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Assessment of Carbon Sequestration Potential Through Cotton Crop Residue Incorporation in Adilabad District of Telangana, India

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Abstract

Cotton (*Gossypium hirsutum L.*) is the predominant cash crop of Adilabad district, Telangana, occupying approximately 1,60,000 hectares of the total cultivated area. Given the district's semi-arid climate and deep black cotton soils, cotton residue incorporation presents a significant opportunity for Soil Organic Carbon (SOC) sequestration. This study assesses the carbon sequestration potential of cotton crop residue incorporation in Adilabad district using ground-truth biomass measurements, satellite-derived Normalized

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Difference Vegetation Index (NDVI) from Sentinel-2 imagery and FAO Global Soil Organic Carbon Sequestration Potential (GSOC seq) database. Above Ground Biomass (AGB) measurements were conducted at farmers' fields and the instructional farm, yielding average residue biomass of 1.80 t/ha. Soil organic carbon sequestration potential across 30 villages confirmed with sequestration rates ranging from 0.109 to 0.170 t/ha/year (district average: 0.14 t ha^{-1} $year^{-1}$). Applying a carbon sequestration rate (t ha^{-1} $year^{-1}$) of 0.14, the average carbon stock was estimated at 0.25 t C ha^{-1} $year^{-1}$. Extrapolated across the district's cotton area, the total annual carbon sequestration potential is 40,000 t C $year^{-1}$. A multi-pronged adoption strategy encompassing adoption of residue management, mechanization and conservation agriculture through farmers training, policy incentives, digital monitoring and carbon market linkages is proposed to operationalize soil carbon sequestration across the district.

Keywords: Carbon sequestration; biomass; soil organic carbon; NDVI; climate smart agriculture.

1. Introduction

Climate change poses an existential threat to agricultural systems worldwide and rainfed farming regions in peninsular India are particularly vulnerable to its consequences. Telangana, a predominantly agrarian state, has been experiencing increasingly erratic monsoon patterns, recurrent droughts and rising temperatures that undermine the productivity of its staple crops (IPCC, 2022). In this context, carbon sequestration through agricultural soils has emerged as a dual-benefit strategy: it mitigates greenhouse gas emissions while simultaneously improving soil health, water retention and long-term crop productivity (Poeplau & Don, 2015; Minasny et al., 2017; Ravi et al., 2025).

Adilabad district in northern Telangana is one of the state's major cotton-growing districts. The district covers approximately 5.5 lakh gross cropped of area, of which cotton alone occupies around 4 lakh acres (approximately 1,61,874 ha), making it the dominant cash crop. The deep, swelling Vertisol soils (locally called 'regur' or black cotton soil) characteristic of the district possess inherently high clay content and significant potential for carbon stabilization, particularly when enriched with organic residues.

Cotton crop residues comprising stalks, leaves and boll shells represent a substantial biomass pool that is largely burned or removed post-harvest in current farming practice, releasing stored carbon back into the atmosphere. Systematic incorporation of these residues into the soil can meaningfully increase the SOC pool, contributing to climate mitigation targets while building soil fertility (Lal, 2004). Global estimates suggest that agricultural soils have the potential to sequester 0.9 - 1.85 Gt C/year through improved management practices, with South Asian rainfed systems being significant contributors (Minasny et al., 2017).

Despite the theoretical potential, empirical assessment of cotton residue carbon sequestration in semi-arid Deccan plateau conditions remains limited. Most existing studies from India focus on Indo-Gangetic Plain crops (wheat-rice systems) or focus on SOC under irrigation (Singh et al., 2021). The unique biophysical conditions of Adilabad its rainfall regime (900-1,100 mm/year), soil type and farming system necessitate district specific quantification. This study bridges this gap through a field based biomass survey integrated with NDVI satellite data and FAO Global Soil Organic Carbon Sequestration Potential Map (GSOCseq) soil carbon databases, providing the first comprehensive carbon sequestration assessment for cotton residues in Adilabad district.

1.1 Study Area and Agro Ecological Profile

Adilabad district is located in the northernmost part of Telangana state (18°13' to 19°56' N latitude; 77°46' to 79°36' E longitude) and borders Maharashtra to the north and Chhattisgarh to the northeast. The district has a total geographical area of approximately 4153 km², characterized by undulating terrain with elevation of 264 m above mean sea level. The climate is sub-humid to semi-arid, with average annual rainfall between 900 and 1100 mm received predominantly (85%) during the southwest monsoon (June-September).

