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Empirical assessment of soil carbon sequestration management practices among sugarcane growers: Adoption dynamics, technological barriers and policy implications

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Abstract

Soil carbon sequestration (SCS) in Sugarcane (*Saccharum officinarum* L.) agroecosystems offers a vital mechanism for climate change mitigation and long-term soil health improvement. This study evaluates the extent of adoption of twenty-one carbon sequestration management practices across six key agronomic domains among sugarcane growers (N = 320). Using structured field surveys, descriptive metrics, and diagnostic analysis, the study reveals significant heterogeneity in adoption rates. High adoption was observed for conventional nutrient practices such as Farmyard Manure (FYM) application (100.00 per cent), vermicompost usage (79.37 per cent), leguminous intercropping (67.50 per cent), green manuring (62.82 per cent), and North-South row orientation (60.62 per cent). Conversely, advanced carbon management interventions experienced severe adoption deficits: biochar preparation was completely absent (0.00 per cent), organic sugarcane farming remained marginal (1.56 per cent), zero-till seed drill utilization for intercropping was critically low (7.18 per cent), soil testing before sowing was sparse (11.56 per cent), and solar irrigation pumps were limited to (10.93 per cent). Constraints analysis reveals structural challenges including high capital investments, lack of technical calibration knowledge, labour constraints during peak seasonal windows, shading competition in agroforestry systems, and inadequate extension mechanisms. The paper formulates an integrated policy framework emphasizing targeted subsidies, extension modernization, custom hiring centres, and carbon credit mechanisms to bridge the practice-adoption gap in sugarcane agriculture.

Keywords: Soil carbon sequestration, sugarcane agroecosystems, integrated nutrient management, sustainable tillage, biomass incorporation, climate-smart agriculture

1. Introduction

Sugarcane (*Saccharum officinarum* L.) is one of the most vital industrial crops worldwide, playing a multi-faceted role in sugar production, bioethanol renewable energy, and rural economic livelihood. As C4 photosynthetic plants, sugarcane crops exhibit exceptional biomass accumulation capacities, fixating substantial quantities of atmospheric carbon dioxide (CO₂) per unit land area per annum. Consequently, sugarcane agroecosystems possess immense potential to act as major carbon sinks through soil organic carbon (SOC) sequestration. SOC sequestration not only mitigates greenhouse gas emissions but also enhances soil structural stability, water-holding capacity, cation exchange capacity, and microbial biodiversity (Hossain *et al.*, 2024) ^[3]. Despite the ecological and agronomic benefits of SCS management, the actual realization of soil carbon potential depends heavily on farm-level adoption of sustainable management practices. Traditional sugarcane production is often characterized by

intensive soil tillage, excessive reliance on synthetic mineral fertilizers, burning of post-harvest trash, and flood irrigation practices that accelerate soil organic matter mineralization, degrade soil structure, and contribute to off-farm environmental degradation. Transitioning toward climate-smart agricultural practices (CSAPs), such as reduced tillage, green manuring, trash mulching, biofertilizer cation, micro-irrigation, and agroforestry, is essential for long term agricultural sustainability (Jadhav *et al.*, 2025) ^[4]. However, the transition to SCS practices is governed by complex socio-economic, technical, and institutional dynamics. Farmers' decisions to adopt or reject carbon-sequestering practices are dictated by immediate economic returns, labour availability, technical know-how, and perceive risk. Understanding the current empirical landscape of practice adoption by growers, is critical for formulating effective agricultural policy interventions. This study presents a comprehensive evaluation of SCS practices followed by 320 sugarcane

growers across six thematic domains: tillage management, intercropping practices, sugarcane trash management, integrated nutrient management (INM), integrated water management (IWM), and agroforestry integration.

2. Methodology

A rigorous quantitative survey research design was employed to assess the adoption behaviour of sugarcane growers. The sample frame comprised $N = 320$ sugarcane farming households selected via simple random sampling from major sugarcane growing districts. A structured, pre-tested interview schedule was administered to collect empirical data regarding twenty-one specific soil carbon management practices categorized into six primary domains. Data were quantified using frequency (F) and percentage (P)

distributions for binary adoption choices ("Followed" vs. "Not Followed"). The theoretical percentage adoption rate (P_i) for practice i was calculated as:

$$P_i = (F_i/N) \times 100$$

where F_i represents the number of growers practicing intervention i and $N = 320$ is the total respondent pool.

