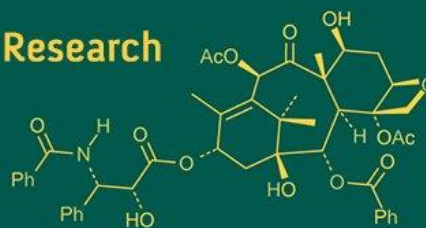
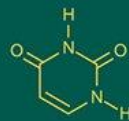
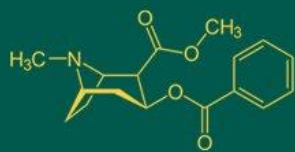


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## Carbon concentration under *Dendrocalamus brandisi* (Munro) Kurz. Across culm age classes under varying spacing and nutrient regime

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### Abstract

Carbon sequestration in bamboo ecosystems is highly dependent on tissue maturation, planting density, and silvicultural fertilization management. This study evaluated the variation in carbon content (%) across tissue components (culm, branch, leaves) and age classes (<1, 1-2, 2-3, and 3-4 years) of *Dendrocalamus brandisi* (Munro) Kurz. subjected to two spacing regimes (M<sub>1</sub>: 4.00 m × 5.00 m; M<sub>2</sub>: 5.00 m × 5.00 m) and three nutrient regimes (S<sub>1</sub>: optimum NPK; S<sub>2</sub>: 25% above optimum; S<sub>3</sub>: 50% above optimum). Elemental carbon analysis was performed using a CHNS Analyzer. Carbon concentration varied significantly across plant organs, following the order: Culm > Branch > Leaves. Older culm tissues exhibited progressively higher carbon percentages, peaking in 3-4-year-old culms (48.84% under M<sub>2</sub>S<sub>3</sub>). Nutrient enrichment significantly enhanced carbon content across all tissue components, with S<sub>3</sub> delivering maximum concentrations. Wider plant spacing (M<sub>2</sub>) coupled with elevated fertilization (S<sub>3</sub>) optimized tissue carbon density. These empirical findings provide critical baselines for maximizing carbon storage through targeted harvesting cycles and precision nutrition in commercial bamboo plantations.

**Keywords:** *Dendrocalamus brandisi*, carbon sequestration, tissue carbon, planting spacing

### Introduction

Bamboos represent one of the most vital non-timber forest resources in tropical and subtropical regions, playing a pivotal role in terrestrial carbon sequestration, soil conservation, and sustainable bio-economy supply chains (Scurlock *et al.*, 2000; Yuen *et al.*, 2016) [6, 8]. Due to their rapid growth rate, short rotation cycles, and high annual biomass accumulation, bamboo forests are increasingly recognized as dynamic global carbon sinks capable of mitigating climate change (Nath *et al.*, 2015; Yuen *et al.*, 2016) [4, 8]. Among giant bamboo species, *Dendrocalamus brandisi* (Munro) Kurz. stands out due to its superior structural wood density, massive culm dimensions, and exceptional biomass production potential (Shanmughavel *et al.*, 1996) [5]. Effective carbon accounting and precision yield modeling in bamboo ecosystems require accurate quantification of elemental carbon concentration across specific plant structural components—culm, branch, and foliage—as well as across distinct physiological age classes (Nath *et al.*, 2015; Yuen *et al.*, 2016) [4, 8]. Carbon partitioning in woody perennials is dictated by tissue anatomical development, cell wall secondary deposition, lignification, and photosynthetic sink strength (Magel *et al.*, 2001). As bamboo culms mature, structural carbohydrates such as cellulose, hemicellulose, and lignin accumulate within the secondary cell wall matrices, leading to progressive increases in elemental carbon density (Magel *et al.*, 2001) [3]. Previous studies on various giant bamboo species such as *Phyllostachys pubescens*, *Bambusa bambos*, and *Dendrocalamus latiflorus* have demonstrated substantial variations in tissue carbon content depending on age and plant organ type (Shanmughavel *et al.*, 1996; Ying *et al.*, 2010) [5, 7]. Furthermore, silvicultural intervention techniques, specifically stand density management through planting geometry and nutrient additions via NPK fertilization, substantially alter canopy light interception, stomatal conductance, photosynthetic efficiency, and net carbon assimilation (Embaye *et al.*, 2005; Li *et al.*, 2018) [1, 2].

