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Farm-level climate change adaptation in cotton: A climate-smart agriculture approach

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Abstract

The cotton crop is considered to be climate-sensitive as it needs favourable growing conditions with respect to temperature, Sunlight and soil moisture. A marked dry season is also essential for the bolls to open properly and for harvesting. The effects of climate change on cotton production are manifested in increased temperature, irregular rainfall, soil degradation and, in turn, lower production, productivity and quality degradation of cotton. The current study assessed the level of adaptation strategies followed by cotton growers to mitigate the impact of climate change in Nalgonda district of Telangana. Two tehsils namely Nampalley and Gurrempode were selected with sample size of 140 respondents from 10 villages. Ex-post facto design was used for the study. The study revealed that the adoption of Climate-Smart Agriculture (CSA) adaptation strategies by cotton farmers across key dimensions: water-smart practices, climate-resilient varieties, crop and farm diversification, pest and disease management, and information-based adaptation. Results indicated wide variation in adoption levels. Water smart practices showed low adoption, with micro-irrigation adopted by 34.28% of farmers, while contour and graded bunding were not adopted. In contrast, climate-resilient varieties showed a greater rate of adoption, particularly early-sown cotton varieties (69.28%) and pest and disease resistant cultivars (61.42%). Crop and farm diversification practices exhibited moderate adoption, with timely harvesting (66.42%) and crop diversification (46.42%) being more common than intercropping. Pest and disease management practices showed the highest adoption, especially control measures for bollworm (90.71%), sucking pests (86.42%), and diseases (87.14%). Weather-based agro-advisory services were adopted by half of the respondents. Overall, farmers favoured practices with immediate benefits, while long-term resource-conserving measures require stronger extension and awareness efforts.

Keywords: Climate change, cotton, climate-smart agriculture, adaptation strategies

Introduction

Climate Change and Agriculture: A Global and National Concern

IPCC, Inter governmental Panel on Climate Change has defined Climate change as any form of change in climate that occurs over time as a result of both human action and natural variability, whereas UNFCCC (United Nations Framework Convention on Climate Change) defines Climate change as a change in climate caused directly or indirectly by human activities and has an impact on the composition of the global atmosphere.

One of the most important issues facing global agriculture in the twenty-first century is climate change. Global agricultural productivity and food security are being severely impacted by rising temperatures, changing precipitation patterns, and an increase in extreme weather events including heat waves, floods, and droughts. Agricultural systems are extremely vulnerable to climatic variability, especially in tropical and subtropical countries where smallholder farming is predominant, according to the IPCC's Sixth Assessment Report (2022) [2]. According to the

report, crop yields are already declining in a number of areas due to climate change, and in the upcoming decades, hazards to livelihoods, ecosystems, and food systems are predicted to increase.

According to IPCC (2021) [2]. In comparison to the decade before it since 1850, each of the last four decades has been successively warmer. Global surface temperature in the first two decades of the 21st century (2001-2020) was 0.99 (0.84 to 1.10) °C higher than 1850-1900. Global surface temperature was 1.09 (0.95 to 1.20) °C higher in 2011-2020 than 1850-1900, considerably greater rises over land (1.59 [1.34 to 1.83] °C) than on the ocean (0.88 [0.68 to 1.01] °C). Furthermore, precipitation variance is expected to be erratic, with an increase in mean annual rainfall at high altitudes and a decrease in mean annual rainfall at mid altitudes. As a result of anthropogenic gas emissions, the quantities of carbon dioxide, methane and nitrous oxide in the atmosphere have increased. Atmospheric CO₂ levels in 2019 were the highest they had been in at least 2 million years and levels of CH₄ and N₂O were the highest they had been in at least 800,000 years. Since 1750, increases in CO₂

(47%) and CH₄ (56%) concentrations far exceed and increases in N₂O (23%) are similar to the natural multi-millennial changes between glacial and interglacial periods over at least the past 800,000 years.

The effects of climate change are particularly noticeable in developing nations like India, where agriculture continues to be a major source of income for a sizable segment of the population. Due to its heavy reliance on monsoon rainfall, Indian agriculture is extremely vulnerable to temperature extremes and variations in rainfall. According to empirical data, cropping calendars are being disrupted and yield stability is being diminished by changes in rainfall distribution, delayed monsoon arrival, extended dry spells, and an increase in pest and disease prevalence. These issues call for immediate action to support sustainable farming methods and increase farming communities' ability for adaptation.

Vulnerability of Cotton Cultivation to Climate Change

Cotton (*Gossypium* spp.) is one of India's most important commercial crops, generating major income for farmers, creating jobs, and supporting the national textile industry. Cotton farming, however, is extremely sensitive to climate conditions such as temperature, rainfall, and humidity. The crop requires certain climatic conditions throughout important growth phases like flowering and boll production, and even little departures from ideal circumstances can result in significant yield losses.

