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Climate-Smart Agriculture Practices in the Indo-gangetic Plain: A Micro-level Cost-benefit Perspective

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Authors' contributions

This work was carried out in collaboration between both authors. Author AK designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Author SPS generated the idea and corrected the first draft. Both authors read and approved the final manuscript.

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ABSTRACT

Aims: This study assesses the economic rationality of climate-smart agriculture (CSA) practices implemented by cultivators in the Indo-Gangetic Plain (IGP) region of India. Despite the growing body of international literature, the economic feasibility of CSA practices in the Indian IGP context remains underexplored.
Methodology: The analysis is based on primary data collected in 2024, from a survey of 400 randomly selected farmers across five districts in the state of Uttar Pradesh.

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Results: The findings indicate a high level of awareness and widespread adoption of CSA practices among the respondents. The empirical estimates derived from the Benefit-Cost Ratio (BCR) and Net Present Value (NPV) analyses suggest that, with the exception of conventional fertilizer application and Site-Specific Integrated Nutrient Management (SSINM), all assessed Climate-Smart Agriculture (CSA) interventions exhibit positive net economic returns and satisfy the threshold criteria for financial viability.

Conclusion: These findings underscore the critical role of CSA in enhancing farm-level resilience and agricultural productivity under changing climatic conditions.

Keywords: Climate-smart agriculture; Indo-Gangetic plain; adaptation; economic evaluation; cost-benefit analysis.

1. INTRODUCTION

The detrimental effects of climate change on farming fertility have led to an urgent need for effective adaptation and mitigation strategies. Adaptation serves as a risk management tool to reduce the impacts of climate change through modifications in existing agricultural practices, while mitigation involves the adoption of innovative technologies aimed at reducing the severity of climate-induced disruptions (Saxena and Kumar, 2019).

In India, agriculture is a cornerstone of the economy, engaging more than half of the population. The Indo-Gangetic Plain (IGP), one of the remarkably fertile and agriculturally substantial zones in the country, is experiencing climate-related challenges such as erratic rainfall and rising temperatures. These changes have prompted both researchers and farmers to explore adaptive measures. Farmers in the region are increasingly adopting climate-smart agriculture (CSA) practices, which combine traditional knowledge and modern techniques. However, despite increased awareness, the adoption of CSA practices remains relatively low due to high implementation costs and limited resilience among farming communities.

While a number of studies have assessed the adaptation levels of CSA practices in various contexts, there is a noticeable lack of research focused on their economic viability, particularly in the IGP region. For example, Khatri et al. (2016) raise that practices such as crop diversification and zero tillage enhanced farmers' net returns in parts of India. Similarly, Sain et al. (2017), using CBA in Guatemala, concluded that seven out of eight CSA practices were profitable, with agroforestry and conservation tillage among the most beneficial.

Aryal et al. (2018) identified factors influencing CSA adoption, such as land characteristics, market access, and climate risk perception, through a survey of farmers in Haryana and Bihar. Azumah et al. (2020) in Ghana, and Ng'ang'a et al. (2021) using BCR and NPV techniques reported that zero tillage and strip cropping were economically promising. Studies by Branca et al. (2021) in Malawi and Zambia, and Mujeyi and Mudhara (2021) in Zimbabwe, confirmed the affirmative impact of CSA practices on farm income, particularly those related to land and soil management.

More recently, Mogaka et al. (2022) observed in Kenya that agroforestry yielded the highest NPV among CSA options. Akinyi et al. (2022) similarly found that improved seed varieties and conservation agriculture are both popular and economically viable among smallholder farmers in Sub-Saharan Africa; similar results were also found in the Gandaki River Basin in Nepal (Poudel, Thapa & Mishra, 2024).

Despite this growing body of international literature, the economic feasibility of CSA practices in the Indian IGP context remains underexplored. This study fills that gap by evaluating the economic returns of various CSA practices based on primary data collected from 400 farmers in Uttar Pradesh.

2. METHODOLOGY

Cost–benefit analysis (CBA) is applied to evaluate the economic viability of CSA practices. CBA is a standardized path that compares the expected benefits and costs of a project or intervention. Following the methodology proposed by Mujeyi and Mudhara (2021), this study calculates benefits as the revenue from the main agricultural product and its by-products. Costs include variable cultivation expenditures such as labor, seeds, irrigation, and inputs. Fixed costs such as land rent and interest on capital are excluded to focus solely on operational profitability.

