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Impact of tractor-operated cotton shredder for sustainable residue management and soil health improvement in Raichur district

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Abstract

Cotton (*Gossypium hirsutum* L.) cultivation generates substantial quantities of crop residues after harvest, particularly cotton stalks, which are often burnt in the field because of labour shortages and the need for rapid land preparation. Residue burning results in significant nutrient losses, deterioration of soil health, environmental pollution and increased production costs. Mechanized residue management through tractor-operated cotton shredders has emerged as an efficient alternative for sustainable cotton production. The present investigation was conducted in three villages of Raichur district, Karnataka, namely Matamari, Purtipli and Jakaldinni, to evaluate the effect of cotton stalk shredding and incorporation on soil fertility, soil health parameters and operational economics. The results indicated a substantial improvement in soil fertility following residue incorporation. Available nitrogen increased by 15%, phosphorus by 31.66% and potassium by 14.00% over the initial soil status. Soil porosity improved by 4.00%, microbial population increased by 35.13%, while soil organic carbon recorded an enhancement of 41.80%. Mechanized residue incorporation reduced labour requirement from eight to one labourer per hectare and reduced residue management cost from ₹5,250 ha⁻¹ under conventional practice to ₹2,340 ha⁻¹. The tractor-operated cotton shredder completed one hectare of residue management within one hour compared with eight hours required under manual uprooting and burning. The findings clearly demonstrate that mechanized cotton stalk incorporation enhances nutrient recycling, improves soil physical and biological properties, lowers production costs and eliminates residue burning, thereby contributing to sustainable cotton production and climate-smart agriculture.

Keywords: Cotton residue management, cotton shredder, nutrient recycling, soil organic carbon, soil microbial population, sustainable agriculture, mechanization

Introduction

Cotton (*Gossypium hirsutum* L.) is one of the most important commercial fibre crops cultivated throughout the tropical and subtropical regions of the world. The crop contributes significantly to agricultural income, employment generation and industrial development through its close linkage with the textile sector (Ritchie *et al.*, 2007; ICAC, 2023) ^[12, 7]. India is currently the world's largest cotton-growing country, cultivating nearly 12.34 million hectares annually (Directorate of Economics and Statistics, 2023-24; Ministry of Agriculture & Farmers Welfare, 2024). Karnataka is one of the major cotton-producing states with an area of approximately 0.765 million hectares, while Raichur district contributes nearly 0.186 million hectares under cotton cultivation (DES, Government of Karnataka, 2023-24). Such extensive cultivation generates enormous quantities of crop residues after harvest, particularly cotton stalks, ranging from 5-7 t ha⁻¹ depending on cultivar, plant population, irrigation and crop management practices (Kumar *et al.*, 2015; Lal, 2005) ^[8, 10].

Crop residues are an important component of sustainable agriculture as they serve as a source of plant nutrients, organic matter and energy for soil microorganisms. Cotton stalks contain appreciable quantities of nitrogen (N), phosphorus (P) and potassium (K), and their incorporation into the soil improves soil fertility, enhances soil organic carbon and sustains long-term crop productivity.

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Recycling crop residues also reduces nutrient losses and fertilizer requirements for succeeding crops while contributing to improved soil physical, chemical and biological properties (Lal, 2005; Govaerts *et al.*, 2009) ^[5].

Table 1: Cotton area, stalk production and nutrient content

Cotton		
Places	Area (mha)	Stalk production (t/ha)
India	12.34	5-7
Karnataka	0.765	
Raichur	0.186	
Nutrient	Cotton stalk (kh/ha)	Total Loss (kg/ha)
N	12.40-20	26.20-35.20
P	1.60	
K	12.20-13.60	

In many cotton-growing regions of India, cotton stalks are manually uprooted and burnt in the field due to labour shortages, high labour costs and the short interval between cotton harvest and sowing of the succeeding crop. However, residue burning results in the loss of valuable nutrients and organic matter, deteriorates soil health and releases greenhouse gases and particulate matter into the atmosphere, contributing to environmental pollution and climate change. The increasing scarcity of agricultural labour has further emphasized the need for efficient mechanized residue management technologies (Gupta *et al.*, 2004; Sidhu and Beri, 2008) ^[6, 14].