3. Results and Discussion

The comprehensive empirical findings regarding the adoption of soil carbon sequestration practices across 320 sugarcane growers are summarized in Table 1. The practices are analysed across six structural agronomic domains.

Table 1: Soil carbon sequestration management practices followed by Sugarcane growers (N = 320)

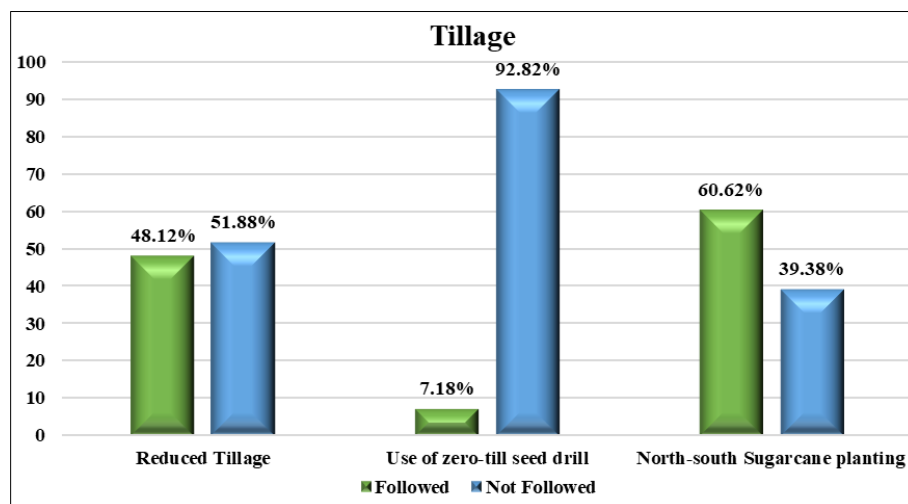
Sr. No.	Management practices	Followed		Not followed	
		F	P	F	P
A.	Tillage				
1.	Reduced tillage	154	48.12	166	51.88
2.	Use of zero-till seed drill for intercropping	23	07.18	297	92.82
3.	North-south planting of Sugarcane	194	60.62	126	39.38
B.	Intercropping				
4.	Planting leguminous crops like Cowpea, Black gram, Green gram	216	67.50	104	32.50
5.	Incorporating green manure crops such as sunhemp, Dhaincha at the time of flowering	201	62.82	119	37.18
6.	Adoption of Sugarcane-ratoon-Wheat cropping system	139	43.43	181	56.57
C.	Sugarcane trash management				
7.	Sugarcane trash incorporation (5 to 6 ton/ha)	157	49.06	163	50.94
8.	Biochar preparation from Sugarcane trash	00	00.00	320	100
9.	Sugarcane trash mulching	171	53.43	149	46.57
10.	Adoption of Integrated Sugarcane Trash Management Technology	86	26.87	234	73.13
D.	Integrated nutrient management				
11.	Application of FYM (12.5 ton/ha)	320	100.00	00	00.00
12.	Application of compost like Vermicompost (5 to 10 ton/ha)	254	79.37	66	20.63
13.	Utilization of organic fertilizers like Jeevamrut (500 L/ha)	107	33.44	213	66.56
14.	Use of organic pesticides like Beejamrut, Dashparni arka, Neem cake powder	103	32.18	217	67.82
15.	Application of biofertilizers like Azospirillum and Acetobacter (10 kg/100 L for 30 min)	112	35.00	208	65.00
16.	Soil testing before fallow period/planting	37	11.56	283	88.44
17.	Organic Sugarcane farming	05	01.56	315	98.44
E.	Integrated water management				
18.	Implementation of micro-irrigation systems such as drip, sprinkler	153	47.81	167	52.19
19.	Use of solar pumps instead of diesel pumps	35	10.93	285	89.07
F.	Agroforestry				
20.	Integrating trees like Gliricidia, Sesbania, Neem within Sugarcane field	68	21.25	252	78.75
21.	Windbreaks like Bamboo, Moringa, Eucalyptus in Sugarcane field	102	31.87	218	68.13