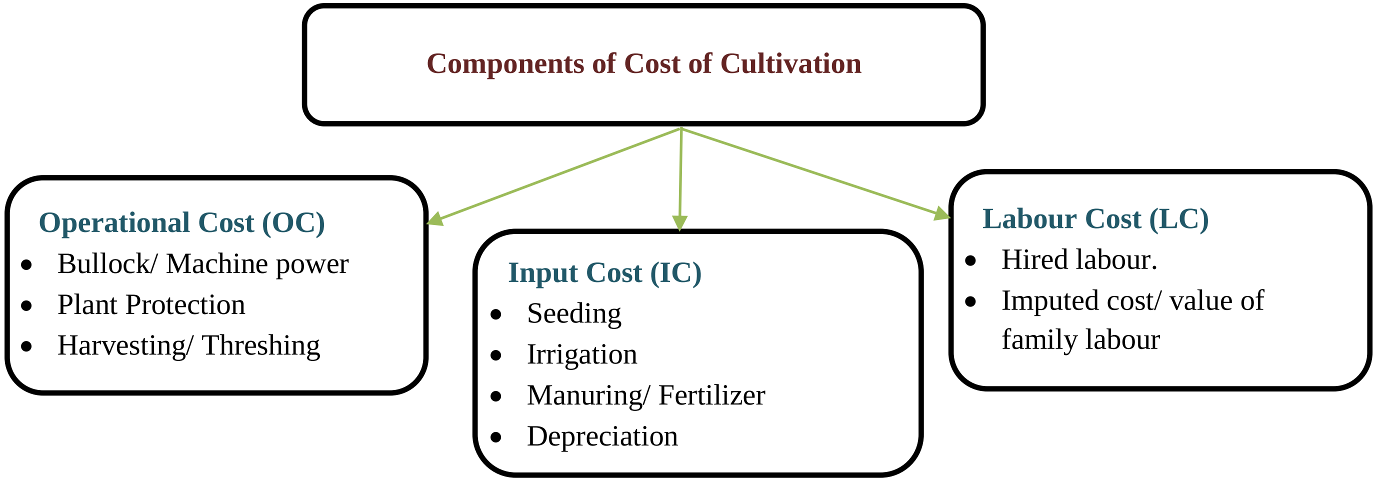

Fig. 1. Components of cost of cultivation

Source: Author's Generated

The entire cost and benefit components related to cultivation have been monetized and expressed on a per-hectare basis in Indian Rupees (INR). The total cost of cultivation is disaggregated into three major components: operational expenditure, material input costs, and human labour costs.

Several empirical studies (e.g., Banjara et al., 2021; Aryal et al., 2018) have previously employed the Cost-Benefit Analysis (CBA) framework to evaluate the economic feasibility and adoptability of Climate-Smart Agriculture (CSA) technologies under diverse agro-ecological and socio-economic conditions. In line with this analytical precedent, the present study employs the CBA methodology to evaluate the economic efficiency of selected CSA interventions within the rice–wheat cropping system of the Indo-Gangetic Plain (IGP) region in northern India.

2.1 Analytical Framework

The study applies the Cost-Benefit Analysis (CBA) approach to quantify the economic viability of selected CSA practices using the following financial indicators:

- Benefit–Cost Ratio (BCR): A relative measure of profitability indicating the return per unit of cost incurred.
- Net Present Value (NPV): A discounted metric that captures the present value of net economic returns over time.

2.2 Study Location

India's physiographic divisions include six major regions, with the Indo-Gangetic Plain (IGP) forming a crucial part of northern India. This region encompasses the states of Punjab, Haryana, Uttar Pradesh, Bihar, and West Bengal, covering nearly 15% of the country's geographical area (Koshal, 2014) and accounting for 38.4% of the population (Census, 2011). Major river systems such as the Indus, Ganga, and Brahmaputra flow through this region, contributing to its rich alluvial soils and abundant water resources.

The IGP is one of India's most agriculturally productive regions, contributing 15.3% of the total land area, producing 40% of the country's foodgrains, and accounting for nearly 80% of groundwater-based irrigation (Patil et al., 2014). The dominant cropping pattern includes rice–wheat rotation, with other crops like maize, millet, sugarcane, and cotton. This region plays a critical role in ensuring food security and employment across South Asia (Kumar & Saxena, 2021).

2.3 The Data

Uttar Pradesh is the largest state of the IGP region, and the districts included in the sample yield the highest agricultural (wheat and rice) produce in the state. The sample size of 384 respondents was estimated by using Cochran's (1977) sampling methodology. Accordingly, a sample size of 400 informants was considered for the present study.

