UNIVERSIDAD DISTRITAL
FRANCISCO JOSÉ DE CALDAS

Colombia FORESTAL
Publicación de la Facultad del Medio Ambiente y Recursos Naturales–Proyecto Curricular de Ingeniería Forestal
revistas.udistrital.edu.co/ojs/index.php/colfor/index

https://doi.org/10.14483/2256201X.20898

ARTÍCULO DE INVESTIGACIÓN

ISSN 0120-0739 • e-ISSN 2256-201X

Biomass Storage Potential and Improvement in Soil Properties under Different Bamboo Plantations in the Terai Region of Central Himalaya

Almacenamiento de biomasa y mejora del suelo en plantaciones de bambú en la región de Terai en el Himalaya central

Nidhi Sharma[a], Dhirender Kumar[b], Narendra Singh[c], Sudhakara N. R.[d], Mohammad Yeasin[e], Bharti Juneja[e]

[a] Temperate Animal Husbandry Division, ICAR-Indian Veterinary Research Institute. Mukteswar, Uttarakhand, 263138, India
[b] Department of Silviculture and Agroforestry, Dr. Yashwant Singh Parmar University of Horticulture and Forestry. Nauni, Solan, Himachal Pradesh, 173230, India
[c] Division of Agroforestry, G. B. Pant University of Agriculture and Technology Pantnagar, Uttarakhand, 263145, India
[d] ICAR- Central Institute of Temperate Horticulture. Rangreth, Srinagar, Jammu and Kashmir, 191132, India
[e] ICAR- Indian Agricultural Statistics Research Institute. New Delhi, 110012, India

Recibido: 25 de mayo de 2023 **Aceptado:** 20 de noviembre de 2023

Citation: Sharma, N., Kumar, D., Singh, N., Sudhakara N. R., Yeasin, M., & Bharti, J. (2024). Biomass storage potential and improvement in soil properties under different bamboo plantations in the Terai region of Central Himalaya. *Colombia Forestal, 27*(1), e20898.

Highlights

- *D. hamiltonii* exhibited the maximum total aboveground biomass, followed by *B. nutans*.
- The highest aboveground N, P, and K uptake was reported by *D. hamiltonii*, and the lowest values were found in *D. asper.*
- There was a reduction in soil porosity, EC, SOC, and available soil N, P, and K, as well as an increase in soil BD, PD, and pH, as the soil depth increased.
- The highest SOC and soil fungal and bacterial counts were found under *D. hamiltonii*.
- Bamboo plantations are an excellent option to improve the biomass production and soil conditions of fallow lands in the Central Himalayas.

Abstract

This study evaluates six bamboo species, *i.e.*, *Dendrocalamus hamiltonii*, *Bambusa nutans*, *Dendrocalamus asper*, *Bambusa bambos*, *Bambusa balcooa*, and *Dendrocalamus strictus*, regarding their growth behavior, nutrient uptake, and effect on the soil properties of the Terai region. Various aboveground growth parameters exhibited significant variations with the maximum clump girth (8.60 m) and internodal length (35.37 cm) of *B. nutans*, which was also reported by the culm diameter (5.70 cm) of *D. hamiltonii* and the number of culms per clump (65) of *D. strictus*. The total aboveground biomass ranged from 51.14 Mg.ha^{-1} in *D. asper* to 362.56 Mg.ha^{-1} in *D. hamiltonii*. The most significant variation in soil properties was observed in the 0-40 cm soil layer. Under *D. hamiltonii,* the lowest soil bulk density (1.07 g.cm^{3}; 1.21 g.cm^{3}) and the maximum soil porosity (59.00%; 56.40%), soil organic carbon (1.54%; 0.72%), and available soil nitrogen (228.29 kg.ha^{-1}; 173.73 kg.ha^{-1}) were found the 0-40 and 40-80 cm soil layers. Furthermore, significant enhancements in soil microbial population were recorded. Thus, bamboo plantations have great potential to enhance the biomass generation and fertility quotient of fallow lands.

