases in farm productivity and household welfare (Musafiri *et al.*, 2022; Wekesa *et al.*, 2022; Kpadonou *et al.*, 2026) [31, 41].

2. Conceptual framework of CSA economics

2.1 Definition and principles

Climate-Smart Agriculture (CSA) is an integrated approach that seeks to improve productivity, strengthen resilience and mitigate emissions from agricultural systems (Joy *et al.*, 2025; FAO, 2023) ^[25]. The economic basis of CSA is to manage trade-offs between resource use and environmental externalities and climate risk (Bekuma, 2024; Kompas *et al.*, 2024) ^[8, 30]. The increasing productivity of agriculture attributable to CSA practices is a result of improved soil, water, and crop management (Rahut *et al.*, 2024). Simultaneously, CSA increases the resilience of farmers by promoting diversified and flexible production systems conducive to adapting to climatic variability (Musafiri *et al.*, 2022; Lipper *et al.*, 2014) ^[34, 41]. CSA also has climate change mitigation significance in that it reduces greenhouse gas emissions through sustainable land management (Springer, 2024; Thierfelder *et al.*, 2024) ^[56].

Economic evaluation of CSA revolves around cost-benefit analysis, which analyzes the costs and benefits of using different practices (Heena *et al.*, 2025; Khatri-Chhetri *et al.*, 2017) ^[20, 27]. Likewise the risk-return considerations in CSA economics, farmers face balancing potential returns with uncertainties inherent to climate variation (Arslan *et al.*, 2018; Makate *et al.*, 2020) ^[6, 36]. An efficient use of resources is also important, as CSA contributes to better management of resource inputs like water, fertilizers, and energy (World Bank, 2023).

2.2 Economic theory behind CSA

CSA is based on a set of economic theories, including sustainable development theory that focuses on reconciling economic development with environment protection (Raveloaritiana & Wanger, 2024; Yeshawanth *et al.*, 2025) ^[48, 61]. Production economics is also essential for analyzing the effects of CSA practices on input-output relationships and farm income (Bekuma, 2024; Di Falco *et al.*, 2022) ^[8, 12]. Theory of risk management is more so applicable given

that CSA enables farmers to reduce their exposure to climate-related risks and uncertainties (Arslan *et al.*, 2018; Wossen *et al.*, 2023; Manda *et al.*, 2025) ^[5, 37, 60].

From the theoretical standpoint, CSA may be seen as the solution to a dynamic optimization problem farmers seek to maximize their long-run welfare under climate uncertainty (Rahut *et al.*, 2024). Decisions related to this process include the allocation of resources, the adoption of technology, and the risk management policy to be followed in the long run (Musafiri *et al.*, 2022). The determinants of adoption of CSA practices are related to anticipated benefits, risk attitudes and support system as institution (Heena *et al.*, 2025; Jaleta *et al.*, 2023) ^[20, 24].

3. Economic benefits of climate-smart agriculture

3.1 Productivity and income enhancement

CSA interventions have reported substantial positive impacts on agricultural production and farm income in various context (Wekesa *et al.*, 2022; Khonje *et al.*, 2026) ^[28]. Conservation agriculture (minimum tillage and retention of crop residues) practices, for example, may lead to a 10-20% increase in yields compared to conventional farming (Rahut *et al.*, 2024; Portner *et al.*, 2022). These practices also lower the cost of inputs by reducing the need for labor, fuel, and chemicals, which means higher net farm income (Hellin *et al.*, 2023; Bekuma, 2024) ^[8, 21]. Through the combination of trees, crops, and livestock, agroforestry systems offer more diversified income sources, and hence better economic resilience (Raveloaritiana & Wanger, 2024; Vermeulen *et al.*, 2023) ^[48, 57]. In the same way, micro-irrigation methods, including drip and sprinkler irrigation systems contribute to enhanced water use efficiency, higher crop productivity and farm income (World Bank, 2023; Antle *et al.*, 2017) ^[4]. Crop diversification also reduces production risk (Musafiri *et al.*, 2022; Barrett *et al.*, 2021) ^[7, 41]. In general, adoption of CSA results in increased income and less poverty in farm households (Rahut *et al.*, 2024; Tesfaye *et al.*, 2024) ^[55].