Primary data on cultivation costs and gross returns for both conventional and CSA-based production rice-wheat systems (excluding the sugarcane–wheat cropping model) were gathered through structured interviews with 400 randomly selected farm households and personnel from Kisan Seva Kendras (Farmer Service Centers). The stratified distribution of sampled respondents across selected districts is presented in Table 1.

Based on collected information, it was found that non-adaptation of CSA practice reduces revenue by 10% on average.

Table 1. Sample distribution

District	No. of Cultivators*	No. of Respondents	% of Respondents
Agra	2,85,471	103	25.75
Bulandshahar	2,92,901	107	26.75
Etawah	1,70,828	62	15.50
Hapur	80,836	30	7.50
Meerut	2,70,888	98	24.50
Total	11,00,924	400	100.00

***** *Census-2011, (Compiled), www.censusindia.gov.in. Cultivators in West UP: 53, 75,301.*
Source: Primary data

For calculating Benefit–to–Cost Ratio (BCR), firstly, the benefit from each CSA practice is calculated using the following equation.

$$\mathrm{BCSAPn} = (\mathrm{RCSAPnt} - \mathrm{TVCSAPnt})$$

Where: BCSAP_n represents the benefit from the n^{th} climate-smart agriculture practice, RCSAP_{nt} is revenue from the n^{th} climate-smart agriculture practice in year t, and TVCSAP_{nt} represents the total variable cost of the n^{th} climate-smart agriculture practice in year t.

The benefit-to-cost ratio (BCR), which is a financial ratio used to determine whether the amount of money made through a project will be greater than the costs incurred in its execution, is calculated by using the following formula.

$$\mathrm{BCR} = \frac{\mathrm{Benefit}}{\mathrm{Total\ Costs}}$$

In the domain of economic evaluation, NPV and Internal Rate of Return (IRR) are among the most widely adopted discounted cash flow techniques to ascertain the long-term profitability of agricultural interventions. However, the present analysis employs only the Net Present Value (NPV) criterion to estimate the cumulative discounted net benefits attributable to the adoption of CSA technologies.

The net economic benefit derived from each CSA intervention is computed using the standard NPV formulation:

$$\begin{aligned}&\mathrm{Net\ Benefit} = \\ &(\mathrm{Benefit\ with\ use\ of\ CSA\ Practice} - \\ &\mathrm{Benefit\ without\ use\ of\ CSA\ Practice})\end{aligned}$$

NPV of each CSA practice is calculated by using the following formula.

$$\mathrm{NPV} = \sum_{t}^{n} \mathrm{PVF}(\mathrm{Bt} - \mathrm{Ct})$$

Where: Bt = Net benefit from CSA practice at time t, Ct = Additional cost from CSA practice at time t, t = Time horizon of CSA technique (assumed 1 year for all CSA techniques), r = Discounting rate (i.e., Average marginal cost of funds) is considered at 11.70% (State Bank of India’s lending rate for farm mechanization as on 15 February 2024. PVF = Present value factor of the Rupee. The present value factor of the Rupee is calculated by using the following formula.

$$\mathrm{PVF} = \left(\frac{1}{1+\mathrm{r}}\right)^{\mathrm{n}}$$

3. RESULTS AND DISCUSSION

3.1 Cost-benefit Analysis of CSA Practices

Crop rotation, the practice of alternating the flora of diverse breeds on the same land across seasons, helps in controlling pests, enhancing soil health, and boosting productivity. In the IGP, rice–wheat and sugarcane–wheat rotations are common. The sugarcane–wheat system yields an additional net benefit of ₹91,272 over the rice–wheat system. With a BCR of 1.9 and net present value (NPV) of ₹67,092, this system demonstrates superior economic viability.

Climate change has strained water availability for agriculture. Adoption of modern irrigation technologies mitigates this issue and enhances yield. Results indicate an additional net benefit of ₹18,695, a BCR of 1.56, and an NPV of ₹8,309, confirming the productivity and feasibility of these practices (Okyere and Usman, 2021; Mukherji, 2022).

Balanced and efficient use of fertilizers and pesticides is vital for crop productivity. Though modern practices entail slightly higher costs, they generate a net benefit of ₹6,067/ha, despite a BCR of 2.26 and negative NPV for traditional practices. Modern approaches support plant growth, climate change mitigation, and higher yields (Sapkota et al., 2021).