Despite growing interest in bamboo carbon dynamics, conventional carbon inventory protocols frequently apply generic default conversion factors (e.g., 45-50% carbon fraction across all biomass components) (Nath *et al.*, 2015) [4]. Such broad assumptions introduce significant errors in forest carbon stock estimations, as they overlook organ-specific anatomical variations and age-dependent lignification trajectories (Nath *et al.*, 2015; Yuen *et al.*, 2016) [4, 8]. Comprehensive assessments utilizing high-precision elemental analysis (e.g., CHNS analyzer) to evaluate the interaction effects of planting density, fertilization regimes, and culm age in *Dendrocalamus brandisii* remain remarkably limited (Nath *et al.*, 2015) [4]. This research quantifies the carbon percentage dynamics of *Dendrocalamus brandisii* across age classes and organ types under varied spacing and fertilization regimes to establish empirical baselines for carbon accounting and silvicultural optimization.

## Materials and Methods

The field experiment was conducted in a dedicated research plantation of *Dendrocalamus brandisii* using a split-plot factorial design comprising two spacing regimes as the main plot factor and three nutrient regimes as the subplot factor, with systematic replications. The spacing treatments consisted of M<sub>1</sub> (4.00 × 5.00 m; 500 clumps ha<sup>-1</sup>) and M<sub>2</sub> (5.00 × 5.00 m; 400 clumps ha<sup>-1</sup>), while the nutrient treatments included S<sub>1</sub> (recommended optimum NPK dose), S<sub>2</sub> (25% above the recommended NPK dose), and S<sub>3</sub> (50% above the recommended NPK dose). Destructive sampling was carried out by collecting representative culm, branch, and leaf samples from four culm age classes (<1 year, 1-2 years, 2-3 years, and 3-4 years). The harvested samples were oven-dried at 65±2 °C until constant weight, ground into a fine powder using a ball mill, and passed through a 0.2 mm sieve to obtain homogeneous material for elemental analysis. Carbon concentration (%) of the prepared samples was determined on a dry-weight basis using a high-precision CHNS (Carbon, Hydrogen, Nitrogen, and Sulfur) Elemental Analyzer, which operates on the principle of high-temperature combustion in an oxygen-enriched atmosphere, with calibration performed using a high-purity sulfanilamide standard. The observed carbon percentage data were subjected to arcsine transformation prior to statistical analysis to stabilize variance. Analysis of variance (ANOVA) was performed to evaluate the effects of spacing, nutrient regimes, and their interaction, while treatment means were compared using the Standard Error of Mean (S.E.m±) and Critical Difference (CD) at the 5% level of significance. Means sharing the same superscript within a column were considered statistically at par.

## Results and Discussion

The carbon concentration of different tissues of *Dendrocalamus brandisii* varied significantly with tissue type, culm age, spacing, nutrient regime and their interactions (Table 1). Overall, carbon content followed the order culm > branch > leaves, with a progressive increase as culms matured from less than one year to 3-4 years of age. Culm carbon content increased from 44.34-44.44% in <1-year-old culms to 48.67-48.84% in 3-4-year-old culms, while branch carbon content ranged from 44.25-45.77% and leaf carbon content from 42.98-43.87% across the respective age classes. The greater carbon concentration in culms compared to branches and leaves can be attributed to the higher proportion of structural compounds such as cellulose, hemicellulose and lignin in mature woody tissues. As bamboo ages, secondary