Tractor-operated cotton shredders provide an efficient alternative by shredding standing cotton stalks into small fragments that can be easily incorporated into the soil during tillage. Residue incorporation enhances nutrient recycling, microbial activity, carbon sequestration, soil moisture retention and soil structure while facilitating timely field preparation and reducing labour dependence. Although cotton shredders have shown considerable potential for residue management, information on their impact on soil health and economics under the black soil conditions of north-eastern Karnataka remains limited. Therefore, the present study was undertaken to evaluate the effect of mechanized cotton residue shredding and incorporation on soil properties and economic returns under farmers' field conditions.

The present study was undertaken to evaluate the effectiveness of a tractor-operated cotton shredder for cotton residue management in Raichur district, Karnataka. Specifically, the study aimed to quantify nutrient recycling through residue incorporation, assess changes in soil fertility and soil health indicators, compare the operational efficiency and economics of mechanized residue management with conventional residue burning, and demonstrate the potential of this technology as a sustainable alternative for cotton-based cropping systems.

The present investigation was undertaken to evaluate the effectiveness of a tractor-operated cotton shredder for residue management. The study aimed to quantify nutrient recycling through cotton stalk incorporation, assess its effect on soil fertility and soil health parameters such as available nitrogen, phosphorus, potassium, soil organic carbon, porosity and microbial population, compare the labour requirement, operational efficiency and cost of mechanized residue management with the conventional practice of manual uprooting and burning, and evaluate its potential for promoting sustainable cotton production and improving soil health.

2. Materials and Methods

2.1 Experimental site

The study was conducted during the post-harvest period of

cotton in Raichur district of Karnataka, India, under farmers' field conditions. The demonstrations were organized by ICAR-Krishi Vigyan Kendra (KVK), Raichur to evaluate the performance of a tractor-operated cotton shredder for efficient cotton stalk management and to assess its impact on soil health and nutrient recycling. The demonstrations were conducted in three representative cotton-growing villages, namely Matamari, Purtipli and Jakaldinni, which represent the major cotton production areas of the district.

Raichur district lies in the North-Eastern Dry Zone (Zone II) of Karnataka and is characterized by a semi-arid tropical climate. The region experiences hot summers, moderate monsoon rainfall and mild winters. The soils of the demonstration sites are predominantly medium to deep black soils (Vertisols), which are well suited for cotton cultivation because of their high clay content and moisture-retention capacity. Cotton is one of the principal commercial crops grown in the district under both rainfed and irrigated conditions, making crop residue management an important issue for sustaining soil productivity.

2.2 Selection of farmers and demonstration layout

Frontline demonstrations were conducted in collaboration with progressive cotton farmers from the selected villages. Farmers were selected based on their willingness to participate, uniformity of crop management practices and availability of cotton fields suitable for residue incorporation.

Each demonstration consisted of approximately one hectare of cotton area where a tractor-operated cotton shredder was used for cutting and incorporating cotton stalks immediately after harvest. The results were compared with the prevailing farmer practice involving manual uprooting, collection and open-field burning of cotton stalks. All other agronomic practices remained similar to ensure that the observed differences were primarily due to the residue management method.

2.3 Tractor-operated cotton shredder

The cotton shredder used in the demonstrations was a tractor-operated implement designed to cut standing cotton stalks into small pieces immediately after harvest. The machine was operated using a standard agricultural tractor through the power take-off (PTO) system.

The shredder performed two important functions like Cutting and shredding standing cotton stalks and facilitating incorporation of shredded residues into the soil during subsequent tillage.