According to the IPCC's Sixth Assessment Report (2022) [2] indicate that a rise of 1°C in mean temperature can lead to a decline in cotton yields ranging from 5 to 15 per cent, primarily due to heat stress and moisture deficits and heat stress during flowering reduces boll formation by 20-30 per cent. In India, nearly two-thirds of the cotton area is rain fed, making the crop particularly vulnerable to erratic rainfall and drought conditions. The ICAR (2018) [3] has reported that rainfall variability and increased frequency of dry spells can reduce cotton productivity by 20-30 per cent in rain fed regions.

In addition to abiotic stresses, climate change has contributed to biotic stresses in cotton ecosystems. Warmer temperatures and changing humidity regimes promote the spread of insect pests and diseases, resulting in larger agricultural losses and a greater reliance on chemical pesticides. These interrelated issues show how urgently effective adaptation solutions are needed to help cotton growers manage climate risks while maintaining environmental health and productivity.

Climate-Smart Agriculture as a Strategic Response

The idea of Climate-Smart Agriculture (CSA) has acquired international attention as an integrated and forward-thinking approach in response to the increasing challenges that climate change poses to agriculture. According to the FAO (2013) [1], CSA is a method that seeks to accomplish three interconnected goals: (i) boosting agricultural output and incomes in a sustainable manner; (ii) adapting to and strengthening resistance to climate change; and (iii) minimizing or eliminating greenhouse gas emissions wherever feasible.

Climate-Smart Agriculture (CSA) emphasizes context-specific practices and solutions that address local climate

concerns while promoting sustainability rather than prescribing a standard set of technologies. Core elements of CSA are frequently described as practices including effective water management, climate-resilient crop types, soil conservation, integrated pest control, and better access to climate information. FAO (2013) [1], Climate-smart agriculture practices have been shown to enhance productivity by 10-25 per cent while reducing water use and greenhouse gas emissions by up to 40 per cent and 30 per cent, respectively. Adaptation is seen as the main pillar of the CSA framework for smallholder farmers, especially in poorer nations where mitigation capabilities may be restricted. Therefore, putting CSA ideals into practice at the farm level requires an understanding of how farmers view climate change and the tactics they use in response.

Farmers' Adaptation Strategies: The Human Dimension of CSA

Climate change adaptation in agriculture is a behavioural and decision-making process driven by farmers' perspectives, knowledge, resources, institutional support, and technical developments. Farmers manage climate risks using a number of adaptation strategies, such as crop variety changes, sowing date adjustments, crop and livelihood diversification, improved water and soil management methods, and increasing use of climate and weather data. From a CSA view, farmer-led adaptation solutions are at the heart of climate-smart agriculture. The effectiveness of CSA initiatives is primarily determined by how well they correspond with farmers' current practices, risk perceptions, and socioeconomic situations. Several studies have found that farmers frequently prioritise short-term adaptation methods that minimize current production risks, even if the mitigation effects are indirect or unintended.

In cotton-based farming systems, adaption measures such as the use of drought-tolerant varieties, micro-irrigation technology, integrated pest management (IPM), and soil fertility management are crucial for minimizing climate sensitivity. These techniques not only increase resilience, but they also improve resource efficiency and contribute to environmental sustainability, achieving numerous CSA goals at once.

Adaptation-Mitigation Linkages in Cotton Farming

Although mitigation is sometimes regarded as a secondary priority for smallholder farmers, CSA understands the need of developing adaption strategies with mitigation co-benefits. Several regularly used adaptation measures in cotton farming, such as reduced chemical fertilizer usage, enhanced irrigation efficiency, conservation tillage, and increased organic manure application, can reduce greenhouse gas emissions while increasing soil carbon storage.

The IPCC has emphasized that agricultural adaptation and mitigation should not be considered as separate goals, especially when synergistic methods are encouraged. Understanding these linkages at the farm level is critical for developing policies and extension programs that promote climate-resilient and low-emission agriculture.

Research Gap and Rationale of the Study

Despite the increased emphasis on climate-smart agriculture

in policy and research discussions, empirical evidence on farmer-level adaptation techniques in cotton farming is scarce, particularly in developing countries such as India. Most present research focuses on the biophysical effects of climate change and technological solutions, with little emphasis on farmers' behavioural responses and decision-making processes.

Furthermore, there are few studies that explicitly examine farmers' adaptation techniques using the CSA framework, particularly for cotton farming. Understanding how farmers' current practices connect with the CSA pillars can help improve climate-resilient extension services, devise targeted interventions, and scale up effective adaptation measures.

Objective of the Study and Linkage to CSA

In this context, the current study focused into farmers' adaptation strategies to deal with the effects of climate change on cotton crops. By examining these strategies through the perspective of climate-smart agriculture, the study hopes to gain a better understanding of how CSA principles are being implemented at the farm level.

