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Effect of nutrient management on soil organic carbon fractions and sequestration under bamboo plantation

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ABSTRACT

An investigation was conducted to evaluate the influence of integrated nutrient management on soil organic carbon fractions and soil carbon sequestration under a *Bambusa balcooa* plantation. The field experiment was laid out in a randomized block design comprising six graded fertilizer treatments, ranging from 100 % to 150 % of the recommended dose of fertilizer, applied in combination with a bio-decomposer to facilitate in-situ decomposition of leaf litter. The results indicated that graded fertilizer applications significantly enhanced all oxidizable soil carbon fractions. The highest fertilizer treatment consistently outperformed all other treatments, recording the maximum values for very labile carbon (5.34 g kg⁻¹), labile carbon (2.50 g kg⁻¹), less labile carbon (2.02 g kg⁻¹) and non-labile carbon (3.72 g kg⁻¹). Consequently, the active and passive carbon pools reached their highest values under the maximum fertilizer dose. Improved soil carbon stabilization was reflected in the carbon management index, which increased substantially from 177.69 in the lower fertilizer treatment to 269.56 in treatment T₆. Furthermore, enhanced carbon stabilization led to superior below-ground carbon capture capacity. The highest soil carbon stock (52.45 t ha⁻¹) and a maximum soil carbon sequestration rate of 7.06 t ha⁻¹ yr⁻¹ were recorded under the highest fertilizer treatment. It is concluded that the application of 150 % of the recommended fertilizer dose, integrated with leaf litter decomposition, is an effective nutrient management strategy for improving soil carbon quality, enhancing stable carbon pools and maximizing long-term soil carbon sequestration in bamboo plantations.

Keywords: Bamboo, Carbon fractions, Carbon management index, Carbon sequestration, Integrated nutrient management, Soil health

1. Introduction

Climate change, driven by escalating atmospheric concentrations of greenhouse gases such as carbon dioxide (CO₂), remains one of the most pressing global environmental challenges. Anthropogenic activities, coupled with the continuous and indiscriminate use of chemical fertilizers, have exacerbated soil degradation, nutrient imbalances and the severe depletion of soil organic matter. According to Powlson *et al.* (2011) [1], this over-reliance on synthetic chemical inputs adversely affects long-term agricultural sustainability and ecological productivity. To combat these interrelated issues, enhancing carbon sequestration through appropriate land-use systems and sustainable nutrient management is widely recognized as a cost-effective mitigation strategy.

Soils represent the largest terrestrial carbon reservoir, holding more carbon than the atmosphere and vegetation combined. However, soil organic carbon (SOC) is not a homogeneous entity; it consists of distinct fractions—very labile, labile, less labile and non-labile—that vary significantly in their stability and turnover rates. The labile fractions serve as immediate energy sources for soil microorganisms and act as highly sensitive indicators of short-term soil management. Conversely, the non-labile fractions provide the recalcitrance necessary for long-term carbon stabilization. As Lal (2004) [2] emphasized, evaluating the distribution of carbon among these specific pools provides a much more accurate understanding of a land-use system's true carbon sequestration potential than measuring total SOC alone.

Perennial vegetation systems, particularly fast-growing bamboo species like *Bambusa balcooa*, have garnered global attention as highly efficient carbon sinks. Bamboo is characterized by its rapid biomass production, extensive rhizome-root networks and continuous, high-volume litter deposition. Previous research by Nath *et al.* (2015) [3] and Paudyal *et al.* (2022) [4] has demonstrated the exceptional capacity of bamboo-based systems to sequester substantial amounts of carbon in both above-ground biomass and below-ground soil pools. However, the magnitude of soil carbon stabilization under bamboo is heavily dictated by the agronomic interventions applied, particularly nutrient management.

