

International Journal of Agriculture Extension and Social Development

Volume 9; Issue 2; February 2026; Page No. 34-38

Received: 05-11-2025
Accepted: 13-01-2026

Indexed Journal
Peer Reviewed Journal

Economic-environmental trade-offs in cotton-based cropping systems: Evidence from Telangana, India

¹V Sneha, ²A Amarendar Reddy, ³T Lavanya, ⁴V Ravinder and ⁵Dhandapani

¹Department of Agricultural Economics, College of Agriculture, PJS AU, Rajendranagar, Hyderabad, Telangana, India

²Joint Director, ICAR- National Institute of Biotic Stress Management (ICAR-NIBSM), Raipur, Chhattisgarh, India

³Department of Agricultural Extension, BJR Agriculture College, PJS AU, Siricilla, Telangana, India

⁴Department of Agricultural Economics, Agricultural College, PJS AU, Warangal, Telangana, India

⁵Principal Scientist, Department of Statistics, ICAR-NAARM, Telangana, India

DOI: <https://www.doi.org/10.33545/26180723.2026.v9.i2a.3012v>

Corresponding Author: V Sneha

Abstract

Cotton (*Gossypium* spp.) is a major commercial crop in India, contributing significantly to farm incomes, rural employment, and export earnings. However, its cultivation is input-intensive, high-cost, and associated with considerable environmental impacts, particularly greenhouse gas (GHG) emissions. This study evaluates the economic performance and environmental sustainability of two dominant cotton-based cropping systems Cotton-Groundnut (CGL-2) and Cotton-Maize (CML-1) in Nagarkurnool district, Telangana, using farm-level data from the 2022-23 agricultural year. Costs and returns were estimated through standard farm management accounting procedures, while crop-specific GHG emissions and water footprints were quantified using the Cool Farm Tool. A multi-objective Pareto optimization framework was employed to identify cropping system combinations that maximize net returns while minimizing emissions. Results indicate that the Cotton-Groundnut system generates higher net returns (₹1,16,889/ha) but also higher GHG emissions (7,043 kg CO₂e/ha), whereas the Cotton-Maize system exhibits lower emissions (5,820 kg CO₂e/ha) with reduced profitability (₹97,109/ha). Pareto-optimal solutions reveal intermediate cropping combinations, such as 61% Cotton-Groundnut and 39% Cotton-Maize, which achieve substantial emission reductions (6,562 kg CO₂e/ha) while maintaining most of the economic gains (₹1,09,116/ha). These findings underscore the trade-offs between profitability and environmental sustainability in cotton-based systems and highlight the potential of diversified cropping strategies for climate-smart agriculture. Policy measures promoting mixed cotton-based systems, efficient input use, and targeted extension services can help reconcile economic and environmental objectives, contributing to sustainable cotton cultivation in semi-arid regions of India.

Keywords: Cotton-based systems, greenhouse gas emissions, cost of cultivation, Pareto optimization, trade-offs, Telangana

1. Introduction

Agriculture continues to play a pivotal role in the Indian economy, providing livelihoods to nearly half of the population and contributing substantially to national income and food security. Within the agricultural sector, commercial crops such as cotton assume particular importance due to their strong linkages with agro-processing industries, export markets, and employment generation across rural and urban regions. Cotton (*Gossypium* spp.), often referred to as “white gold,” is one of the most important fiber crops cultivated in India, accounting for nearly one-fourth of the global cotton area. India has consistently ranked among the world’s leading cotton producers, exporters, and consumers, underscoring the crop’s strategic relevance to the national economy.

Globally, cotton production during 2022-23 was estimated at approximately 114.4 million bales cultivated over 32.5 million hectares, with China, India, Brazil, and the United States emerging as the major producers. India alone accounted for nearly 25.5 million bales, cultivated over an area exceeding 12.5 million hectares (USDA, 2023). Cotton

contributes significantly to India’s agricultural exports, supporting a vast textile industry that employs millions of workers and contributes around 2% to national GDP and over 10% to total exports.

In addition to economic challenges, environmental concerns associated with cotton cultivation have gained increasing attention in recent years. Cotton is widely recognized as an input-intensive crop with a relatively high environmental footprint. The extensive use of nitrogen fertilizers contributes significantly to nitrous oxide (N₂O) emissions, a potent greenhouse gas with a global warming potential far exceeding that of carbon dioxide. Energy consumption for irrigation, mechanization, and fertilizer production further adds to carbon dioxide emissions. Several studies have identified cotton as one of the major contributors to agricultural greenhouse gas emissions in India, particularly in regions characterized by intensive input use and groundwater exploitation.