Specifically, the study aims to:

- Identify key adaptation strategies adopted by cotton farmers in response to climate change
- Examine the alignment of these strategies with the core pillars of CSA
- Highlight the implications for extension services, policy formulation, and sustainable cotton production

The study offers evidence-based insights to help the creation of climate-resilient and sustainable cotton farming systems by placing farmers' adaptation options inside the CSA framework.

Materials and Methods

The current study employed an ex-post facto social research design and was carried out in the Nalgonda district, which has the maximum cotton acreage in the state of Telangana. As a result, the district of Nalgonda was selected on purpose. There are thirty-one Tehsils in Nalgonda District,

of which two, namely Nampalley and Gurrempode, were chosen and 5 villages were selected from each selected tehsil. Thus, in all, 10 villages were selected for the study. From each selected village 14 cotton growers were selected, total 140 cotton growers were selected for present study by using simple random method.

To conduct survey a list of statements was prepared to identify the various adaptation strategies used by cotton growers in order to determine the extent of adaptation strategies used by cotton growers. This was accomplished by reading numerous literatures and consulting specialists. The survey included queries on soil and water conservation measures, crop management practices, plant protection and other adaptation strategies adapted by farmers towards climate change. Two continuums were used to measure the level of use of adaptation strategies by cotton growers and numerical values were assigned to the responses received. A numerical score of 1 was assigned to 'Yes,' and a numerical score of 0 was assigned to 'No.' Each cotton grower's total score was computed. Based on percentage of cotton growers adopting particular activity, they were categorized in 3 groups based on Mean and Standard deviation.

Results and Discussion

Table 1: Distribution of the Cotton Growers according to their Overall Use of Adaptation Strategies

Sr. No.	Overall Adaptation	Frequency	Per cent
1.	Low (up to 7)	25	17.86
2.	Medium (8 to 15)	99	70.71
3.	High (16 and above)	16	11.43
	Total	140	100.00

(Mean = 10.48) (SD = 3.659)

Table1 it is clear that majority 70.71 per cent of the cotton growers were having medium level use of adaptation strategies while 17.86 per cent were having low level adaptation strategies and only 11.43 per cent of cotton growers were having high level use of adaptation strategies to mitigate the impacts of climate change.

Table 2: Distribution of the Cotton Growers according to their Adaptation Strategies classified under CSA dimension

CSA Dimension	Recommended adaptation strategies	Adapted		Not adapted	
		Frequency	Per cent	Frequency	Per cent
Water-smart practices	<i>In situ</i> soil moisture	30	21.42	110	78.57
	Adapted water management systems like contour, graded bunding	0	00.00	140	100.00
	Drainage structures for draining wet lands	24	17.14	116	82.85
	Adapted mulching	21	15.00	119	85.00
	Adapted micro irrigation	48	34.28	92	65.71
Climate resilient varieties	Cotton varieties adapted for early sowing particularly due early onset of monsoon	97	69.28	43	30.71
	Location specific Cotton varieties resistant to heat and drought	53	37.85	87	62.14
	Cotton cultivars resistant to pest and disease	86	61.42	54	38.57
Crop & farm diversification	Adapted crop Diversification	65	46.42	75	53.57
	Adapted Multi- tier vegetable intercropping	31	22.14	109	77.85
	Adapted crop rotation	49	35.00	91	65.00
	Harvesting the cotton at right stage	93	66.42	47	33.57
Pest & disease management	Seed treatment with Trichoderma viride or Pseudomonas Fluorescence	23	16.42	117	83.57
	Adapted any practice to control the attack of bollworm	127	90.71	13	9.28
	Adapted any practice to control the attack of sucking pest	121	86.42	19	13.57
	Adapted any practices to control the incidence of minor pest and non-insect pest	33	23.57	107	76.42
Information-based adaptation	Adapted practices to control the incidence of diseases	122	87.14	18	12.85
	Weather agro advisory Services	70	50.00	70	50.00

Results from the Table 2 shows that the cotton growers mostly used water-smart practices as an adaptive reaction to rising rainfall unpredictability and moisture stress imposed on by climate change. Practices such as *in situ* soil moisture conservation (21.42%) and micro-irrigation (34.28%) were more widely used because they immediately address water scarcity during crucial crop growth stages and enhance water efficiency. Farmers' attempts to deal with frequent excessive rainfall and waterlogging situations, especially in low-lying cotton fields, are reflected in the adoption of drainage infrastructure (17.14%). A number of variables, including landholding size, labor requirements, initial investment costs, and poor technical understanding, may be responsible for the comparatively lower adoption of mulching (15.00%) and non-adoption of contour or graded bunding.