cell wall thickening and lignification increase, leading to greater accumulation of structural carbon. Younger culms contain higher moisture and non-structural carbohydrates, whereas mature culms possess well-developed sclerenchymatous tissues rich in lignin, resulting in higher carbon percentages. Similar observations were reported by Scurlock *et al.* (2000) [6], Ying *et al.* (2010) [7], Yuen *et al.* (2016) [8], and Shanmughavel and Francis (1996) [5], who documented increasing carbon concentration with culm maturity in several bamboo species. Spacing regime significantly influenced carbon accumulation in plant tissues. The wider spacing (M<sub>2</sub>: 5.00 × 5.00 m) recorded significantly greater carbon concentrations than the closer spacing (M<sub>1</sub>: 4.00 × 5.00 m) in younger culms and all branch age classes. For example, carbon content in <1-year and 1-2-year culms was 44.42% and 45.24% under M<sub>2</sub> compared with 44.39% and 45.21% under M<sub>1</sub>, respectively. However, differences between spacing treatments for older culms (2-3 and 3-4 years) were statistically non-significant. Branch tissues consistently exhibited higher carbon concentration under wider spacing throughout all age classes. The beneficial effect of wider spacing may be attributed to reduced intra-clump competition for light, soil moisture and nutrients, thereby improving photosynthetic efficiency and assimilate production. Enhanced light penetration promotes greater carbohydrate synthesis and subsequent deposition of structural compounds in bamboo tissues. Similar findings have been reported by Nath *et al.* (2015) [4] and Li *et al.* (2018) [2], who observed improved canopy development, higher photosynthetic activity and increased carbon accumulation under lower planting densities. Nutrient regime also exerted a significant influence on tissue carbon concentration. Increasing fertilizer application from S<sub>1</sub> (recommended NPK) to S<sub>3</sub> (50% above recommended NPK) significantly increased carbon content in all plant components and age classes. In 3-4-year-old culms, carbon concentration increased from 48.68% under S<sub>1</sub> to 48.82% under S<sub>3</sub>. Similar increasing trends were observed in branches and leaves, with the treatment order consistently following S<sub>3</sub> > S<sub>2</sub> > S<sub>1</sub>. The enhanced carbon concentration under higher nutrient application may be explained by improved photosynthetic activity and biomass synthesis. Nitrogen enhances chlorophyll formation and photosynthetic enzymes, phosphorus supports ATP-mediated energy transfer, while potassium regulates stomatal function and translocation of photosynthates from leaves to structural tissues. Consequently, greater availability of these nutrients promotes cellulose and lignin synthesis, leading to higher carbon concentration in bamboo tissues. Similar responses have been reported by Magel *et al.* (2001) [3] and Embaye *et al.* (2005) [1], who demonstrated that balanced nutrient supply accelerates structural development and carbon deposition in bamboo culms.

The interaction between spacing and nutrient regimes was significant for selected tissues and age groups. The combination of wider spacing with the highest nutrient level (M<sub>2</sub>S<sub>3</sub>) produced the maximum carbon concentration in all plant components, recording 48.84% in 3-4-year-old culms, 45.77% in branches and 43.87% in leaves. In contrast, the lowest carbon concentration (42.98%) was observed in leaves of the M<sub>1</sub>S<sub>1</sub> treatment. These findings indicate that the combined effect of reduced competition and adequate nutrient availability promotes greater carbon assimilation and storage in bamboo biomass than either factor alone. The results demonstrate that carbon concentration in *D. brandisii* is strongly influenced by tissue maturity and silvicultural

management. Mature culms contained substantially greater carbon than younger tissues, indicating that age-specific carbon values should be considered for accurate biomass carbon estimation. Furthermore, the superior performance of the M<sub>2</sub>S<sub>3</sub> treatment highlights the importance of integrating optimum spacing with enhanced nutrient management to

maximize carbon sequestration potential in commercial bamboo plantations. These findings support the recommendation that organ-specific and age-specific carbon concentrations should be incorporated into carbon accounting frameworks to improve the accuracy of bamboo carbon stock assessments.