Unlike conventional residue removal, where stalks are manually uprooted and burnt, mechanized shredding leaves finely chopped biomass on the soil surface, which decomposes rapidly after incorporation. The smaller particle size increases the surface area available for microbial decomposition, thereby accelerating nutrient mineralization and organic matter recycling.

2.4 Residue incorporation

Immediately after shredding, the chopped cotton residues were incorporated into the soil using conventional tillage implements available with the farmers. Incorporation was completed soon after harvest to ensure adequate decomposition before sowing of the succeeding crop. Residue incorporation promotes gradual decomposition of lignocellulosic biomass by soil microorganisms. During decomposition, nutrients present in the cotton stalks are mineralized and released into the soil solution, improving nutrient availability and contributing to soil organic matter accumulation.

2.5 Soil sampling

Composite soil samples were collected from each demonstration field before residue incorporation (initial sampling) and after decomposition of incorporated cotton residues (final sampling). Samples were collected from representative locations within each field to minimize variability. The collected soil samples were air-dried, gently crushed, sieved through a 2-mm sieve and analysed using standard laboratory procedures. The soil parameters which were determined are Available nitrogen (kg ha⁻¹), Available phosphorus (kg ha⁻¹), Available potassium (kg ha⁻¹), Soil porosity (%), Microbial population (CFU g⁻¹ soil) and Soil organic carbon (%). These parameters were selected because they represent important indicators of soil fertility, soil biological activity and overall soil health.

2.6 Estimation of soil fertility parameters

Available nitrogen, phosphorus and potassium were estimated using standard analytical procedures commonly followed in soil testing laboratories. Initial and final nutrient status was recorded for each village to determine the contribution of cotton residue incorporation to nutrient recycling.

The percentage increase in each nutrient was calculated using the following equation:

$$\text{Percentage Increase} = \frac{\text{Final value} - \text{Initial value}}{\text{Initial value}} \times 100$$

The calculated values were used to compare improvements in nutrient availability following residue incorporation.

2.7 Assessment of soil physical and biological properties

To evaluate the influence of residue incorporation on soil quality, soil porosity, microbial population and soil organic carbon were measured before and after the demonstrations.

- **Soil porosity:** Soil porosity was used as an indicator of soil physical condition. Improved porosity reflects better aggregation, enhanced aeration and greater water infiltration resulting from decomposition of incorporated residues.
- **Microbial population:** The microbial population was estimated by standard microbiological techniques and expressed as colony-forming units (CFU g⁻¹ soil). Increased microbial colonies indicate enhanced biological activity resulting from the availability of decomposable organic substrates supplied by cotton residues Table 3.
- **Soil organic carbon:** Soil organic carbon was determined to assess the contribution of incorporated cotton residues to carbon sequestration and improvement of soil fertility. Organic carbon serves as a major indicator of soil quality because it influences nutrient cycling, water retention, aggregate stability and microbial activity.

2.8 Operational performance and economic analysis

Operational efficiency of the tractor-operated cotton shredder was evaluated by recording total working hours required per hectare, labour requirement, fuel consumption, machine hiring charges and total operational cost. The cost of mechanized residue management included diesel consumption and machine hiring charges. The conventional method included labour charges associated with manual uprooting, collection and burning of cotton stalks. The economic advantage of mechanized residue management was evaluated by comparing total cost of residue management (₹ ha⁻¹), labour savings, reduction in operational time and cost reduction over conventional practice. The economic analysis also considered

the indirect benefits arising from nutrient recycling, reduced residue burning and improved soil health.

2.9 Data analysis

The observations recorded from the three demonstration villages were compiled and summarized using descriptive statistical methods. Mean values and percentage changes between the initial and final observations were calculated for each soil parameter. Percentage improvement in soil nutrients, soil porosity, microbial population and soil organic carbon was used to evaluate the effectiveness of cotton residue incorporation. Similarly, reductions in labour requirement, working hours and operational costs were calculated to compare mechanized residue management with the conventional farmer practice. Since the demonstrations were conducted under farmers' field conditions, the results were interpreted using comparative analysis to evaluate the practical performance of the technology.