India’s commitment to climate change mitigation under national and international frameworks, including the

Nationally Determined Contributions (NDCs), necessitates the identification of agricultural strategies that can reduce emissions without compromising farm incomes. This dual challenge has shifted the policy focus from mere productivity enhancement to sustainable intensification, where economic viability and environmental performance are jointly considered.

Telangana has emerged as a major cotton-producing state in India over the last decade. The state witnessed a rapid

expansion in cotton area following its formation, driven by favorable prices, improved market access, and policy support as shown in table 1. During 2022-23, Telangana accounted for nearly 16% of India's total cotton area, with production increasing steadily across districts such as Nagarkurnool, Adilabad, Nalgonda, Sangareddy, and Warangal. However, cotton cultivation in Telangana is predominantly rain-fed and resource-intensive, raising concerns about long-term sustainability, groundwater depletion, and environmental degradation.

Table 1: Increase in cotton area and production in Telangana

Particulars	2021-22	2022-23	% Age increase
Area under cotton (lakh ha)	18.89	20.24	7.1
Production (lakh bales*)	48.08	54.42	13.2

Therefore, cotton-based cropping systems, where cotton is grown in combination with *Rabi* crops such as groundnut and maize offer potential opportunities for income diversification and resource use optimization. Groundnut, a leguminous crop, has the potential to enhance soil fertility and generate higher market returns, while maize offers relatively lower production costs and reduced environmental footprint. Understanding the economic and environmental implications of such cropping systems is critical for designing climate-smart agricultural strategies.

The present study seeks to address this gap by conducting an integrated economic and environmental assessment of cotton-based cropping systems in semi-arid Telangana. By combining farm-level cost and return analysis with greenhouse gas emission estimation and Pareto-based multi-objective optimization, the study provides empirical evidence on the trade-offs between profitability and environmental sustainability. The findings are expected to inform policy interventions aimed at promoting sustainable cotton cultivation while ensuring livelihood security for farmers.

1.1 Objectives of the study

- To estimate the economic returns from cotton-based cropping systems followed by farmers in Nagarkurnool district of Telangana.
- To quantify greenhouse gas (GHG) emissions from cotton-based cropping systems during the *Kharif* and *Rabi* seasons.
- To optimize both economic returns and environmental impacts of cotton-based cropping systems using a multi-objective framework and develop optimal model farm scenarios for policy guidance.

1.2 Hypotheses of the study

Null hypotheses (H_0)

- The existing cotton-based farming practices do not optimize economic returns and environmental sustainability.
- The choice of cotton-based cropping systems and management practices is independent of agro-climatic zones and farm size categories.

Alternate hypotheses (H_1)

- Trade-offs exist between farm profitability and environmental impacts in cotton-based cropping systems.

- Adoption of optimal model farms can enhance farmer profitability while minimizing environmental impacts.

Research gap

Cotton cultivation supports livelihoods for millions of farmers in Telangana and across India. However, it is characterized by high input intensity, significant labour requirements, and substantial environmental impacts, including greenhouse gas emissions and water consumption. While several studies have documented the costs, returns, and GHG emissions of cotton (Ramasamy *et al.*, 2019; BIRTHAL *et al.*, 2021) ^[6, 1], few have explicitly examined the trade-offs between profitability and environmental sustainability at the farm level in semi-arid regions. Furthermore, there is limited empirical evidence on optimal model farms that integrate economic and environmental objectives to guide decision-making by policymakers and farmers. Addressing this gap is crucial for promoting cotton-based farming systems that are both economically viable and environmentally sustainable, particularly in regions facing water scarcity, climate variability, and high agrarian risk (Youssef *et al.*, 2019) ^[10].

2. Review of Literature

A substantial body of research has examined the economics of cotton cultivation across India, consistently highlighting its high-cost and high-risk nature. Cotton production relies heavily on purchased inputs such as fertilizers, pesticides, and labour, making it more expensive than competing crops like maize and pulses (Ramasamy *et al.*, 2019) ^[6]. Variable costs constitute over 70% of total cultivation expenses, with human labour, fertilizers, and pesticides as the dominant components (BIRTHAL *et al.*, 2021) ^[1]. Comparative studies of cotton-based cropping systems indicate that diversification can enhance profitability. For instance, cotton-groundnut systems often generate higher net returns than cotton monocropping due to favorable groundnut prices and risk-spreading benefits, whereas cotton-maize systems tend to be less profitable but carry lower production risks, given maize's shorter duration and reduced susceptibility to pests (Sankar & Naidu, 2017) ^[8]. These findings underscore the economic trade-offs and management challenges inherent in cotton-based farming, particularly in semi-arid regions where climatic variability further influences productivity and income stability.