Table 1: Economic benefits of CSA practices

CSA Practice	Economic Benefit	Evidence
Conservation agriculture	Reduced input costs, higher yields	10-20% yield increase
Agroforestry	Diversified income	50-100% income increase
Micro-irrigation	Water and energy savings	25-40% income rise
Crop diversification	Risk reduction	Higher income stability

3.2 Cost-benefit analysis

Cost-benefit analysis is commonly applied to analyze the cost-effectiveness of CSA practices (Heena *et al.*, 2025; Garrity, 2004) ^[17, 20]. Reviews show that returns on investments in CSA are generally high with benefit-cost ratios of around 1.5 to 2.5 according to the practice and the region (Rahut *et al.*, 2024; Mbow *et al.*, 2020) ^[39]. In certain instances, returns from investments in CSA can be as high

as four times the initial cost, especially in climate resilient agriculture systems (World Bank, 2023; Miller *et al.*, 2022) ^[40]. While some CSA practices need significant up-front investment, such as drip irrigation systems, they deliver significant benefits over time (Bekuma, 2024; Snapp, 2020) ^[8, 52]. Costs for practices such as conservation tillage are so relatively low and returns so rapid that smallholder farmers can adopt them (Musafiri *et al.*, 2022) ^[41].

Table 2: Cost-Benefit comparison of CSA practices

Practice	Initial Cost	Returns	Payback Period
Drip irrigation	High	High	Medium
Agroforestry	Medium	Very high	Long
Conservation tillage	Low	Moderate	Short

3.3 Risk reduction and resilience

Climate-Smart Agriculture (CSA) has a significant and growing contribution to the reduction of climate-related

risks in agricultural systems, by increasing the adaptive capacity of farmers and the resilience of production systems in the face of climatic variability and change (Arslan *et al.*,

2018; FAO, 2023; Kremen *et al.*, 2012) [5, 32]. This is done through the adoption of sustainable land management practices, use of improved crop varieties, and good water and nutrient management, which altogether contribute to reduce the exposure to climatic shocks including droughts, floods and temperature extremes (Rahut *et al.*, 2024; Hussein & Toru, 2024; Pretty *et al.*, 2012) [22, 47]. Among the ways in which CSA mitigates risk is improved soil quality and water retention for crops to better endure dry seasons and irregular rainfall distribution (Wekesa *et al.*, 2022; Bekuma, 2024; Duff *et al.*, 2021) [8, 13]. Such applications as conservation tillage, mulching and organic amendments enhance the level of soil organic matter to improve soil structure and its ability to hold moisture, which is important to crop growth in arid environments (Musafiri *et al.*, 2022; FAO, 2023; Altieri *et al.*, 2025) [2, 41]. These practices, through the control of soil erosion and improved nutrient cycling, enhance long term productive capacity and resilience, and consequently the chances of crop failure under adverse climate scenarios are reduced (Rahut *et al.*, 2024; Springer, 2024; Gliessman, 2020) [18]. Along with soil-based strategies, CSA also endorses drought-tolerant and climate-resilient cultivars better adapted to evolving environmental conditions which mitigate production risks even further (Hussein & Toru, 2024; World Bank, 2023; Zhu, & Burney, 2022) [22, 64].

4. CSA and Farm income sustainability

Diversified farming systems also constitute a central aspect of the CSA model and improve adaptability through risk-sharing across diverse enterprises such as crops, animals, and agroforestry (Musafiri *et al.*, 2022; Raveloaritiana & Wanger, 2024; Rede *et al.*, 2025) [41, 48, 49]. The diversification on the production side allows farmers to hedge against reliance on one crop or source of revenue, protecting them from commodity-specific shocks to production or prices (Bekuma, 2024; Rahut *et al.*, 2024; Frimpong *et al.*, 2023) [8, 16]. For instance, the raising of animals integrated with crop cultivation can be a source of supplemental income and food security, while agroforestry is a means of obtaining long-term advantages from timber, fruits and ecosystem services (Raveloaritiana & Wanger, 2024; FAO, 2023) [48]. This diversity not only enhances economic resilience but also strengthens ecological stability through biodiversity, sustainable land use and reduction of chemical reliance (Springer, 2024; Wekesa *et al.*, 2022). Moreover, by contributing to stable yields over time, CSA also reduces risk, which in itself diminishes income uncertainty and increases the degree of financial security for farmers (Rahut *et al.*, 2024; Musafiri *et al.*, 2022; Kapoor *et al.*, 2022) [26, 41]. In the context of climate change, stability of agricultural production matters because it guarantees production continuity in the face of environmental variations, thereby showing a lesser probabilities of income shocks (Bekuma, 2024; World Bank, 2023; Bell *et al.*, 2022) [8, 9].