3. Results and Discussion

3.1 Cotton stalk production and nutrient recycling

Cotton is an important commercial crop that generates substantial quantities of stalk biomass after harvest, providing considerable potential for nutrient recycling. In India, cotton is cultivated over 12.34 million ha, while Karnataka accounts for 0.765 million ha, with Raichur district contributing 0.186 million ha. Cotton produces approximately 5-7 t ha⁻¹ of dry stalk biomass, containing appreciable quantities of nitrogen, phosphorus, and potassium. If these residues are removed or burnt, about 26.20-35.20 kg ha⁻¹ of major nutrients are lost, besides causing environmental pollution and depletion of soil organic matter. Therefore, mechanized shredding and in situ incorporation of cotton stalks offer a sustainable alternative by conserving nutrients, improving soil health, and reducing dependence on chemical fertilizers.

The incorporation of shredded cotton stalks significantly improved the availability of major nutrients in the soil. Available nitrogen increased from 296.4 to 343.8 kg ha⁻¹ in Matamari, 286.2 to 326.2 kg ha⁻¹ in Purtilpli, and 294.6 to 338.7 kg ha⁻¹ in Jakaldinni, recording an overall increase of 15.00% following residue incorporation Table 2. The increase in available nitrogen can be attributed to microbial decomposition and mineralization of organic nitrogen present in cotton residues, which gradually releases ammonium and nitrate into the soil. Similar improvements in soil nitrogen following crop residue incorporation have been reported by Turmel *et al.* (2015)^[17] and Srinivasarao *et al.* (2020)^[16], who observed enhanced nutrient cycling and microbial activity under conservation agriculture.

Table 2: Nutrient mass returned by cotton stalks to the soil

Village	N (kg/ha)		P (kg/ha)		K (kg/ha)	
	Initial	Final	Initial	Final	Initial	Final
Matamari	296.4	343.8	22.23	25.34	148.5	170.7
Purtilpli	286.2	326.2	24.70	27.66	141.2	159.5
Jakaldinni	294.6	338.7	19.76	22.72	138.8	158.2
% Increase	15.00		13.66		14.00	

Available phosphorus also increased significantly after cotton stalk incorporation. Phosphorus content increased from 22.23 to 25.34 kg ha⁻¹ in Matamari, 24.70 to 27.66 kg ha⁻¹ in Purtilpli, and 19.76 to 22.72 kg ha⁻¹ in Jakaldinni, with an overall increase of 13.66%. The increase may be due to the mineralization of organic phosphorus compounds and the production of organic acids during residue decomposition, which enhance phosphorus

solubility and reduce fixation in Vertisols. Similar findings were reported by Blanco-Canqui and Lal (2009) ^[1], who highlighted the positive role of crop residue retention in improving phosphorus availability and nutrient-use efficiency.

Likewise, available potassium increased from 148.5 to 170.7 kg ha⁻¹ in Matamari, 141.2 to 159.5 kg ha⁻¹ in Purtipli, and 138.8 to 158.2 kg ha⁻¹ in Jakaldinni, resulting in an overall increase of 14.00%. Potassium is predominantly present in soluble ionic form in crop residues and is released rapidly during decomposition, making it readily available for plant uptake. Improved potassium availability enhances water-use efficiency, enzyme activation, and crop tolerance to abiotic stress. Similar observations have been reported by Pittelkow *et al.* (2015) ^[11] and FAO (2017) ^[4], who emphasized that residue incorporation improves soil nutrient status while promoting sustainable and environmentally friendly crop production.