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To optimize this carbon storage potential while mitigating soil degradation, Integrated Nutrient Management (INM) has emerged as an essential solution. INM optimizes nutrient-use efficiency by judiciously combining chemical fertilizers with organic inputs. Earlier literature, including studies by Blair *et al.* (1995) [5] and Mandal *et al.* (2007) [6], has consistently demonstrated that INM practices significantly improve SOC content, microbial activity and labile carbon fractions compared to the application of chemical fertilizers alone.

Despite the recognized ecological benefits of bamboo plantations and INM, systematic research evaluating their interactive effects on the dynamics of specific soil carbon fractions remains limited. Specifically, there is a critical knowledge gap regarding how varying INM regimes influence active and passive carbon pools under bamboo cultivated in the Inceptisols of central India. To address this gap, this study evaluates an integrated method combining graded levels of inorganic fertilizers with the in-situ decomposition of accumulated bamboo leaf litter. The primary objective of this study was to quantify the effect of this INM strategy on soil carbon fractionation, biomass productivity and long-term ecosystem carbon sequestration under *Bambusa balcooa* plantation.

2. Materials and Methods

2.1 Study area

The research was conducted during the 2025–26 academic year at the Agroforestry Farm (Futala farm), College of Agriculture, Nagpur, Maharashtra, India. The site is geographically located in the subtropical zone at 21°10' N latitude and 79°19' E longitude, with an altitude of 321.26 m above mean sea level. The climate is characterized by hot, dry summers and fairly cold winters, with mean temperatures ranging from 9.6 °C to 35.3 °C and an average annual rainfall of 1250 mm.

2.2 Experimental details

The experimental soil is classified as an Inceptisols. The *Bambusa balcooa* plantation utilized for this study was established in August 2019 at a spacing of 3 m × 3 m, resulting in a density of 1111 clumps ha⁻¹. The field experiment was laid out in a Randomized Block Design (RBD) featuring six treatments and four replications. The treatments comprised graded levels of Integrated Nutrient Management (INM) based on the Recommended Dose of Fertilizer (RDF: 150:40:125 NPK g clump⁻¹), applied via urea, single super phosphate (SSP) and muriate of potash (MOP).

2.3 Treatment details

- T1:** 100% RDF (150:40:125 NPK g clump⁻¹)
T2: 110% RDF (165:44:137.5 NPK g clump⁻¹)
T3: 120% RDF (180:48:150 NPK g clump⁻¹)
T4: 130% RDF (195:52:162.5 NPK g clump⁻¹)

T5: 140% RDF (210:56:175 NPK g clump⁻¹)

T6: 150% RDF (225:60:187.5 NPK g clump⁻¹)

A bio-decomposer was uniformly sprayed on the accumulated leaf litter in all treatment plots to facilitate in-situ decomposition.

2.4 Soil sampling and preparation

Representative soil samples were collected from a depth of 0–30 cm. For bulk density analysis, undisturbed samples were extracted using a cylindrical metal core (Blake *et al.*, 1986) [7] and dried in a hot air oven at 105 ± 2 °C until a constant weight was obtained. For chemical analyses, the collected soil was shade-dried, gently ground using a mortar and pestle and passed through a 0.5 mm sieve for the estimation of Total Organic Carbon (TOC) and soil organic carbon (SOC) fractions.

2.5 Estimation of soil carbon fractions and indices

To determine oxidizable carbon, modified concentrations of concentrated sulphuric acid (5 mL and 10 mL) were used instead of the 20 mL specified in the original Walkley and Black (1934) method. These variations created three different acid-to-aqueous ratios: 0.5:1, 1:1 and 2:1, corresponding to 12 N, 18 N and 24 N concentrations of H₂SO₄. This approach enabled a comparative analysis of oxidizable organic carbon extracted under progressively stronger oxidizing conditions (Chan *et al.*, 2001) [8]. Total Organic Carbon (TOC) was determined using a TOC analyzer as described by Tiessen *et al.* (1993) [9]. The soil organic carbon fractions were quantified using the modified Walkley and Black wet oxidation method proposed by Chan *et al.* (2001) [8].