**Table 1:** Variation in carbon content (%) of *Dendrocalamus brandisii* under different spacing and nutrient regime

| Age of the culm<br>Treatment              | Clum                          |                               |                               |                               | Branch                        |                               |                               |                               | Leaves                        |                               |                               |                    |
|-------------------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|--------------------|
|                                           | < 1 year                      | 1-2 year                      | 2-3 year                      | 3-4 year                      | < 1 year                      | 1-2 year                      | 2-3 year                      | 3-4 year                      | < 1 year                      | 1-2 year                      | 2-3 year                      | 3-4 year           |
| <b>Spacing regimes</b>                    |                               |                               |                               |                               |                               |                               |                               |                               |                               |                               |                               |                    |
| M <sub>1</sub>                            | 44.39 <sup>b</sup><br>(41.77) | 45.21 <sup>b</sup><br>(42.25) | 46.95                         |                               |                               |                               |                               |                               |                               |                               |                               |                    |
| (43.25)                                   | 48.73                         |                               |                               |                               |                               |                               |                               |                               |                               |                               |                               |                    |
| (44.27)                                   | 44.54 <sup>b</sup><br>(41.86) | 44.79 <sup>b</sup><br>(42.01) | 45.05 <sup>b</sup><br>(42.15) | 45.29 <sup>b</sup><br>(42.29) | 43.02 <sup>a</sup><br>(40.98) | 43.15 <sup>a</sup><br>(41.06) | 43.59 <sup>a</sup><br>(41.31) | 43.81 <sup>a</sup>            |                               |                               |                               |                    |
| (41.44)                                   |                               |                               |                               |                               |                               |                               |                               |                               |                               |                               |                               |                    |
| <b>M<sub>2</sub></b>                      |                               |                               |                               |                               |                               |                               |                               |                               |                               |                               |                               |                    |
| (41.46)                                   |                               |                               |                               |                               |                               |                               |                               |                               |                               |                               |                               |                    |
| S. Em (±)                                 | 0.0000                        | 0.000                         | 0.0100                        | 0.0000                        | 0.0060                        | 0.0040                        | 0.0060                        | 0.0060                        | 0.0000                        | 0.0000                        | 0.0000                        | 0.000<br>0         |
| CD (@ 5%)                                 | 0.0100                        | 0.0100                        | NS                            | NS                            | 0.0360                        | 0.0240                        | 0.0360                        | 0.0360                        | 0.0000                        | 0.0000                        | 0.0000                        | 0.000<br>0         |
| <b>Nutrient regimes</b>                   |                               |                               |                               |                               |                               |                               |                               |                               |                               |                               |                               |                    |
| S <sub>1</sub>                            | 44.37 <sup>c</sup><br>(41.76) | 45.19 <sup>c</sup><br>(42.23) | 46.89 <sup>c</sup><br>(43.21) | 48.68 <sup>c</sup><br>(44.24) | 44.30 <sup>c</sup><br>(41.72) | 44.57 <sup>c</sup><br>(41.88) | 44.83 <sup>c</sup><br>(42.02) | 45.07 <sup>c</sup><br>(42.17) | 43.00 <sup>c</sup><br>(40.94) | 43.13 <sup>c</sup><br>(41.02) | 43.57 <sup>c</sup><br>(41.27) | 43.79 <sup>c</sup> |
| (41.40)                                   |                               |                               |                               |                               |                               |                               |                               |                               |                               |                               |                               |                    |
| S <sub>2</sub>                            | 44.40 <sup>b</sup><br>(41.78) | 45.23 <sup>b</sup><br>(42.25) | 46.93 <sup>b</sup><br>(43.27) | 48.73 <sup>b</sup><br>(44.27) | 44.55 <sup>b</sup><br>(41.87) | 44.80 <sup>b</sup><br>(42.01) | 45.05 <sup>b</sup><br>(42.15) | 45.30 <sup>b</sup><br>(42.30) | 43.04 <sup>b</sup><br>(41.00) | 43.17 <sup>b</sup><br>(41.07) | 43.61 <sup>b</sup><br>(41.33) | 43.83 <sup>b</sup> |
| (41.46)                                   |                               |                               |                               |                               |                               |                               |                               |                               |                               |                               |                               |                    |
| S <sub>3</sub>                            | 44.44 <sup>a</sup><br>(41.80) | 45.26 <sup>a</sup><br>(42.28) | 47.02 <sup>a</sup><br>(43.29) | 48.82 <sup>a</sup><br>(44.32) | 44.95 <sup>a</sup><br>(42.10) | 45.19 <sup>a</sup><br>(42.24) | 45.44 <sup>a</sup><br>(42.40) | 45.68 <sup>a</sup><br>(42.51) | 43.07 <sup>a</sup><br>(41.01) | 43.20 <sup>a</sup><br>(41.09) | 43.64 <sup>a</sup><br>(41.35) | 43.86 <sup>a</sup> |
| (41.47)                                   |                               |                               |                               |                               |                               |                               |                               |                               |                               |                               |                               |                    |
| S. Em (±)                                 | 0.0000                        | 0.0020                        | 0.0079                        | 0.0035                        | 0.0100                        | 0.0052                        | 0.0065                        | 0.0071                        | 0.0000                        | 0.0008                        | 0.0008                        | 0.000<br>7         |
| CD (@ 5%)                                 | 0.0100                        | 0.0064                        | 0.0259                        | 0.0113                        | 0.0200                        | 0.0169                        | 0.0212                        | 0.0230                        | 0.0000                        | 0.0023                        | 0.0023                        | 0.002<br>1         |
| <b>Spacing regimes × Nutrient regimes</b> |                               |                               |                               |                               |                               |                               |                               |                               |                               |                               |                               |                    |
| M <sub>1</sub> S <sub>1</sub>             | 44.34 <sup>a</sup><br>(41.75) | 45.17 <sup>b</sup><br>(42.22) | 46.89<br>(43.21)              | 48.67<br>(44.23)              | 44.25<br>(41.69)              | 44.52<br>(41.85)              | 44.78<br>(42.00)              | 45.03 <sup>b</sup><br>(42.14) | 42.98 <sup>c</sup><br>(40.93) | 43.11 <sup>c</sup><br>(41.01) | 43.55 <sup>c</sup><br>(41.26) | 43.77 <sup>c</sup> |