The soils of the district are predominantly deep black vertisols (locally called black cotton soils), with moderate to high organic matter potential due to their 2:1 expanding clay lattice structure. The dominant farming system is rainfed cotton-sorghum or cotton-fallow rotation, cultivated on approximately 4 lakh acres (1,61,874 ha). The district is divided into 18 mandals, spanning a diverse agroecological gradient from the more humid Indravelly-Utnoor belt in the east to the drier Talamadugu-Tamsi areas in the west.

2. Materials and Methods

2.1 Cotton Biomass Estimation

Above-ground biomass of standing cotton crop was estimated by sampling at harvest maturity (December 2024). At each sampling location, four quadrats of 25 m^2 each were randomly placed within the field. All cotton stalks, leaves and dry boll shells within each quadrat were clipped at ground level, pooled, weighed fresh and subsampled for dry weight determination after oven-drying at 70°C to constant weight. The number of plants within each quadrat was also recorded to calculate per-plant biomass. Measurements were conducted at two sites: a representative farmers' field at Palsi K village and the Instructional Farm at KVK, Adilabad.

Table 1. Soil Organic Carbon Sequestration Potential and Sequestration Rate (t ha^{-1} $year^{-1}$) in different areas of Adilabad district

S. No.	Village	Mandal	Sequestration Rate (t ha^{-1} $year^{-1}$)
1	Devapur	Talamadugu	0.109
2	Talamadugu	Talamadugu	0.151
3	Kuchulapur	Talamadugu	0.155
4	Ponnari	Tamsi	0.160
5	Rajgada	Bheempur	0.122
6	Jainath	Jainath	0.157
7	Sirsanna	Bela	0.157
8	Pardi K	Jainath	0.118
9	Burnur	Jainath	0.109
10	Pippaldhari	Adilabad R	0.146
11	Indravelly	Indravelly	0.141
12	Keslapur	Utnoor	0.138
13	Damanguda	Gudihathnoor	0.139
14	Borigama	Ichoda	0.149
15	Raiguda	Ichoda	0.143
16	Kokasmannur	Ichoda	0.167
17	Wadoor	Neradigonda	0.136
18	Boath	Boath	0.140
19	Neradigonda	Neradigonda	0.146
20	Sonala	Boath	0.170
21	Sirikonda	Sirikonda	0.137
22	Bela	Bela	0.156
23	Tantoli Beside	Adilabad R	0.107
24	Ramachandrapurm	Adilabad R	0.022
25	Jamidi	Ichoda	0.132
26	Girnur	Bazarhathnur	0.161
27	Jatharla	Bazarhathnur	0.162
28	Khapparla	Tamsi	0.122
29	Belsari Rampur	Bheempur	0.152
30	Umdam	Tamsi	0.125
	Average		**0.14**

(Source: https://data.apps.fao.org/glosis/)

2.2 NDVI-Based Above Ground Biomass (AGB)

Sentinel-2 Level-2A surface reflectance images were acquired for the period June to December 2024 via the VEDAS (Visualization of Earth Observation Data and Archival System) platform of ISRO (https://vedas.sac.gov.in). Monthly NDVI composites were generated for selected representative cotton fields. The average NDVI for the cotton growing season was 0.4, consistent with moderate-density rainfed cotton canopies. Above-ground biomass was estimated using the relationship:

AGB (kg/ha) = NDVI × Maximum Biomass (kg/ha)

where Maximum Biomass was the field-measured peak biomass for Deccan cotton. Carbon stock was then derived as:

Carbon Stock (t C/ha/yr) = AGB (kg/ha) × Carbon Sequestration Rate (t ha^{-1} year^{-1}) / 1000

Study sites were selected across 30 representative villages spanning 15 mandals to capture the spatial variability of soil carbon dynamics and the details given below (Table 1).

Based on village-level data, the mean soil organic carbon sequestration rate of 0.14 t ha^{-1}yr^{-1} shows the central tendency with little variation. To ensure methodological consistency, a carbon sequestration rate (t ha^{-1} year^{-1}) of 0.14 was chosen as a region-specific coefficient for assessing sequestration potential.

2.3 District level Carbon Sequestration Calculation

The total annual carbon sequestration potential of the district was estimated using following formula.

Annual Carbon Sequestration Stock (t C ha^{-1} year^{-1}) in the district = District cotton crop area (ha) X Carbon Stock (t C ha^{-1} year^{-1})

3. Results and Discussion

3.1 Cotton Residue Biomass

The biomass assessment at harvest revealed significant variation between the farmers' field and the Instructional Farm, reflecting differences in plant density, variety and input management (Table 2).