- Very labile carbon (VLC) (12 N H₂SO₄): Represents the organic carbon fraction that is oxidizable under the weakest acid strength (12 N H₂SO₄).
- Labile carbon (LC) (18 N - 12 N H₂SO₄): Denotes the additional organic carbon oxidized between 12 N and 18 N acid strength.
- Less labile carbon (LLC) (24 N - 18 N H₂SO₄): Indicates the organic carbon portion further oxidized under 24 N acid conditions, relative to 18 N. Notably, 24 N H₂SO₄ reflects the acid strength used in the standard Walkley Black method.
- Non-labile carbon (NLC) (TOC - 24 N H₂SO₄): Accounts for the residual organic carbon not oxidized even under 24 N acid, estimated by comparing with total carbon content obtained via dry combustion.

These fractions were aggregated into an active pool (VLC+LC) and a passive pool (LLC+NLC).

Carbon management indices were calculated to evaluate soil carbon quality (Blair *et al.*, 1995) [5] (Sainepo *et al.*, 2018) [10].

$$\text{Carbon pool index (CPI)} = \frac{\text{Sample total C (g kg}^{-1}\text{)}}{\text{Reference total C (g kg}^{-1}\text{)}}$$

$$\text{Lability index (LI)} = \left(\frac{\text{VLC}}{\text{TOC}} \times 3 \right) + \left(\frac{\text{LC}}{\text{TOC}} \times 2 \right) + \left(\frac{\text{LLC}}{\text{TOC}} \times 1 \right)$$

$$\text{Carbon management index (CMI)} = \text{CPI} \times \text{LI} \times 100$$

2.6 Soil carbon sequestration

For the calculation of soil carbon sequestration, the initial soil carbon stock for the year 2022–23 was used as the baseline. Soil carbon sequestration was calculated using the following equations.

$$\text{Soil carbon stock (SCS)} = \text{TOC} \times \text{Bulk Density} \times \text{Depth}$$

$$\text{Soil carbon sequestration (SCS)} = \frac{SCS_{\text{final}} - SCS_{\text{initial}}}{\text{No. of years}}$$

3. Results

3.1 Soil bulk density

Soil bulk density, a critical physical parameter governing the computation of soil carbon stocks, decreased significantly with increasing fertilizer application. The bulk density values ranged from a maximum of 1.45 Mg m^{-3} in the lower fertilizer treatment (T_1) down to 1.29 Mg m^{-3} under the T_6 treatment, representing an 11.03% reduction. Treatments T_5 (1.33 Mg m^{-3}) and T_6 were statistically at par at 5% level of significance.

3.2 Soil organic carbon fractions and pools

The application of graded fertilizer levels under integrated nutrient management significantly influenced all oxidizable soil organic carbon fractions. The very labile carbon and labile carbon fractions ex-

panded progressively with increased nutrient application. Very labile carbon increased from 3.42 g kg^{-1} under treatment (T_1) to a maximum of 5.34 g kg^{-1} under the T_6 treatment, representing a 56.14% enhancement. Similarly, labile carbon increased from 1.78 g kg^{-1} in T_1 to 2.50 g kg^{-1} in T_6 . Consequently, the active carbon pool increased significantly from 5.20 g kg^{-1} under T_1 to 7.84 g kg^{-1} under T_6 . The stable carbon pools exhibited a comparable positive response to the nutrient treatments. The less labile carbon fraction increased from 1.37 g kg^{-1} under T_1 to 2.02 g kg^{-1} under T_6 . The non-labile carbon demonstrated the highest relative increase among the fractions, rising from 1.98 g kg^{-1} in T_1 to 3.72 g kg^{-1} in T_6 . The cumulative passive carbon pool was subsequently highest under the T_6 treatment (5.74 g kg^{-1}) compared with treatment T_1 (3.35 g kg^{-1}).