The environmental dimension of cotton cultivation has been increasingly examined using life cycle assessment (LCA) and

IPCC-based emission coefficient approaches. Fertilizer-induced nitrous oxide emissions have been identified as a major source of agricultural greenhouse gases (Paustian *et al.*, 2004; Pathak *et al.*, 2010) ^[3, 5], while crop-specific studies indicate that cotton exhibits higher emissions per hectare than cereals due to intensive input use (Zhang *et al.*, 2018) ^[11]. Cotton-based systems in semi-arid regions significantly contribute to regional emission profiles, emphasizing the need for improved input-use efficiency and alternative cropping strategies (Paramesh *et al.*, 2023) ^[4]. The inherent trade-off between profitability and environmental performance has motivated the application of Pareto-based multi-objective optimization in agriculture. Such approaches identify efficient solutions that balance economic and environmental objectives, with intermediate cropping strategies offering compromise solutions that retain substantial economic benefits while reducing emissions (Ray *et al.*, 2020; Li *et al.*, 2024) ^[7, 2]. Despite this progress, empirical applications of integrated economic-environmental frameworks in cotton-based systems remain limited in India, a gap that the present study addresses using farm-level data and Pareto optimization techniques.

3. Materials and Methods

3.1 Study area

The study was conducted in Nagarkurnool district of Telangana, located in the semi-arid agro-climatic zone of southern India. The district is characterized by erratic rainfall, limited irrigation coverage, and predominance of small and marginal farmers. Agriculture is the primary livelihood source, with cropping decisions strongly influenced by monsoon performance and groundwater availability. Cotton is the dominant *kharif* crop in the district, occupying approximately 1,46,009.8 hectares. During the *Rabi* season, groundnut and maize are the major crops, occupying 51,673.8 hectares and 3,821.4 hectares, respectively. Achampet mandal was selected for the study as it represents typical cotton-based cropping systems prevalent in the district.

3.2 Sampling and data collection

Primary data were collected from 40 sample farmers during the agricultural year 2022-23 using a structured questionnaire. The sample consisted of 20 farmers practicing Cotton-Groundnut systems and 20 farmers practicing Cotton-Maize systems. Data were collected on input use, labour employment, costs, yields, prices, and crop management practices.

3.3 Economic analysis

Costs of cultivation were estimated following standard farm management accounting procedures. Costs were classified into variable costs (human labour, bullock and machine labour, seeds, fertilizers, pesticides, irrigation, and interest on working capital) and fixed costs (rental value of land, depreciation, land revenue, and interest on fixed capital). Gross returns were calculated based on yield and prevailing market prices, while net returns were obtained by deducting total costs from gross returns.

3.4. Environmental impact assessment

Greenhouse gas emissions were estimated using the Cool Farm Tool (CFT), which calculates emissions from fertilizer

use, energy consumption, field operations, and residue management. Emissions were expressed in kg CO₂-equivalent per hectare. Crop-wise emissions were aggregated to obtain total emissions for each cropping system. Water footprint was also estimated to assess water use intensity.

3.5 Pareto optimization framework

A multi-objective optimization framework was employed with the objectives of maximizing net returns and minimizing GHG emissions. The optimization was subject to land availability constraints and non-negativity conditions. Pareto-optimal solutions were generated to identify trade-offs and balanced cropping system combinations. Here's a general formulation along with the mathematical equations:

Problem: Maximizing and minimizing objective functions simultaneously subjected to constraints.

Formulation: Let:

Decision variables

x_i = proportion (or area share) of the i -th cropping system, where
 $i=1,2,\dots,n$

In the present study, the decision variables represent alternative cotton-based cropping systems (*e.g.*, cotton-groundnut and cotton-maize).

Objective functions

Objective 1: Maximize net returns

$$\text{Maximize } Z_1 = \sum_i [(GR - C)x_i]$$

- GR = Gross returns (₹/ha)
- C = Cost of cultivation (₹/ha)

Objective 2: Minimize Greenhouse Gas Emissions

$$\text{Minimize } Z_2 = \sum_i (x_i)$$

Where:

- E = GHG emissions (kg CO₂-equivalent per ha or per LU), estimated using CFT

Constraints

Land availability constraint

$$\sum_i x_i = 1$$

This ensures that the total allocated area across cropping systems does not exceed 1 ha

Non-negativity Constraints

$$x_i \geq 0$$

Solution Approach

Since the objectives of maximizing net returns and

minimizing GHG emissions are inherently conflicting, no single solution simultaneously optimizes both objectives. Therefore, a Pareto-based multi-objective optimization approach was adopted to generate a set of Pareto-optimal solutions. These solutions represent efficient trade-offs where any improvement in net returns would lead to an increase in GHG emissions and vice versa.