The findings show a significant difference in the above-ground biomass of cotton between the instructional farm and the farmer's field. In addition to having a higher plant population density (81 vs. 61 plants per 25 m^2), the instructional farm had a higher fresh weight per plant (220 g) than the farmer's field (185 g). The dry matter accumulation per plant was nevertheless better (162.80 g vs. 153.55 g) even though the instructional farm had a comparatively greater moisture content (26%).

As a result, the maximum biomass yield per unit are 202120a was much larger in the instructional farm (13186.80 g per 25 m^2), or 5.28 t ha^{-1}, than in the farmer's field (3.75 t ha^{-1}). The average maximum biomass yield for all locations was 4.52 t ha^{-1}, which indicates moderate productivity under the current circumstances.

Table. 2. Cotton above ground biomass at harvest (2024)

Particulars	(A) Fresh Weight (g) of the plant	(B) No. of Plants / 25 m^2	(C) Moisture (%) content	(D) Dry matter Weight (g) (Biomass) (A x (100-C))	(E) Biomass per 25 m^2 (g) (BxD)	Maximum Biomass t ha^{-1} (10000 m^2)
Farmer's Field	185	61	17	153.55	9366.55	3.75
Instructional Farm	220	81	26	162.80	13186.80	5.28
Average	202.5	71	21.5	159	11289.00	4.52

Enhanced productivity was achieved through a combination of increased plant population and higher individual plant biomass. The lower biomass in farmer fields could be due to suboptimal agronomic practices, moisture stress and nutrient limitations (Anantha et al., 2018; Ramteke et al., 2024).

3.2 NDVI based Above Ground Biomass (AGB) and Carbon Stock Estimation

The results indicate from the (Table. 1) that soil organic carbon (SOC) sequestration potential across all selected villages of Adilabad district varying from 0.022 to 0.170 t ha^{-1} year^{-1}. The highest rate was observed in Sonala (0.170 t ha^{-1} year^{-1}), followed by Kokasmannur (0.167 t ha^{-1} year^{-1}), while the lowest was recorded in Ramachandrapuram (0.022 t ha^{-1} year^{-1}). Most villages exhibited values between 0.12 and 0.16 t ha^{-1} year^{-1}, indicating relatively consistent carbon dynamics. The overall mean sequestration rate was 0.14 t ha^{-1} $year^{-1}$, suggesting moderate to high potential for carbon sequestration under prevailing agro-ecological conditions.

Sentinel-2 derived NDVI values averaged 0.4 across cotton fields in Adilabad district during the peak growing season (June-December 2024). Both fields had a NDVI value of 0.4, which indicates that the canopy conditions were similar. The estimated above-ground biomass was significantly different, reaching 2112 kg ha^{-1} in the instructional farm versus 1500 kg ha^{-1} in the farmers' field. The average crop growth under the prevailing conditions was moderate, with an average biomass of 1808 kg ha^{-1} (Table 3).

Table 3. Estimation of carbon stock (t C ha^{-1} $year^{-1}$) using Above Ground Biomass (AGB) and sequestration rate

Particulars	AGB (kg ha^{-1})	Sequestration Rate (t ha^{-1} $year^{-1}$)	Carbon stock (kg C ha^{-1} $year^{-1}$)	Carbon stock (t C ha^{-1} $year^{-1}$)
Farmer’s field	1500	0.14	210.00	0.21
Instructional farm	2112	0.14	295.68	0.30
Average	1808	0.14	253.12	0.25

The carbon stock estimation revealed notable variations between management conditions. The instructional farm recorded higher AGB (2112 kg ha^{-1}), resulting in greater carbon sequestration (295.68 kg C ha^{-1} $year^{-}1$; 0.30 t C ha^{-1} $year^{-1}$) compared to the farmer’s field (1500 kg ha^{-1}; 210.00 kg C ha^{-1} $year^{-1}$ 0.21 t C ha^{-1} $year^{-1}$). The average carbon stock was 0.25 t C $year^{-1}$, which indicates a moderate sequestration potential. Carbon accumulation was primarily governed by differences in biomass production while estimation was consistent across sites due to the uniform carbon sequestration rate (0.14 t ha^{-1} $year^{-1}$). This study highlights how improved agronomic practices can improve carbon sequestration in cotton based systems (Parihar et al., 2022; Windeatt et al., 2014).