3.2 Effect of cotton stalk incorporation on soil physical and biological properties

The incorporation of shredded cotton stalks significantly improved soil physical and biological properties, indicating its positive role in enhancing soil health and long-term productivity. Soil porosity increased from 49 to 51% in Matamari, 48 to 50% in Purtipli, and 47 to 49% in Jakaldinni, resulting in an overall increase of 4.00% following residue incorporation Table 3. The improvement in soil porosity may be attributed to the decomposition of cotton residues, which increased soil organic matter and promoted the formation of stable soil aggregates. Organic residues act as binding agents between soil particles and stimulate the production of microbial polysaccharides that improve aggregate stability, thereby increasing pore space, water infiltration, aeration, and root proliferation. Improved soil porosity is particularly advantageous in the Vertisols of Raichur, where repeated tillage often leads to soil compaction. Similar improvements in soil physical properties following crop residue incorporation have been reported under conservation agriculture systems by Blanco-Canqui and Lal (2009) ^[1] and Turmel *et al.* (2015) ^[17].

Table 3: Effect of Cotton Stalk Incorporation on Soil Porosity, Microbial Population and Organic Carbon

Porosity		
Villages	Initial values	Final values
Matamari	49	51
Purtiple	48	50
Jakaldinni	47	49
% Increase	4.00	
Microbial colonies		
Villages	Before	After
Matamari	4.5×10^7	6.0×10^7
Purtiple	4.0×10^7	5.0×10^7
Jakaldinni	3.5×10^7	4.7×10^7
% Increase	35.13	
Organic Carbon		
Villages	Before	After
Matamari	0.60	0.85
Purtiple	0.65	0.90
Jakaldinni	0.55	0.80
% Increase	41.80	

A substantial increase in soil microbial population was also

observed after incorporation of cotton stalks. Microbial counts increased from 4.5×10^7 to 6.0×10^7 CFU g⁻¹ soil in Matamari, 4.0×10^7 to 5.0×10^7 CFU g⁻¹ soil in Purtipli, and 3.5×10^7 to 4.7×10^7 CFU g⁻¹ soil in Jakaldinni, recording an overall increase of 35.13%. The increase in microbial population can be attributed to the availability of readily decomposable carbon compounds released during residue decomposition, which serve as an energy source for bacteria, fungi, and actinomycetes. Enhanced microbial activity accelerates the mineralization of nutrients, improves enzyme activity, and promotes efficient nutrient cycling. Increased microbial biomass also contributes to better soil fertility and resilience by suppressing certain soil-borne pathogens and improving soil biochemical processes. Similar findings have been reported by Srinivasarao *et al.* (2020) ^[16] and Lal (2020) ^[9], who observed that residue retention significantly enhances soil biological activity and ecosystem functioning Table 3.

Cotton stalk incorporation also markedly improved soil organic carbon (SOC), one of the most important indicators of soil quality. Soil organic carbon increased from 0.60 to 0.85% in Matamari, 0.65 to 0.90% in Purtipli, and 0.55 to 0.80% in Jakaldinni, with an overall increase of 41.80% after residue incorporation. The increase in SOC reflects the addition of carbon-rich organic residues to the soil, which contributes to carbon sequestration and improves cation exchange capacity, nutrient retention, aggregate stability, and water-holding capacity. Higher SOC also enhances fertilizer-use efficiency and increases the sustainability of cotton-based production systems. From an environmental perspective, incorporation of cotton residues retains carbon within the soil rather than releasing it into the atmosphere through burning, thereby contributing to climate-smart agriculture and sustainable residue management. Similar benefits of residue incorporation on soil organic carbon have been documented by FAO (2017) ^[4], Pittelkow *et al.* (2015) ^[11], and Lal (2020) ^[9] Table 3.