From the Pareto set, extreme solutions (maximum returns and minimum emissions) and an intermediate knee-point solution were identified to aid policy-relevant interpretation and practical decision-making for sustainable cotton-based cropping systems.

4. Results and Discussion

4.1 Costs and returns of cotton-based cropping systems

The economic analysis revealed notable differences in cost structure and profitability between the two cotton-based systems as shown in table 2. The total cost of cultivation was

₹2,81,018 per hectare for the Cotton-Groundnut system and ₹2,44,998 per hectare for the Cotton-Maize system. Variable costs accounted for nearly three-fourths of total costs in both systems, highlighting the input-intensive nature of cotton cultivation.

Human labour constituted the largest cost component, reflecting labour-intensive operations such as weeding, pesticide application, and harvesting. Seed costs were significantly higher in the Cotton-Groundnut system due to the high seed rate and price of groundnut. Fertilizer and manure costs were higher in the Cotton-Maize system, indicating greater nutrient requirements.

Despite higher costs, the Cotton-Groundnut system generated higher gross returns (₹3,97,907/ha) and net returns (₹1,16,889/ha), compared to ₹3,42,107/ha and ₹97,109/ha for the Cotton-Maize system. This indicates the superior economic performance of cotton-groundnut systems driven by favorable market prices and diversification benefits.

Table 2: Cost of cultivation and returns for cotton-based cropping systems

Component	Unit	CM-1			CG-2		
		Cotton	Maize	Total	Cotton	Groundnut	Total
Seed	₹/ha	8,264	6,072	14,336	7,697	17,290	24,987
Manures & Fertilizers	₹/ha	12,032	15,685	27,717	14,422	7,781	22,203
Pesticides & Weedicides	₹/ha	6,381	9,491	15,872	5,739	8,301	14,040
Human Labour	₹/ha	33,138	21,798	54,936	35,486	15,861	51,347
Bullock Labour	₹/ha	6,138	3,396	9,534	5,089	3,811	8,900
Machine Labour	₹/ha	6,900	14,950	21,850	6,275	8,301	14,576
Miscellaneous Costs	₹/ha	1,265	849	2,115	654	685	1,339
Interest on Working Capital	₹/ha	2,594	2,528	5,123	2,638	2,171	4,809
Rental Value of Owned Land	₹/ha	16,604	14,658	31,262	16,953	14,474	31,427
Depreciation	₹/ha	647	647	1,294	934	934	1,868
Interest on Fixed Capital	₹/ha	1,725	1,531	3,256	1,789	1,541	3,330
Total Fixed Cost	₹/ha	18,976	16,836	35,812	19,676	16,949	36,625
Total Cost of Cultivation	₹/ha	95,689	91,605	2,44,998	97,676	81,149	2,81,018
Yield	q/ha	18.3	64.0	82.3	17.8	22.4	40.2
Gross Returns	₹/ha	1,41,458	1,23,093	3,42,107	1,37,282	1,16,525	3,97,907
Net Returns	₹/ha	45,769	31,488	97,109	39,606	35,376	1,16,889

4.2 Environmental impacts of cotton-based cropping systems

The environmental assessment revealed that the Cotton-Groundnut system emitted 7,043 kg CO₂e/ha, while the Cotton-Maize system emitted 5,820 kg CO₂e/ha. Carbon dioxide emissions constituted the largest share in both systems, followed by nitrous oxide emissions arising from

fertilizer use. Methane emissions were negligible in all cropping systems

The higher emissions in the Cotton-Groundnut system can be attributed to greater input use and longer crop duration. The Cotton-Maize system, although less profitable, exhibited better environmental performance, indicating a trade-off between income and emissions.