3.1 Tillage Management

Tillage practices directly influence soil bulk density, aggregate stability, and organic matter decomposition rates. A clear majority (60.62 per cent, $n = 194$) of sugarcane growers adopted North-South row planting, whereas 39.37 per cent did not. North South row orientation maximizes intercepted solar radiation across the crop canopy throughout the day, optimizing photosynthetic activity, enhancing dry matter accumulation, and ultimately yielding greater root biomass and surface litter input for soil carbon pools (Hossain *et al.*, 2024) ^[3]. Reduced tillage was practiced by 48.12 per cent ($n = 154$) of growers, while 51.88 per cent maintained conventional deep tillage regimes. While reduced tillage preserves macro-aggregates and protects carbon sequestered within soil micro-aggregates, growers encounter an initial

transition lag of 2 to 3 years before structural and biological benefits fully translate into yield stabilization. During this gestation phase, initial challenges such as subsoil compaction and weed pressures discourage risk-averse farmers (TNAU-Agritech Portal).

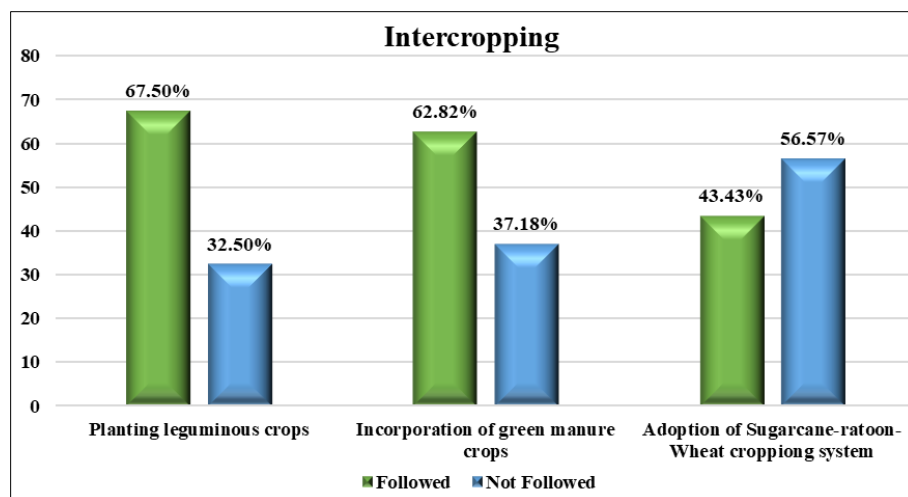
Extremely low adoption was recorded for zero-till seed drills during intercropping (7.18 per cent, $n = 23$), leaving 92.82 per cent non-adopters. Sugarcane requires deep soil loosening for extensive root anchorage, which conflicts with zero-tillage principles. Furthermore, non-adoption is driven by high capital costs of seed drill machinery, lack of technical knowledge regarding seed drill calibration, and acute shortages of localized machinery training facilities (Devinder *et al.*, 2010) ^[1].



3.2 Intercropping Systems and Biomass Addition

Intercropping provides dual benefits of early financial returns and organic biomass accretion. Over two-thirds (67.50 per cent, $n = 216$) of respondents intercropped short-duration leguminous crops (Cowpea, Black gram, Green gram). As sugarcane exhibits slow initial growth during the first 90 to 100 days, legume intercropping utilizes unoccupied inter-row spatial niches (Rajula *et al.*, 2023) ^[9]. Subsequent incorporation of legume crop stubbles fixes atmospheric nitrogen and adds easily degradable carbonaceous matter to