Developed by ICAR, these varieties are tailored to withstand climatic stresses. The adoption of such varieties results in an additional benefit of ₹27,912, a BCR of 1.55, and an NPV of ₹24,812, highlighting their economic and agronomic superiority over traditional crops.

Adjusting the sowing and fertilization schedules to climate conditions has proven effective in reducing input costs—especially irrigation—and enhancing returns. This adaptation yields a net benefit of ₹37,523, a BCR of 1.80, and an NPV of ₹42,021, particularly effective in western Uttar Pradesh.

Integrated nutrient management practice (INM) involves the combined use of organic, inorganic, and bio-fertilizers to maintain soil fertility. While traditional practices are marginally less expensive, site-specific INM improves productivity and climate resilience. It has a BCR of 1.87, and although the NPV is negative, the method shows potential in long-term sustainability.

Table 2. Benefit–Cost Ratio for adaptation and non-adaptation of CSA practices

Farming Practices	OC	IC	LC	TC	TR	BF	BCR
Crop Rotation (From Rice - Wheat to Sugarcane - Wheat)							
With CSA	52426	31220	49446	133092	385869	252777	1.90
Without CSA	34435	45955	36372	116762	278267	161505	1.38
Modern Irrigation Practices							
With CSA	32268	41909	35802	109979	281087	171108	1.56
Without CSA	32268	32495	35802	100565	252978	152413	1.52
Fertilizers and Pest Management							
With CSA	32268	41909	12105	86282	281087	194805	2.26
Without CSA	32268	18867	12105	63240	251978	188738	2.98
Change in Crop Varieties							
With CSA	32268	42106	35802	110176	281087	170911	1.55
Without CSA	32268	41909	35802	109979	252978	142999	1.30
Modification in Timing of Sowing, Planting, Fertilizing, and Harvesting Practices							
With CSA	32268	32495	35802	100565	281087	180522	1.80
Without CSA	32268	41909	35802	109979	252978	142999	1.30
Site-Specific Integrated Nutrient Management							
With CSA	32268	41909	23697	97874	281087	183213	1.87
Without CSA	32268	23252	12105	67625	252978	185353	2.74
Conservation (Zero Tillage or Reduced Tillage)							
With CSA	15231	41909	35802	92942	281087	188145	2.02
Without CSA	32268	41909	35802	109979	252979	142999	1.30
Agro-Forestry							
With CSA	32268	44380	38450	115098	281087	165989	1.44
Without CSA	32268	41909	35802	109979	252979	143000	1.30

OC = Operational cost, IC = Input cost, LC = Labor cost, TC = Total cost, TR = Total revenue, BF = Benefits, BCR = Benefit-Cost Ratio
(Source: Authors' Own computation)

Table 3. Net present value of CSA practices

Farming Practices	Net Benefit	(Bt – Ct) *	NPV
Crop Rotation (Rice - Wheat to Sugarcane - Wheat)	91272	74942	67092
Modern Irrigation Practices	18695	9281	8309
Fertilizers and Pest Management	6067	-16975	-15197
Change in Crop Varieties	27912	27715	24812
Modification in the Timing of Sowing, Fertilizing, etc.	37523	46937	42021
Site-Specific Integrated Nutrient Management	-2140	-32389	-28996
Conservation (Zero or Reduced Tillage)	45145	62182	55669
Agro-Forestry	22989	17870	15998

** (B_t – C_t) = The surplus of net benefit over the incremental cost associated with the adoption of a CSA practice at time t*
(Source: Own Calculations)

This CSA practice minimizes soil disturbance by directly sowing seeds into untilled land, thereby reducing operational costs. The data reveals a net benefit of ₹45,145, a BCR of 2.02, and an NPV of ₹55,669, proving its economic efficiency and sustainability.

Agroforestry integrates tree planting with crop cultivation to improve soil fertility, reduce erosion, and enhance productivity. Despite higher initial costs, the practice yields a net benefit of ₹22,989, a BCR of 1.44, and an NPV of ₹15,998, establishing it as a financially and environmentally sound strategy.

4. CONCLUSION

The above analysis underscores that climate-smart agriculture (CSA) practices in the IGP region not only offer environmental benefits but are also economically viable. Practices such as crop rotation, climate-resilient varieties, modern irrigation, timely sowing, and zero tillage contribute significantly to increased farm productivity and climate adaptation. Moreover, they support sustainable development by conserving soil fertility, reducing emissions, and enhancing farmers' income. The cost-benefit and NPV assessments substantiate the financial feasibility and scalability of these practices for climate-resilient agriculture in India.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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