Keywords: aboveground biomass, bamboo species, nutrient uptake, soil microbial population, soil properties, Terai region

Resumen

Este estudio evalúa seis especies de bambú, *i.e.*, *Dendrocalamus hamiltonii*, *Bambusa nutans*, *Dendrocalamus asper*, *Bambusa bambos*, *Bambusa balcooa* y *Dendrocalamus strictus*, respecto a su comportamiento de crecimiento, absorción de nutrientes y efecto sobre las propiedades del suelo de la región de Terai. Varios parámetros de crecimiento sobre el suelo mostraron variaciones significativas con la circunferencia máxima del macizo (8.60 m) y la longitud internodal (35.37 cm) de *B. nutans*, lo cual también se reportó para diámetro del culmo (5.70 cm) de *D. hamiltonii* y el número de culmos por macizo (65) de *D. strictus*. La biomasa aérea total varió de 51.14 Mg.ha^{-1} en *D. asper* a 362.56 Mg.ha^{-1} en *D. hamiltonii*. La variación más significativa en las propiedades del suelo se observó en la capa de suelo de 0-40 cm. Bajo D. *hamiltonii,* la densidad aparente del suelo más baja (1.07 g.cm^{3}; 1,21 g.cm^{3}) y los máximos valores de porosidad del suelo (59 %; 56.40 %), carbono orgánico del suelo (1.54 %; 0.72%) y nitrógeno disponible del suelo (228.29 kg.ha^{-1}; 173.73 kg.ha^{-1}) se encontraron en las capas de 0-40 y 40-80 cm de profundidad. Además, se registró una mejora significativa en la población microbiana del suelo. Por lo tanto, las plantaciones de bambú tienen un gran potencial para mejorar la generación de biomasa y el cociente de fertilidad de las tierras en barbecho.

Palabras clave: absorción de nutrientes, especies de bambú, biomasa aérea, población microbiana del suelo, propiedades del suelo, región de Terai

INTRODUCTION

The establishment of fast-growing plantations with short-rotation woody crops in marginal and degraded lands is globally prevalent and has been the focus of research at every national and international level (Silva *et al*., 2019). However, such plantations are not only emerging as the primary source for meeting the ever-increasing need for wood, bioenergy, and raw materials for a variety of forest-based industries (Arce, 2019), but also hold great potential to restore the productivity and biodiversity of the degraded ecosystems (Silva *et al*., 2019). Apart from bolstering the ecological functions of degraded lands, they also help to preserve dwindling natural forests (Farooq *et al*., 2021), reduce atmospheric CO_2, and improve the socioeconomic status of local communities.

At a global level, bamboo is regarded as the most versatile, sustainable, and replenishable plant resource, with enormous economic, social, and environmental benefits and covering an area of around 37 million ha (Goh *et al*., 2020). Bamboo has multifaceted uses like food, fuel, fiber, and construction material, playing an integral role in the sustainable development of equatorial countries (Akinlabi *et al*., 2017). For a few decades, bamboo planting has become more popular around the world, with Asia accounting for 30% of all bamboo resources planted (Lobovikov *et al*., 2007). In India alone, around 136 bamboo species in 29 genera are prevalent, both in cultivated plantations as well as forest ecosystems, with maximum species diversity in the forest subgroups: 2B, 3B, and 3C (Sharma & Nirmala, 2015).

Different bamboo species have distinctive growth rates and biomass allocation patterns, and they require various environmental conditions to proliferate. The assessment and evaluation of the growth performance of bamboo species are integral to calculating their adaptive capacity, production potential, and nutrient transport during harvest (Alemayehu *et al*., 2015). Comparative studies on the growth behavior of the various bamboo species are integral for the selection for commercial plantations, agroforestry/social forestry programs, and plantations for ecosystem conservation activities, among other things.