Table 1. Effect of treatments of INM on total organic carbon, active carbon pool, passive carbon pool, lability index, carbon pool index and carbon management index.

Treatments	TOC (g kg^{-1})	AP (g kg^{-1})	PP (g kg^{-1})	LI	CPI	CMI
T_1 :100% RDF (150:40:125 NPK g clump^{-1})	8.55	5.20	3.35	1.78	1.00	177.69
T_2 :110% RDF (165:44:137.5 NPK g clump^{-1})	9.75	6.07	3.68	1.82	1.14	207.49
T_3 :120% RDF (180:48:150 NPK g clump^{-1})	10.80	6.28	4.53	1.71	1.26	215.61
T_4 :130% RDF (195:52:162.5 NPK g clump^{-1})	11.95	6.77	5.18	1.67	1.40	233.10
T_5 :140% RDF (210:56:175 NPK g clump^{-1})	12.87	7.45	5.43	1.70	1.51	256.29
T_6 :150% RDF (225:60:187.5 NPK g clump^{-1})	13.58	7.84	5.74	1.70	1.59	269.56
SE (m) $\pm$	0.03	0.02	0.02	0.004	0.004	0.74
CD @ 5%	0.09	0.06	0.07	0.012	0.012	2.22

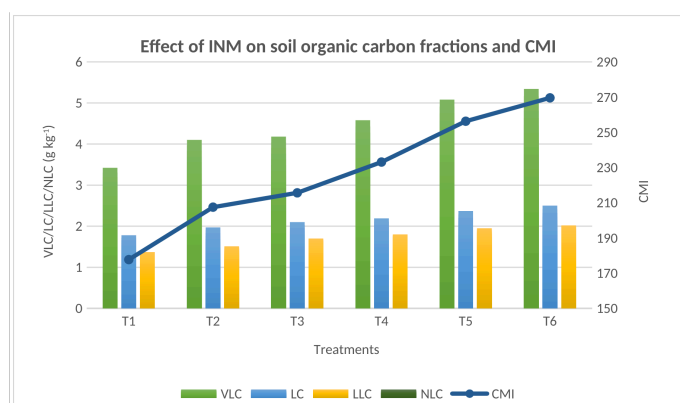


Figure 1. Effect of INM on soil organic carbon fractions and CMI

3.3 Carbon management indices

The Carbon Pool Index and Carbon Management Index both exhibited a consistent and significant increasing trend parallel to the fertilizer application rates. The Carbon Pool Index increased progressively from 1.00 under T_1 to a peak of 1.59 under T_6 . Correspondingly, the Carbon Management Index improved substantially from 177.69 under T_1 to 269.56 under T_6 , representing a 51.7% improvement in overall soil carbon status.

Conversely, the Lability Index displayed distinct behavioral dynamics. The Lability Index initially increased from 1.78 in T_1 to a peak of

1.82 under T_2 . However, subsequent increases in fertilizer levels resulted in a gradual decline, with T_4 recording the minimum value (1.67), before stabilizing at 1.70 under both the T_5 and T_6 treatments.

Table 2. Effect of different INM on initial and final carbon stock

Treatments	Soil carbon stock (t ha^{-1})	
	Initial (2022-23)	Final (2025-26)
T_1 :100% RDF (150:40:125 NPK g clump^{-1})	23.51	36.81
T_2 :110% RDF (165:44:137.5 NPK g clump^{-1})	24.80	40.86
T_3 :120% RDF (180:48:150 NPK g clump^{-1})	25.47	45.12
T_4 :130% RDF (195:52:162.5 NPK g clump^{-1})	29.02	48.76
T_5 :140% RDF (210:56:175 NPK g clump^{-1})	30.30	51.45
T_6 :150% RDF (225:60:187.5 NPK g clump^{-1})	31.29	52.45
SE (m) $\pm$	0.44	0.45
CD @ 5%	1.30	1.35