**Note:** Figures with same letter within a column are not significantly different; CD = Critical Difference; NS = Non-significant; Parenthetical values are arcsine transformed; M<sub>1</sub> = 4.00 m × 5.00 m; M<sub>2</sub> = 5.00 m × 5.00 m; S<sub>1</sub> = Optimum NPK; S<sub>2</sub> = 25% above optimum; S<sub>3</sub> = 50% above optimum [cite: 4, 5].

## Conclusion

The present study demonstrated that carbon concentration in *Dendrocalamus brandisii* is significantly influenced by tissue type, culm age, spacing regime, nutrient management, and their interaction. Among the plant components, culms consistently recorded the highest carbon concentration, followed by branches and leaves, with carbon content increasing progressively as culms matured from less than one year to 3-4 years of age. The wider spacing regime (5.00 × 5.00 m) promoted greater carbon accumulation than the closer spacing, while enhanced nutrient application (50% above the recommended NPK dose) significantly improved carbon concentration across all tissues. The combined treatment of wider spacing and higher nutrient application (M<sub>2</sub>S<sub>3</sub>) produced the maximum carbon concentration, indicating that appropriate silvicultural management enhances carbon sequestration potential in bamboo plantations. These findings suggest that harvesting culms at 3-4 years of age and adopting wider spacing with higher nutrient inputs can maximize carbon storage and biomass quality. Furthermore, the study emphasizes the importance of using organ-specific and age-specific carbon concentrations instead of generalized conversion factors for more accurate estimation of carbon stocks in bamboo-based forestry and agroforestry systems.

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