Bamboo plantations play many ecologically beneficial and environmentally sustainable roles, *i.e.*, in controlling soil erosion depletion, reclaiming degraded lands, water resource preservation, and climate change mitigation (Tu *et al*., 2013). Bamboo's fast growth with thick foliage and dense fibrous interconnected root systems, which results in a thick litter layer on the soil, helps to conserve soil moisture, improve soil fertility, and act as a barrier to soil nutrient loss. The impact of bamboo on soil is species-specific and has a varied effect on soil physicochemical properties, with most species tending to improve soil aeration, bulk density, and soil microbial biomass due to the large root surface area and the secretion of root exudes in the rhizosphere (Liu *et al*., 2021). Therefore, the goal of this study is to understand the growth patterns, nutrient uptake, and effects on soil qualities of several bamboo species. We hypothesized that the aboveground growth parameters, nutrient allocation, and soil properties of bamboo are species-specific.

MATERIALS AND METHODS

Study area

This study was conducted in a 14-year-old bamboo plantation at the Agroforestry Research Center, G. B. Pant University of Agriculture and Technology, Pantnagar, Uttarakhand (29°03′73′′ N latitude, 79°45′25′′ E longitude, and 236 m altitude) during the 2021-2022 period. This area is well known as the *Tarai region*, a narrow strip located in the foothills of the Shivalik range of the Himalaya. The climate of the experimentation site is humid semi-tropical, with chilled winters and hot dry summers, falling in the Cwa category of the Koppen-Geiger system. During the research period, the mean maximum temperature reached 45 °C in May, and the average lowest temperature was 0.5 °C in January. Around 80-90% of the rainfall is received from the south-west monsoon in July-September, with a mean annual rainfall of 1405 mm. Alluvial materials with medium to moderately coarse textures make up soils of the Terai region, which are mostly influenced by tall vegetation and moderate to well-drained conditions. The soils are referred to as *mollisols* because they have mollic horizons and weakly developed mollic epipedons.

Experimental design

The plantation was established in 2005 with six bamboo species: *Dendrocalamus hamiltonii*, *Bambusa nutans*, *Dendrocalamus asper*, *Bambusa bambos*, *Bambusa balcooa*, and *Dendrocalamus strictus*. The bamboo stand was established with a 5 m × 5 m clump spacing in a randomized block statistical design with four replications. For each bamboo species, four plants were planted in each plot (block plantation), occupying an area of 10 m^2. In total, there were 24 plots, covering a total area of 240 m^2.

METHODOLOGY

Biomass estimation

A complete enumeration was carried out, counting the number of culms per clump with the help of the cross-stick method. Then, the circumference of the bamboo clump (*i.e.,* clump girth) was determined at breast height (DBH at 1.37 m) using measuring tape. Three culms of different ages (1, 2, or 3 years old or above) from each replication (12 for each species) were selected based on their physiological appearance, *i.e.*, the color of the culm, the presence of culm sheath. The length, diameter, number of nodes, and internodal length of selected culms were measured, which were destructively felled from ground level during December. To determine the fresh weight, branches were parted, and leaves were removed from the felled culms of each bamboo species. To calculate the culm, branch, and leaf biomass of various bamboo species, representative samples were taken from each bamboo species and then oven dried. The oven dry weight of the representative sample was then multiplied by the total number of culms. The total aboveground biomass was calculated by adding the leaf, branch, and culm biomass for each bamboo species.

Nutrient uptake

To estimate the nutrient uptake of the six bamboo species under study, the samples of culm, branches, and leaves from specimens of different ages (1, 2, or 3 years old or above) from each replication were collected and kept under sun, left to dry for 2-3 days. The samples were further dried for two days in a hot air oven at 65±5° C and then ground to fine powder. After grinding, the samples passed through 0.5 mm sieve and were chemically analyzed for nitrogen (Jackson, 1967, *i.e.*, modified KEL PLUS auto N-analyzer), phosphorus (vanado-molybdate method), and potassium (flame emission spectrophotometer). The following formulas were used to determine the nutrient (NPK) uptake by the culm, branch, and leaves of six bamboo species (Singh & Rai, 2012):