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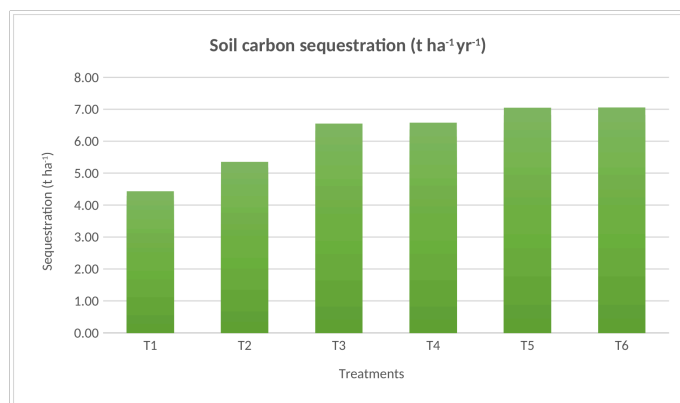


Figure 2. Effect of INM on soil carbon sequestration

3.4 Soil carbon sequestration

Following the experimental period, the soil carbon stock increased across all fertilizer treatments relative to their initial baselines. The initial soil carbon stock ranged from 23.51 to 31.29 t ha⁻¹ across the plots. At the conclusion of the study, the final soil carbon stock expanded significantly, ranging from 36.81 t ha⁻¹ under T_1 to a maximum of 52.45 t ha⁻¹ under T_6 . Treatments T_5 (51.45 t ha⁻¹) and T_6 were statistically at par at the 5% level of significance.

The annual soil carbon sequestration rate reflected this accumulation, increasing from 4.43 t ha⁻¹ yr⁻¹ under T_1 to a maximum of 7.06 t ha⁻¹ yr⁻¹ under T_6 . While T_6 recorded the highest sequestration rate, the differences among the higher fertilizer treatments (T_3 , T_4 , T_5 and T_6) were comparatively narrow, ranging between 6.55 and 7.06 t ha⁻¹ yr⁻¹.

4. Discussions

4.1 Soil bulk density

Soil bulk density serves as a critical physical indicator of soil health and structural integrity. The progressive decline in bulk density under higher INM treatments indicates a substantial improvement in soil structural porosity and a reduction in compaction. This reduction is primarily driven by enhanced organic matter accumulation resulting from continuous leaf litter deposition, increased microbial activity, and greater root proliferation, all of which contribute to improved aggregate stability. The continuous addition of bamboo litter and fine-root turnover under optimally nourished clumps promotes soil porosity and creates a more favorable physical environment for nutrient cycling. These findings are supported by earlier studies (Kaushal *et al.*, 2020) [11], which observed that perennial bamboo plantations significantly lower soil bulk density due to higher fine-root production, rapid litter turnover, and improved soil aggregation.

4.2 Soil organic carbon fractions

The significant enrichment of active (very labile and labile) and passive (less labile and non-labile) carbon pools under higher fertilizer levels highlights the efficiency of *Bambusa balcooa* as a catalyst for soil carbon stabilization when supported by adequate integrated nutrition. The substantial increase in the very labile and labile carbon fractions can be directly attributed to the continuous deposition of bamboo leaf litter and its subsequent rapid turnover, particularly facilitated by the *in-situ* application of a bio-decomposer. Active carbon pools are highly sensitive to recent organic matter inputs and the enhanced vegetative growth resulting from optimally nourished bamboo clumps provides a continuous substrate for microbial proliferation. These findings align with Chan *et al.* (2001) [8] and Thangavel *et al.* (2015) [12], who reported that ecosystems receiving consistent organic matter inputs exhibit greater accumulation of active carbon fractions due to continuous litter deposition and increased root exudation. Furthermore, the pronounced enhancement in the non-labile carbon fraction—the most stable soil carbon pool—demonstrates that the sequestered carbon is being effectively stabilized within the Inceptisols.