5. Determinants of economic adoption

There is a synergistic effect resulting in the adoption of CSA practices being more economically stable and less climate shock vulnerable for the farmer when compared with conventional agriculture practice adoption (Arslan *et al.*, 2018; Rahut *et al.*, 2024; Fishman *et al.*, 2016) [5, 15]. Empirical evidence has demonstrated that the adoption of

CSA reduces income variability, mitigates the management of risks, and improves the capacity to withstand extreme weather events contributing to maintenance of sustainable livelihoods (Wekesa *et al.*, 2022; Musafiri *et al.*, 2022; Hailemariam *et al.*, 2024) [19, 41]. Additionally, CSA increases the ability of farmers to respond to slower climate shifts that are part of long-term climate trends through flexible and adaptive management options for changes in climate trends (FAO, 2023; Bekuma, 2024; Fan *et al.*, 2023) [8, 14].

6. CSA and Poverty reduction

Climate-Smart Agriculture also contributes to sustainable farm income through the development of diversified and resilient farming systems that can sustain their productivity in the long run (Rahut *et al.*, 2024; Raveloaritiana & Wanger, 2024) [48]. Diversification of income is a key element of CSA, which decreases level of financial risks and improve the livelihood security as it offers more sources of income (Musafiri *et al.*, 2022; Bekuma, 2024) [8, 41]. Crop-livestock systems, for instance, enable smallholder farmers to earn off both crop cultivation and livestock production, reducing risk by not relying on a single enterprise and increasing overall profit (FAO, 2023; Raveloaritiana & Wanger, 2024; Izuogu *et al.*, 2025) [23]. Agroforestry systems contribute to diversifying income by incorporating trees within farming systems, trees which yield products including fruits, timber, and fuel wood while also rendering ecosystem services such as enhancing soil fertility and sequestering carbon (Springer, 2024; Rahut *et al.*, 2024). These diversified systems not only lead to greater income stability but also have the potential to contribute to greater climate resilience through the distribution of risk among different farm system components (Bekuma, 2024; Wekesa *et al.*, 2022; Alsanoosy, and Malik, 2025) [1, 8].

7. Policy implications

Adoption of CSA over time results in accrued benefits, which in turn results in long-run financial and environmental gains (Rahut *et al.*, 2024; FAO, 2023). Enhanced soil fertility, Water Use Efficiency (WUE), and biodiversity are some of the CSA impacts that facilitate sustained productivity and income (Musafiri *et al.*, 2022; Springer, 2024; Capetz *et al.*, 2024) [11, 41]. These advantages may be especially significant in a changing climate since they allow farming systems to sustain production in the face of more variable and less predictable weather conditions (Bekuma, 2024; World Bank, 2023) [8].

8. Case studies (Global Evidence)

The decision to adopt CSA practices is determined by a set of interrelated socioeconomic and institutional factors that influence farmers' capacity and willingness to invest in new technologies and practices (Heena *et al.*, 2025; Rahut *et al.*, 2024) [20]. Some of these socio-economic determinants of adoption include farm size, level of education, income, and labor availability, which influence individuals'/households' resource availability and risk bearing capacity (Musafiri *et al.*, 2022; Bekuma, 2024) [8, 41]. In general, larger farms with good access to capital and information tend to be the most adopters of CSA practices, while smallholders farmers commonly encounter barriers associated with insufficient financial means and knowledge (FAO, 2023; World Bank,

2023). Education and awareness also contribute to adoption since these two factors affect farmers' perception of benefits and risks of CSA technologies (Heena *et al.*, 2025; Rahut *et al.*, 2024; Wolfert and Isakhanyan, 2022) ^[20, 59].

Factors such as extension services, market access and government policy also contribute to enabling adoption and improving economic benefits of CSA (World Bank, 2023; Bekuma, 2024; Zhang *et al.*, 2025) ^[8, 62]. Extension services give farmers technical knowledge, training and assistance, which helps them promote CSA practices more effectively and efficiently (FAO, 2023; Musafiri *et al.*, 2022) ^[41]. Market access is also a crucial issue in agricultural production, affecting producers' ability to recoup their investments and the profitability of agricultural production (Rahut *et al.*, 2024; Wekesa *et al.*, 2022). Public policy including subsidies, credit schemes and insurance schemes can positively impact adoption by alleviating financial impediments and risk (World Bank, 2023; Bekuma, 2024) ^[8]. Two other important determinants that emerge from the literature are the cost of technology and the risk factor. Nevertheless, cost of initial investment and credit access are still substantial impediments to adoption for a lot of smallholder farmers in developing countries (FAO, 2023; Heena *et al.*, 2025) ^[20].