Table 3: Environmental impacts of cotton-based cropping systems

Component	Unit	CM-1			CG-2:		
		Cotton	Maize	Total	Cotton	Groundnut	Total
CH ₄	kg/ha	0.0	55.6	55.6	0.0	71.2	71.2
N ₂ O	kg/ha	0.9	1.8	2.7	1.1	1.3	2.4
CO ₂	kg/ha	2,004	888	3,620	2,257	377	2,634
Total GHG emissions	kg CO ₂ -eq/ha	2,272	1,430	5,820	2,585	764	7,043
Water Footprint	m ³ /ha	4,195	5,421	9,625	4,202	3,312	7,531

4.3 Trade-offs and Pareto-Optimal Solutions

The Pareto analysis illustrated in table 4 clearly shows the trade-off between net returns and GHG emissions. The profit-maximizing solution (100% Cotton-Groundnut) yielded the highest net returns but also the highest emissions. Conversely, the emission-minimizing solution (100% Cotton-Maize) resulted in the lowest emissions at the cost of

reduced profitability.

Intermediate solutions offered balanced outcomes. For instance, a cropping pattern comprising 61% Cotton-Groundnut and 39% Cotton-Maize generated net returns of ₹1,09,116/ha while reducing emissions to 6,562 kg CO₂e/ha. Such solutions represent realistic pathways for achieving climate-smart agriculture.

Table 4: Pareto-optimal solutions for net returns and GHG emissions

Pareto Solution	Cropping System Composition	Net Returns (₹/ha)	GHG Emissions (kg CO ₂ e/ha)
S-1 (Maximum Returns)	100% Cotton-Groundnut	116,889	7,043
S-2 (Mid-point / Balanced)	61% Cotton-Groundnut, 39% Cotton-Maize	109,116	6,562
S-3 (Minimum Emissions)	100% Cotton-Maize	97,109	5,820

5. Conclusion and policy implications

The study demonstrates that cotton-based cropping systems in semi-arid Telangana involve inherent trade-offs between economic profitability and environmental sustainability. While cotton-groundnut systems offer higher incomes, they are associated with higher greenhouse gas emissions. Cotton-maize systems, on the other hand, provide environmental benefits at the cost of reduced profitability.

Importantly, Pareto-optimal mixed cropping strategies offer a viable compromise, enabling farmers to reduce emissions without substantial income losses. Policy interventions should focus on promoting such diversified systems through incentives, extension services, and support for input-use efficiency. Encouraging balanced cotton-based systems can contribute to climate mitigation while ensuring livelihood security in semi-arid regions.

References

1. BIRTHAL PS, JOSHI PK, GULATI A. Cost of cultivation and profitability of cotton in India: implications for sustainable production. *Indian Journal of Agricultural Economics*. 2021;76(3):345-362.
2. Li X, Zhang Y, Kumar A, Singh R. Multi-objective optimization of rice-based cropping systems for balancing income and greenhouse gas emissions. *Agricultural Systems*. 2024;221:104651. <https://doi.org/10.1016/j.agry.2023.104651>
3. Paustian K, Parton WJ, Persson J, Rose S. Quantifying greenhouse gas emissions from agricultural soils: a global perspective. *Soil Use and Management*. 2004;20(2):173-180. <https://doi.org/10.1079/SUM2004161>
4. Paramesh K, Rao VUM, Kumar S. Environmental footprint of cotton-based cropping systems in semi-arid regions of India. *Journal of Cleaner Production*. 2023;402:136866. <https://doi.org/10.1016/j.jclepro.2023.136866>
5. Pathak H, Bhatia A, Jain N. Greenhouse gas emissions from Indian agriculture: mitigation options and strategies. *Current Science*. 2010;98(7):919-928.
6. Ramasamy C, Mahendran T, Kumar A. Cost structure and economic viability of cotton cultivation in India. *Indian Journal of Agricultural Sciences*. 2019;89(10):1654-1660.
7. Ray D, Singh S, Mishra A. Trade-offs between farm profitability and environmental impacts in Indian agriculture: evidence from multi-objective optimization. *Environmental Science & Policy*. 2020;112:1-10. <https://doi.org/10.1016/j.envsci.2020.03.006>
8. Sankar K, Naidu S. Profitability and risk analysis of cotton-based cropping systems in India. *Indian Journal of Agricultural Economics*. 2017;72(2):180-192.
9. United States Department of Agriculture, Foreign Agricultural Service. Cotton: world markets and trade. 2023. <https://www.fas.usda.gov/data/cotton-world-markets-and-trade>
10. Youssef S, Kumar A, Singh R. Optimal farm planning for sustainable agriculture: integrating economic and environmental objectives. *Agricultural Economics Research Review*. 2019;32(2):215-230.
11. Zhang H, Li X, Chen J. Crop-specific greenhouse gas emissions: comparing cotton, cereals, and pulses. *Journal of Environmental Management*. 2018;218:383-392. <https://doi.org/10.1016/j.jenvman.2018.04.092>