This stabilization is likely driven by enhanced root biomass and rhizodeposition. Bamboo's extensive rhizome network promotes the formation of stable macro-aggregates, physically protecting the organic matter from microbial decomposition and fostering humification and organo-mineral interactions. Six *et al.* (2002) [13] and Benbi *et al.* (2015) [14] similarly emphasized that perennial vegetation systems significantly enhance non-labile carbon fractions through improved soil aggregation and reduced carbon mineralization.

4.3 Carbon management indices and soil quality

The calculated carbon management indices provide a holistic evaluation of soil health under the bamboo-INM system. The steady rise in the Carbon Pool Index confirms that higher fertilizer doses successfully enhanced total soil organic carbon storage. Interestingly, the Lability Index exhibited a slight decline at higher fertilizer doses following an initial peak. This reduction does not indicate a degradation of soil quality; rather, it suggests that enhanced microbial metabolism—fueled by abundant nutrient availability—accelerated the transformation of readily decomposable active carbon into more stable, humified organic matter.

Because the Carbon Management Index integrates both the Carbon Pool Index and the Lability Index, its progressive increase clearly demonstrates that the considerable gains in total carbon storage more than compensated for the slight reduction in relative carbon lability. This reflects a highly sustainable soil environment where fresh organic inputs are efficiently converted into resilient carbon reserves. Similar improvements in the Carbon Management Index under integrated nutrient management have been widely reported by Kumar *et al.* (2020) [15] and Behera *et al.* (2025) [16], who noted that organic amendments significantly increase the index by improving both annual carbon inputs and carbon stabilization.

4.4 Soil carbon sequestration potential

The improvement in soil carbon fractions was reflected in the increased soil carbon sequestration rates observed under higher fertilizer levels. The maximum sequestration rate achieved under the 150% RDF treatment underscores the capability of managed *Bambusa balcooa* plantations to act as potent below-ground carbon sinks in central India. The enhancement in soil carbon stock is strongly associated with increased root biomass production, greater rhizodeposition and enhanced litter input.

The comparatively tighter clustering of sequestration rates among the higher fertilizer treatments suggests that soil carbon accumulation is a capacity-bound process. It relies on long-term organic matter inputs, fine-root turnover and the gradual structural integration of carbon into the soil matrix. Nath *et al.* (2015) [3] and Yuen *et al.* (2017) [17] observed that enhanced bamboo productivity increases carbon inputs to the soil, thereby promoting greater soil carbon storage. Furthermore, Kaushal *et al.* (2020) [11] reported that balanced nutrient management increases plant residue inputs and facilitates the stabilization of soil organic matter. Ultimately, integrating optimal inorganic fertilizers with *in-situ* leaf litter decomposition maximizes the biological activity within the soil and may contribute to the long-term ecological sustainability.

5. Conclusion

The present study demonstrated that graded application of integrated nutrient management (INM) significantly improved soil carbon fractions and carbon sequestration under *Bambusa balcooa* plantation. Increasing fertilizer levels from 100% to 150% of the recommended dose enhanced very labile, labile, less labile and non-labile carbon fractions, resulting in greater active and passive carbon pools. Consequently, the Carbon Pool Index (CPI) and Carbon Management Index (CMI) increased progressively, indicating improved soil carbon quality and enhanced carbon stabilization. The highest fertilizer level (150% RDF; 225:60:187.5 g NPK clump⁻¹) recorded the maximum soil carbon stock (52.45 t ha⁻¹) and annual soil carbon sequestration rate (7.06 t ha⁻¹ yr⁻¹), recording significantly higher soil carbon

stock and sequestration than the lower fertilizer levels. These findings suggest that the application of 150% RDF, together with in-situ decomposition of bamboo leaf litter, is an effective integrated nutrient management strategy for improving soil carbon quality and enhancing long-term soil carbon sequestration in bamboo plantations.

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