1. $\text{N uptake in leaves (Mg.ha}^{-1}) = \dfrac{\text{N content in leaves (\%) x oven dry leaves biomass (t/ha)}}{100}$
2. $\text{N uptake in branch (Mg.ha}^{-1}) = \dfrac{\text{N content in branch (\%) x oven dry branch biomass (t/ha)}}{100}$
3. $\text{N uptake in culm (Mg.ha}^{-1}) = \dfrac{\text{N content in culm (\%) x oven dry culm biomass (t/ha)}}{100}$

4. Total aboveground N uptake ($Mg.ha^{-1}$) = N uptake by leaves + N uptake by branch + N uptake by culm

5. P uptake in leaves ($Mg.ha^{-1}$) = $\frac{\text{P content in leaves (\%) x oven dry leaves biomass (t/ha)}}{100}$

6. P uptake in branch ($Mg.ha^{-1}$) = $\frac{\text{P content in branch (\%) x oven dry branch biomass (t/ha)}}{100}$

7. P uptake in culm ($Mg.ha^{-1}$) = $\frac{\text{P content in culm (\%) x oven dry culm biomass (t/ha)}}{100}$

8. Total above ground P uptake ($Mg.ha^{-1}$) = P uptake by leaves + P uptake by branch + P uptake by culm

9. K uptake in leaves ($Mg.ha^{-1}$) = $\frac{\text{K content in leaves (\%) x oven dry leaves biomass (t/ha)}}{100}$

10. K uptake in branch ($Mg.ha^{-1}$) = $\frac{\text{K content in branch (\%) x oven dry branch biomass (t/ha)}}{100}$

11. K uptake in culm ($Mg.ha^{-1}$) = $\frac{\text{K content in culm (\%) x oven dry culm biomass (t/ha)}}{100}$

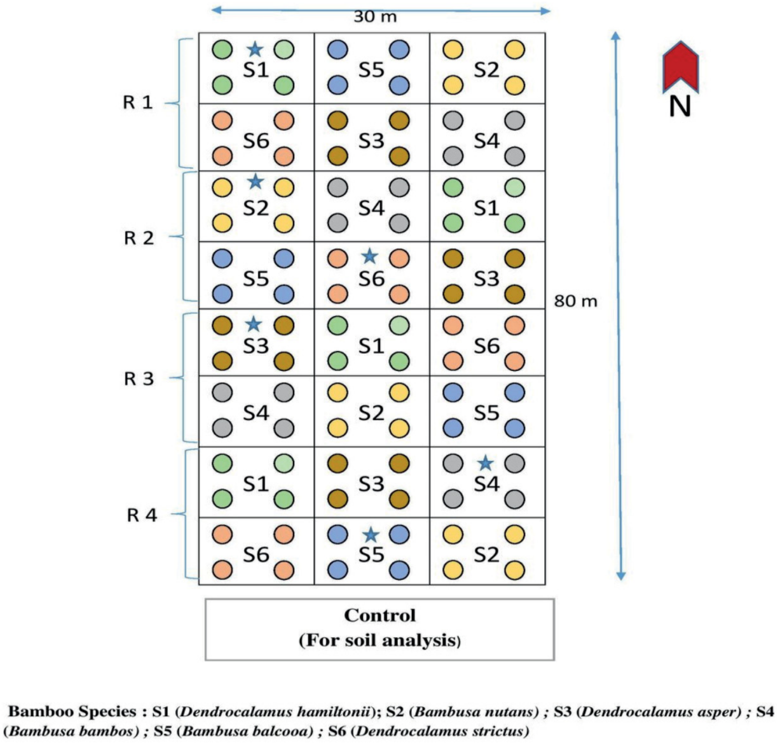
12. Total above ground K uptake ($Mg.ha^{-1}$) = K uptake by leaves + K uptake by branch + K uptake by culm (Mg: Mega gram; ha : hectares).