9. Environmental and Economic synergies

9. Environmental and Economic synergies

CSA is also believed to contribute to poverty reduction through increasing farm income, improving food security and resilience to climate shocks (Rahut *et al.*, 2024; Musafiri *et al.*, 2022) ^[41]. With its focus on increasing production and reducing risks, CSA allows farmers to have better and more stable income which helps reduce poverty and improve livelihoods (Bekuma, 2024; World Bank, 2023) ^[8]. Enhanced food security is another significant impact of CSA because increased and more stable yields guarantee a steady source of nourishment for farming households (FAO, 2023; Wekesa *et al.*, 2022). Literature has revealed that adopters of CSA practices tend to be better off than non-adopters, signifying the importance of CSA for inclusive and sustainable development (Rahut *et al.*, 2024; Musafiri *et al.*, 2022) ^[41].

Commercial policy support is required to scale up CSA adoption and its economic benefit (FAO, 2023; World Bank, 2023). Financial support in the form of subsidies, tax relief and carbon credit schemes may incentivize farmers to adopt CSA practices by lowering the cost of implementation (Bekuma, 2024; Rahut *et al.*, 2024) ^[8]. Institutional backing, eg, raising the capacity of extension services and offering training is essential to enhance awareness and preparedness among farmers (Musafiri *et al.*, 2022; FAO, 2023) ^[41]. Risk management instruments, including crop insurance and climate advisory services, can assist farmers in adapting to climate variability and mitigating risk to encourage adoption (World Bank, 2023; Wekesa *et al.*, 2022).

10. Challenges and Research gaps

The economic profitability of CSA across varied contexts has been substantiated by empirical findings from several countries (Rahut *et al.*, 2024; Bekuma, 2024) ^[8]. In India, for instance, farmers that adopted micro-irrigation systems have experienced rise in income by 25–40% as a result of increased water-use efficiency, the best practice, and larger yield (World Bank, 2023; FAO, 2023). Crop diversification

faring better to increase income and climate vulnerabilities reduction in Ethiopia and integrated farming system in Zimbabwe has led to better household welfare and resilience (Musafiri *et al.*, 2022; Rahut *et al.*, 2024) ^[41]. The adoption of CSA has played a role in the alleviation of poverty and enhancement of food security in Bangladesh, showcasing CSA's capacity to contribute to sustainable development (Wekesa *et al.*, 2022; Bekuma, 2024) ^[8].

CSA fosters convergence of economic and environmental goals by advocating for production systems that increase productivity and mitigate environmental degradation (Springer, 2024; Raveloaritiana & Wanger, 2024) ^[48]. Enhanced soil fertility, sustainable water use, and decreased emissions of greenhouse gases support the durability of agricultural systems (FAO, 2023, Rahut *et al.*, 2024). These synergies are key especially in the context of climate change, as they allow farming systems to pursue dual economic and environmental objectives (Bekuma, 2024; World Bank, 2023) ^[8].

However, the implementation and scaling of CSA is challenged by various bottlenecks (FAO, 2023; Heena *et al.*, 2025) ^[20]. Among the important barriers to adoption are high upfront investment costs, lack of access to finance, and scarcity of long-term economic data (Rahut *et al.*, 2024; Bekuma, 2024) ^[8]. Furthermore, there is a need for economic models that are location-specific, consider local conditions and variability, and for improved uptake of CSA by national and global policy frameworks (World Bank, 2023; FAO, 2023).

11. Future research directions

Further research on CSA is warranted to focus on new frontiers, including digital agriculture, climate finance, and gender responsive approaches for sustainable and equitable development (Rahut *et al.*, 2024; Bekuma, 2024) ^[8]. Application of technology-based tools such as artificial intelligence (AI) and remote sensing (RS) can facilitate decision making and increase the efficiency of CSA practices (World Bank, 2023; Wekesa *et al.*, 2022). Instruments related to climate finance, such as carbon markets and green investments, may also offer additional means to support wider implementation of CSA (FAO, 2023; Rahut *et al.*, 2024).

12. Conclusion

Climate-Smart Agriculture is the way forward for positive farm income and farm resilience in the era of climate change that is both sustainable and commercially attractive. Through increased productivity, risk mitigation and sustainable resource use, CSA finally enhances agricultural sustainability and poverty reduction. However, realizing the full potential of CSA will require dedicated policies, financial support and institutional capacity building to overcome existing constraints and foster wide spread adoption.

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