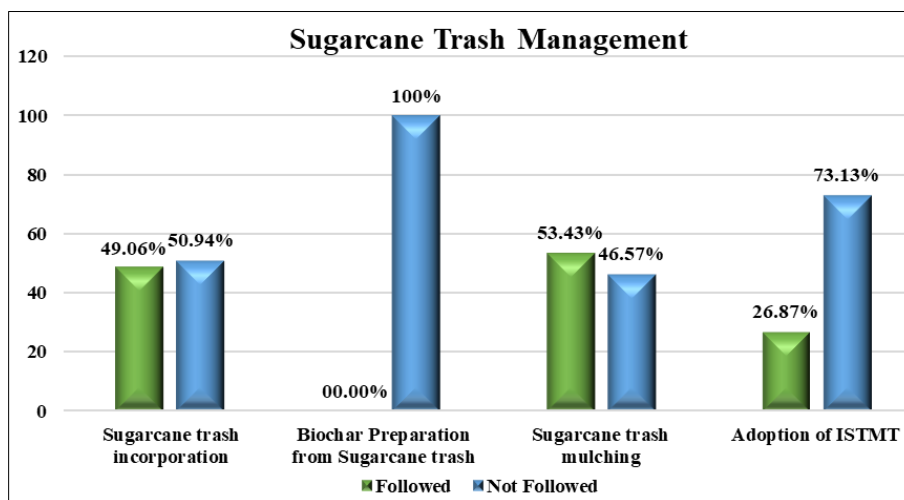
the topsoil. Similarly, 62.82 per cent ($n = 201$) of growers incorporated green manure crops (Sunhemp, Dhaincha) at the flowering stage. Green manure incorporation at flowering maximizes tissue nitrogen content and succulent biomass degradation, rapidly releasing nutrients and augmenting active soil carbon pools (Jadhav *et al.*, 2025) ^[4]. Regarding spatial crop sequences, 43.43 per cent ($n = 139$) followed a Sugarcane-ratoon-Wheat cropping system, whereas 56.57 per cent preferred alternative crop rotations.



3.3 Sugarcane Trash Management and Biochar Potential

Sugarcane generates massive post-harvest biomass residue (trash), typically amounting to 10 to 12 tonnes/ha. Trash mulching was practiced by 53.43 per cent ($n = 171$) of growers, serving as an effective surface cover that suppresses weed growth, conserves soil moisture, and gradually releases carbon into the surface soil layer. Direct trash incorporation at the rate of 5 to 6 ton/ha was adopted by 49.06 per cent ($n = 157$) of growers. However, 50.94 per cent refrained from trash incorporation, citing acute agricultural labour shortages during peak harvest windows and narrow temporal turnarounds required for planting subsequent crops.

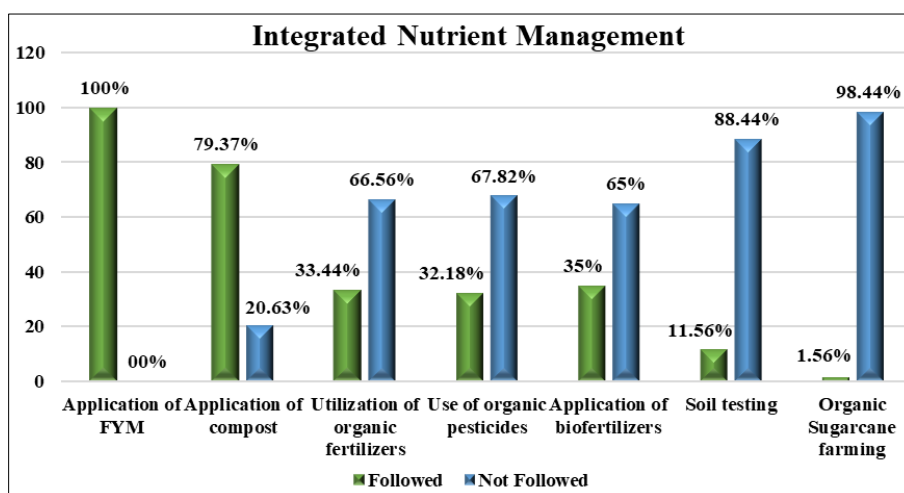
Integrated Sugarcane Trash Management Technology saw adoption by only 26.87 per cent ($n = 86$), while 73.13 per cent relied on traditional practices or field burning. Alarming, zero respondents (0.00 per cent) practiced biochar preparation from sugarcane trash. Biochar pyrolysis represents one of the most stable recalcitrant carbon storage mechanisms available to agriculture. Primary barriers preventing biochar adoption include a total lack of farmer awareness regarding pyrolysis equipment, absent extension support, and lack of conviction regarding long-term return on investment (Rajula *et al.*, 2020) ^[8].