3.3 District Level Carbon Sequestration Potential

Extrapolating the carbon stock estimates across the district cotton area yields a total carbon sequestration potential of 52,147 t C/year from the biomass approach (Table 4). The SOC-based approach, using the GSOCseq average rate of 0.14 t/ha/year across the 160000 ha normal cropped area, yields a complementary estimate of 30,800 t C/year. The difference between the two estimates (21,347 t C/year) likely reflects the fraction of above-ground biomass carbon that is respired or lost rather than stabilized in the soil. Under realistic decomposition and humification assumptions (15-25% humification efficiency for crop residues in tropical soils), these two estimates converge to a plausible stable carbon sequestration rate of ~0.14-0.33 t C/ha/year.

Table 4. Estimation of total carbon sequestration potential for Adilabad district through insitu incorporation of cotton biomass

District cotton area (ha) (approx.)	Carbon stock (t C ha^{-1} $year^{-1}$)	Sequestration potential for the district (t C $year^{-1}$)
160000	0.25	40000

Cotton based systems that incorporate in situ biomass indicate a moderate level of carbon sequestration, with an estimated average carbon stock of 0.25 t C ha^{-1} $year^{-1}$. Field-level observations revealed that variations in above-ground biomass production directly influenced carbon stocks, with higher biomass contributing proportionally to greater carbon accumulation in soil (Anantha et al., 2018; Netsianda & Mhangara, 2025; Causarano et al., 2006). When extrapolated to the district scale, the total sequestration potential was estimated at 40,000 tons of carbon per year over 160,000 hectares (Table 4), demonstrating substantial cumulative impact.

Converting the district total estimated carbon sequestration potential 40,000 tons of carbon per year over 160,000 hectares can capture 1,46,667 t of atmospheric CO_2 per year. Formula is given below.

[Atmospheric CO_2 Capture (t CO_2 $year^{-1}$) = Sequestration Potential (t C $year^{-1}$) × 3.67]

4. Strategy for Increasing Adoption of Soil Carbon Sequestration

4.1 Farmer Awareness and Capacity Building

Knowledge gaps remain the primary barrier to residue incorporation adoption in Adilabad. Many farmers perceive residue burning as a convenient and cost-free field-clearance method, unaware of its long-term soil health costs and the emerging economic value of carbon. A structured awareness campaign through Krishi Vigyan Kendras (KVKs), the Farmers' Producer Organizations (FPOs) and digital channels (using social media) should communicate: (i) the tangible soil fertility benefits of residue incorporation within 2-3 seasons, (ii) savings on chemical fertilizer costs due to improved nutrient cycling and (iii) emerging opportunities under carbon markets and agri-carbon credit schemes.

Demonstration plots ('Krishi Darshan' units) at the village level similar to the Instructional Farm approach used in this study can provide visible proof of practice benefits. Evidence from comparable programs in Maharashtra's Vidarbha region shows that on-farm demonstrations increase residue management adoption rates by 35-50% compared to extension meetings alone (Jat *et al.,* 2016).

4.2 Organizing Training Programmes

Strengthening extension services and farmer capacity building Robust extension systems are critical for translating scientific knowledge into field-level adoption. Training programs should focus on demonstrating biomass incorporation benefits, residue decomposition dynamics, and soil health improvements. Participatory approaches, including on-farm demonstrations and farmer field schools, have been shown to significantly increase adoption of sustainable soil management practices (Lal, 2004).

4.3 Mechanization Support for Residue Management

A critical practical barrier to residue incorporation is the lack of affordable machinery for chopping and incorporating cotton stalks. The thick, woody stems of cotton require specialized shredders or mulchers. The Telangana government's farm mechanization scheme (RIDF and RKVY funds) should be leveraged to establish Custom Hiring Centres (CHCs) in each mandal, equipped with tractor-mounted residue shredders and disc harrows. Subsidizing CHC rentals by 50% for small and marginal farmers (land holding < 2 ha) during the critical November-December post-harvest window would make mechanization economically viable.

4.4 Policy and Regulatory Framework

Telangana should enforce and expand the existing ban on crop residue burning under the National Green Tribunal (NGT) orders, while simultaneously offering positive incentives rather than relying solely on punitive measures. A dedicated 'Adilabad Carbon Agriculture' policy framework could include: (i) input subsidies (organic matter, bioinoculants) conditional on no residue burning certification; (ii) a premium price support for cotton from fields with documented residue management and (iii) linking residue management compliance to access to the PM-KISAN and other government transfer programs. These 'carrots and sticks' approaches have proved effective in shifting farmer behavior in Punjab wheat-rice systems regarding stubble burning.