The results presented in Table 2 shows that cotton growers predominantly adopted climate-resilient varieties and crop management practices as adaptive strategies to deal with production risks and climatic variability. Higher adoption of early-sown cotton varieties (69.28%) indicates farmers' response to the early commencement and uncertainty of monsoon rains, allowing for timely crop establishment and avoidance of terminal moisture stress. Similarly, the adoption of pest and disease resistant cultivars (61.42%) reflects farmers' efforts to reduce climate-induced increases in pest and disease incidence, whereas the moderate adoption of heat- and drought-tolerant varieties (37.85%) indicates selective uptake influenced by accessibility and suitability to local conditions. Crop and farm diversification practices such as crop diversification (46.42%) and crop rotation (35.00%) were used to spread climatic risk and stabilize farm income, whereas multi-tier vegetable intercropping (22.14%) was less widely adopted due to higher management complexity and resource requirements. The high adoption of harvesting cotton at the appropriate stage (66.42%) demonstrates farmers' concern on decreasing post-harvest losses and maintaining fibre quality under changing weather conditions.

The findings show that cotton growers have widely adopted pest and disease management strategies as a critical adaptation approach for dealing with climate-induced increases in pest and disease incidence. The high adoption of strategies for controlling bollworm (90.71%), sucking pests (86.42%), and diseases (87.14%) indicates that farmers see biotic pressures as urgent and serious threats to cotton yield under changing climatic conditions. These practices indicate farmers' preference for interventions that result in a rapid and noticeable reduction in crop damage.

On the other hand, the relatively lower adoption of biological seed treatments employing *Pseudomonas fluorescens* or *Trichoderma viride* (16.42%), methods for controlling minor and non-insect pests (23.57%) may be attributed to the delayed observable benefits of biological control measures, limited availability, and low awareness. Additionally, although there could still be gaps in access and confidence in advisory systems, the moderate uptake of weather-based agro-advisory services (50.00%) shows increased acceptance of information-based adaptation as a way to predict pest outbreaks and plan timely management responses. Overall, these results show that information-based techniques and pest and disease control are essential

elements of farmers' adaptive responses to climate variability in cotton farming.

These methods support the adaptation and production pillars of climate-smart agriculture by minimizing climate-related crop losses and increasing resilience in cotton-based farming systems.

Overall, these findings imply that farmers should give priority to adaptation strategies that provide immediate and clear benefits for managing water stress, thereby enhancing resilience of cotton cultivation under changing climatic conditions. These observations were similar with findings of Mounika (2021)^[8] and Satindra Kumar (2017)^[12].

Conclusion

According to the study, cotton farmers have used a variety of adaptation techniques to deal with the effects of climate change, including higher temperatures, increased insect and disease incidence, rainfall variability, and moisture stress. Water-smart methods, climate-resilient cotton cultivars, timely harvesting, crop and farm diversity, and intense pest and disease control were found to receive more attention. These methods show that farmers give priority to adaptation strategies that lower production risks and stabilize output in the face of unpredictable weather. However, the comparatively poor uptake of biological pest management, long-term structural water conservation techniques, and intricate intercropping systems underscores current limitations pertaining to awareness, resource availability, labor requirements, and technical support.

In addition to providing indirect mitigation co-benefits through increased resource-use efficiency and decreased environmental stress, cotton growers' adaptation strategies are strongly aligned with the adaptation and productivity pillars of CSA when viewed through the lens of climate-smart agriculture. A modest movement towards information-based adaptation is shown in the mild use of weather-based agro-advisory services; nevertheless, climate information delivery and extension services still need to be strengthened. All things considered, the results highlight the necessity of focused extension interventions, policy support, and capacity-building programs to scale up climate-smart practices and improve the sustainability and resilience of cotton agricultural systems in the face of climate change.

Policy Implications

Strengthen Climate-Smart Extension Services

The development of climate-smart adaptation techniques in cotton should be given top priority by agricultural extension systems, with an emphasis on integrated pest and disease control, water-use efficiency, and climate-resilient cultivars. To increase knowledge and acceptance of long-term adaptation strategies including soil and water conservation and biological pest management, capacity-building initiatives, field demonstrations, and farmer training are crucial.

Expand Access to Digital Advisory Services and Climate Information

The provision of location-specific, prompt, and dependable weather-based agro-advisory services via digital platforms and last-mile extension networks should be strengthened by policymakers. Cotton producers can make more informed

decisions and take prompt action to lower output risks caused by climate change if they have better access to climate information.

Encourage incentives for resource-efficient and climate-resilient practices

To promote the use of micro-irrigation, climate-resilient cotton cultivars, and environmentally friendly pest management techniques, policy support in the form of subsidies, financial incentives, and credit facilities should be coordinated. The shift to climate-smart and sustainable cotton production systems can be accelerated by incorporating these incentives into current agriculture and climate action initiatives.

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