3.4 Integrated Nutrient Management (INM) and Organic Inputs

Nutrient management exhibited the widest variance in adoption metrics. Universal adoption (100.00 per cent, $n = 320$) was recorded for Farmyard Manure (FYM) application at the baseline rate of 12.5 ton/ha, confirming high traditional awareness of organic manure value. Compost and vermicompost application (5 to 10 ton/ha) was high at 79.37 per cent ($n = 254$). In contrast, specialized bio-inoculants and liquid organic formulations registered low adoption. Application of biofertilizers (sett treatment with *Azospirillum* and *Acetobacter* @ 10 kg/100 L water for 30 minutes) was followed by only 35.00 per cent ($n = 112$) of growers. Formulations like Jeevamrut (500 L/ha) and organic biopesticides (Beejamrut, Dasharni arka, Neem cake) were

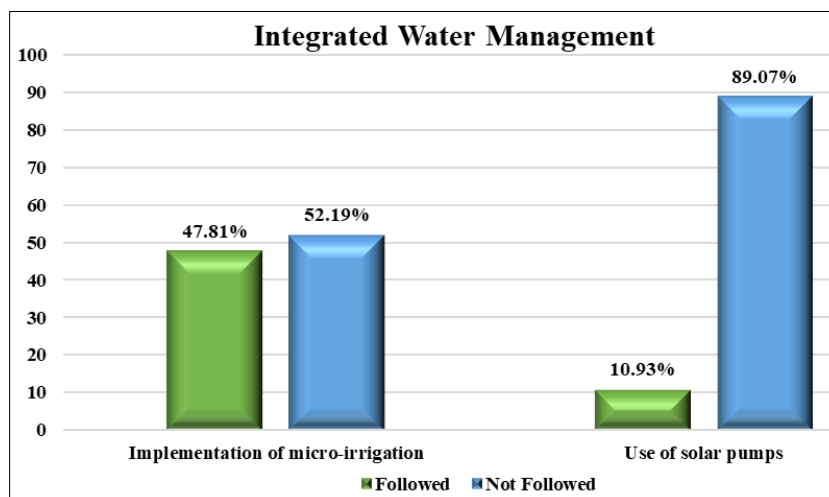
adopted by 33.44 per cent and 32.18 per cent of growers, respectively. Constraints stem from high labour inputs required for liquid preparation, variable efficacy, and limited commercial availability. A critical vulnerability identified is the negligible rate of soil testing prior to planting (11.56 per cent, $n = 37$). Nearly 88.44 per cent of growers apply fertilizers without diagnostic soil testing, driven by poor awareness of analytical facilities and underutilization of government programs like the Soil Health Card scheme (Manisha *et al.*, 2024) [6]. Furthermore, certified Organic Sugarcane farming was practiced by only 1.56 per cent ($n = 5$), constrained by yield penalties during initial transition years, complex certification protocols, and lack of premium market channels (Hossain *et al.*, 2025) [2].