4.5 Carbon Market Linkages and Finance

India's emerging voluntary carbon market and the government-backed Carbon Credit Trading Scheme (CCTS) under the Energy Conservation Act 2022 provide an enabling policy environment for monetizing agricultural SOC gains. At 0.25 t C ha^{-1} $year^{-1}$× 3.67 = 0.92 t CO_2 ha^{-1} $year^{-1}$, even modest carbon prices of USD 5-15/t CO_2 (voluntary market range for agricultural soil carbon) would provide an additional income of USD 4.6-13.8 ha^{-1} $year^{-1}$ to Adilabad cotton farmers. To access these markets, farmer groups need: (i) aggregation into FPOs or cooperatives for transaction cost viability; (ii) standardized monitoring, reporting, and verification (MRV) protocols; and (iii) technical assistance for carbon project registration (e.g., under Verra's VM0042 methodology for agricultural soils).

4.6 Digital Monitoring and Verification

Scaling carbon sequestration verification across 1,60,000 ha requires cost-effective remote sensing-based MRV. The VEDAS NDVI time-series platform used in this study, combined with the ISRO's Bhuvan geoportal and

FAO GSOCseq maps, provides a foundational framework that can be operationalized at scale. A district-level digital carbon monitoring dashboard integrated with existing state crop survey data (Adangal records) and soil health card information would enable transparent, auditable tracking of residue management area, estimated carbon stocks and trend monitoring. Machine learning algorithms trained on ground-truth data can extrapolate fine-scale NDVI-based biomass estimates across the entire district at low marginal cost.

4.7 Research and Long-term Monitoring

Long-term experimental plots (minimum 10-15 years) established at representative sites in Adilabad should monitor actual SOC stock changes under cotton residue incorporation relative to control plots (residue burning). These experiments should: (i) stratify treatments by soil type, topographic position and rainfall gradient; (ii) collect soil samples annually at multiple depths (0-15, 15-30, 30-60 cm); (iii) monitor soil biological health indicators alongside carbon; and (iv) develop and validate region-specific NDVI-biomass-carbon equations for improved remote sensing estimates. Collaboration between PJTAU/ANGRAU/ICAR-CRIDA and the Adilabad district administration will be essential for sustaining these monitoring efforts.

4.8 Site-specific Nutrient and Moisture Management

Efficient decomposition and stabilization of incorporated biomass depend on balanced nutrient supply and soil moisture conditions. Application of nitrogen along with residues accelerates microbial activity and humification processes. In semi-arid Vertisols, moisture conservation practices further enhance carbon retention. Research confirms that integrated nutrient management significantly improves SOC sequestration efficiency.

5. Limitations of the Study

The present study has certain limitations that should be considered while interpreting the findings. The estimation of soil organic carbon sequestration was partly based on NDVI- derived biomass assessments and assumptions of relatively uniform sequestration rate across the study area, which may not fully capture spatial and temporal variability in field conditions. In addition, Uncertains associated with district-level extrapolation and remote sensing data resolution may influence the precision of carbon stock estimations. Variations in management practices, climatic factors and residue incorporation efficiency among farmers were also not comprehensively accounted for in the analysis. Despite these limitations, the study provides useful regional-scale assessment of carbon sequestration potential in semi-arid cotton based systems and offers a foundation for future detailed investigations using long-term filed validation and high resolution datasets.

6. Conclusion

This study provides the first comprehensive assessment of carbon sequestration potential through cotton crop residue incorporation in Adilabad district, Telangana. The present study demonstrates that in situ incorporation of cotton biomass can significantly enhance soil carbon sequestration in the Adilabad district. The average carbon stock was estimated at 0.25 t C ha-1 year-1 and by extrapolating across 160,000 ha under cotton, it was determined that the district could capture 40,000 t C year-1, equivalent to 1,46,800 t CO_2 per year. The findings confirm that cotton-based rainfed systems can function as important carbon sinks when crop residues are retained and incorporated into the soil. Improving climate mitigation, improving soil health, and supporting long-term agricultural sustainability in the district can be achieved through the adoption of residue management, mechanization and conservation agriculture. Realizing this potential requires a coordinated adoption strategy combining mechanization support, policy incentives, carbon market linkages, digital monitoring, and long-term research.

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 writing or editing of this manuscript.

Competing Interests

Authors have declared that no competing interests exist.

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