3.3 Operational Performance, Economics and Overall Implications of Cotton Stalk Incorporation.

The adoption of mechanized cotton stalk management using a tractor-operated cotton shredder proved to be technically efficient, labour-saving, and economically advantageous over the conventional practice of manual uprooting and residue burning (Table 4). The tractor-operated shredder required only 1 hour ha⁻¹ to complete residue management compared to 8 hours ha⁻¹ under the conventional method. Similarly, labour requirement was reduced from 8 labourers ha⁻¹ to 1 labourer ha⁻¹, highlighting the potential of mechanization to address labour scarcity during the post-harvest period. The operational cost of residue management using the shredder was ₹2,340 ha⁻¹, whereas the conventional practice involving manual cutting, collection and burning incurred a cost of ₹5,250 ha⁻¹, representing a reduction of approximately 55.4% in residue management costs. These findings clearly demonstrate that mechanized residue incorporation not only reduces production costs but also facilitates timely field preparation for the succeeding crop, thereby improving cropping system efficiency. Similar economic benefits of mechanized residue management have been reported by Sidhu *et al.* (2007) ^[15] and Sharma *et al.* (2019) ^[13], who observed substantial savings in labour, operational costs and turnaround time through the use of crop residue management machinery.

Table 4: Tractor operated cotton shredder for cotton stalk management

Particulars	Working hours (h/ha)		Total Labour Required/ha		Cost involved/ha (Rs.)	
	Demo	Check	Demo	Check	Demo	Check
Cutting and uprooting of cotton straw	01	08	01	08	2340.00	2000.00
Collection and Burning of cotton straw	-	05	-	05	(10 litre*94 Rs/lit) + Machine Hiring charges Rs.1400)	1250.00
To cover one hectare of area	01	08	01	08		2000.00
Total					2340.00	5250.00

Beyond direct economic gains, mechanized shredding and incorporation offer several agronomic and environmental advantages. Incorporation of shredded cotton stalks recycles valuable nutrients, improves soil physical and biological properties, and eliminates nutrient losses associated with residue burning. The increase in soil available nitrogen, phosphorus, potassium, microbial population, soil porosity and organic carbon observed in the present study demonstrates the effectiveness of residue incorporation in improving soil fertility and sustaining crop productivity. Moreover, avoiding open-field burning reduces greenhouse gas emissions and particulate pollution, contributing to improved environmental quality and climate change mitigation. These observations are in agreement with the findings of Pittelkow *et al.* (2015)^[11], Turmel *et al.* (2015)^[17], and Lal (2020)^[9], who reported that residue retention under conservation agriculture enhances nutrient-use efficiency, improves soil health, and promotes long-term sustainability.

Overall, the results indicate that tractor-operated cotton stalk shredding and in situ incorporation represent an effective strategy for sustainable cotton residue management in the medium to deep black soil of Raichur district. The technology substantially reduces labour and operational costs while improving soil fertility and minimizing environmental pollution. Therefore, wider adoption of mechanized cotton residue incorporation through custom hiring centres, farmer producer organizations, and government-supported mechanization programmes could significantly contribute to sustainable cotton production, conservation of natural resources, and climate-resilient agriculture in major cotton-growing regions of India.

Conclusions

The present study demonstrated that mechanized cotton stalk shredding and in situ incorporation is an effective and sustainable residue management practice for cotton production. Incorporation of cotton stalks significantly improved soil available nitrogen, phosphorus, and potassium, indicating enhanced nutrient recycling and reduced nutrient losses. It also improved soil porosity, microbial population, and soil organic carbon, thereby enhancing overall soil health and fertility. The tractor-operated cotton shredder substantially reduced labour requirement, operational time, and residue management cost compared to the conventional practice of manual uprooting and burning. In addition, residue incorporation minimized environmental pollution by avoiding open-field burning and conserving valuable plant nutrients within the soil. Overall, mechanized cotton stalk incorporation offers economic, agronomic, and environmental benefits, making it a viable technology for sustainable cotton cultivation. Wider adoption of this practice through extension programmes and farm mechanization initiatives can improve soil productivity, reduce cultivation costs, and promote climate-resilient cotton production.

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