3.5 Water Management and Solar Energy Transitions

Micro-irrigation (drip and sprinkler systems) was implemented by 47.81 per cent ($n = 153$) of growers, whereas 52.19 per cent maintained conventional flood irrigation. Micro-irrigation reduces soil carbon loss by preventing waterlogging induced anaerobic conditions and excessive leaching of soluble organic carbon fraction. High capital costs of drip infrastructure, frequent sub-surface emitter clogging, and expensive repair services hinder broader

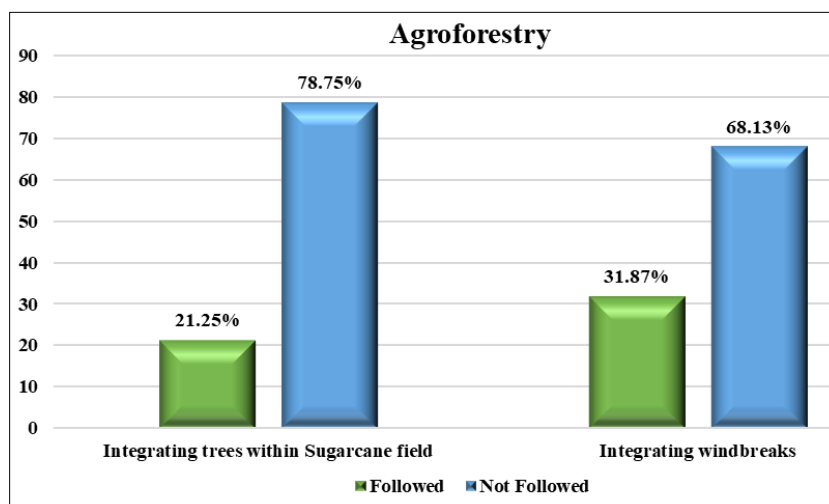
adoption (Shete *et al.*, 2023) [10]. Solar photovoltaic water pumping systems recorded an adoption rate of only 10.93 per cent ($n = 35$), leaving 89.07 per cent dependent on grid electricity or diesel pumps. Financial constraints prevent smallholders from absorbing upfront capital investments. Furthermore, technical limitations such as reduced pumping efficiency during cloudy days and winter seasons coupled with low institutional awareness of subsidized schemes like PM-KUSUM, restrict solar adoption (Nikita *et al.*, 2024) [7].



3.6 Agroforestry Integration

Agroforestry integration offers vertical carbon stratification through root and woody biomass accumulation. Peripheral windbreaks (Bamboo, Moringa, Eucalyptus) were maintained by 31.87 per cent ($n = 102$) of growers. In-field tree integration (Gliricidia, Sesbania, Neem) was practiced by only 21.25 per cent ($n = 68$). Tree integration faces severe adoption barriers due to light competition and operational

interference. Trees shade the light-demanding sugarcane canopy, reducing photosynthetic rates during early vegetative growth. Additionally, tree roots compete aggressively for subsoil moisture and nutrients. From an operational perspective, fixed tree stands impede tractor-drawn tillage, mechanical harvesting, and field transport, presenting major obstacles for modernizing sugarcane farms (Luis *et al.*, 2023) [5].



4. Implications

To accelerate soil carbon sequestration in sugarcane farming, a targeted multi-pronged policy strategy is required. Priorities include:

- Custom Hiring Centres (CHCs):** Establish village-level CHCs equipped with heavy-duty shredders, zero-till seed drills, and trash incorporation machinery to eliminate capital barriers for smallholders.
- Mobile Soil Testing Labs and SHC Reinforcement:** Expand soil testing accessibility via mobile units and digital Soil Health Card integration to enable precision nutrient management.
- Biochar Decentralization:** Provide subsidized mobile pyrolysis kilns to sugar mills and farmer producer organizations (FPOs) to transform post-harvest trash into valuable biochar.
- Carbon Credit Incentivization:** Establish transparent voluntary carbon market mechanisms that directly

reward smallholders for quantified SOC gains resulting from micro-irrigation and trash mulching.

5. Conclusion

Sugarcane production systems possess substantial potential for carbon sequestration, yet current practice adoption remains highly fragmented. While basic organic inputs (FYM, compost) and traditional intercropping enjoy widespread compliance, advanced technical interventions such as biochar conversion, zero-till intercropping, micro-irrigation, and precision soil testing face severe structural, economic, and knowledge barriers. Overcoming these deficits requires synchronized investments in machinery sharing models, localized technical extension, solar energy subsidies, and financial carbon offsets. Bridging these adoption gaps is vital for transforming sugarcane fields into resilient, high capacity carbon sinks.

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