Soil physicochemical properties and microbial activities

The soil samples were collected randomly from between the rows of bamboo and from the plot devoid of bamboo (control plot) at three levels of soil depth, *i.e.*, 0-40, 40-80, and 80-120 cm. A composite sample was then prepared for each soil depth, combining soils from three sampling sites and producing one sample per level from each plot. Following collection, the samples were air dried, ground, and sieved. The bulk density was estimated by using the core sampler technique (Blake & Hartge, 1986), and a steel measuring cylinder was used to gauge the particle density. Soil porosity was calculated via the method described by Danielson & Southerland (1986). The soil pH was measured with a 1:2.5 soil: water suspension ratio (Jackson, 1967), and the electrical conductivity of the soil was measured using a digital microprocessor-based electrical conductivity meter (Bower & Wilcox, 1965). The quick titration method was used to determine the amount of organic carbon in the soil (Walkley & Black, 1934). The alkaline potassium permanganate method was used to determine the available soil nitrogen (Subbaiah & Asija, 1956), the available phosphorus was estimated via Bray no. 1 extraction followed by the reduced molybdate blue color estimation method (Watanabe & Olsen, 1965), and the available potassium was determined by means of neutral normal ammonium acetate solution extraction followed by flame photometry (Jackson, 1958). Regarding the soil microbial population, the soil samples were collected from each plot at a depth of up to 20 cm and air dried, ground, and sieved. The serial dilution plate technique to soil samples from each plot (Chhonkar *et al*., 2007). As for fungi, Martin's Rose-Bengal medium was used, Thornton's medium for bacteria, and Ken-Knight and Munaier’s medium for actinomycetes.

Statistical analysis

A thorough statistical study was carried out, and the range of deviation was calculated using the standard error of the mean. A randomized complete block design with four replications was used to compare the treatment effect (bamboo species) on aboveground growth parameters, nutrient uptake, and soil physico-chemical properties at different soil depths for the same bamboo species and at the same depth for different bamboo species and soil microbial population. A one-way analysis of variance (ANOVA) was performed using R (version 4.2.1) for Windows. To identify significant differences in the treatment means, a *post hoc* test, *i.e.*, Tukey's honest significant difference (HSD), was used at a 0.05 level of significance.



Bamboo Species : S1 (*Dendrocalamus hamiltonii*); S2 (*Bambusa nutans*) ; S3 (*Dendrocalamus asper*) ; S4 (*Bambusa bambos*) ; S5 (*Bambusa balcooa*) ; S6 (*Dendrocalamus strictus*)

Figure 1. Layout of the experimental plot

RESULTS

Growth parameters and biomass

The *post hoc* analysis via Tukey's HSD test (Figures 2 and 3) revealed that all the growth parameters of six bamboo species were significantly different ($p<0.05$), *i.e.*, the clump girth (CG), culm length (CuL), culm diameter (CuD), number of culms per clump (NCu/Cl), number of nodes (NN), and internodal length (IL). The highest CG (8.60 m), CuL (15.68 m), NN (50), and IL (35.37 cm) were observed in *B. nutans.* However*,* the CuL (15.39 m) and NN (48) of *D. hamiltonii* and the NN of *B. balcooa* (49) exhibited insignificant differences with the CuL and NN of *B. nutans*. Among all bamboo species, the highest CuD (5.70 cm) was recorded in *D. hamiltonii*, followed by *B. nutans* (4.70 cm). *D. strictus* exhibited the highest NCu/Cl (65), followed by *B. balcooa* (51), and the lowest value was recorded in *B. bambos* (35). Likewise, for the six bamboo species, Tukey's HSD test revealed significant variations in different components of the biomass (Figures 4a-d), *i.e*, leaf (LB), branch (BB), culm (CuB), and total aboveground biomass (TAGB) ($p<0.05$). *D. hamiltonii* reported the highest LB (29.54 Mg.ha^{-1}), CuB (296.12 Mg.ha^{-1}), and TAGB (362.56 Mg.ha^{-1}), followed by *B. nutans* (LB: 27.18 Mg.ha^{-1}, CuB: 198.48 Mg.ha^{-1}, TAGB: 277.50 Mg.ha^{-1}). *B. nutans* showed the highest BB (51.84 Mg.ha^{-1}), followed by *D. hamiltonii* (36.90 Mg.ha^{-1}). However, *D. asper* revealed minimal BB (7.54 Mg.ha^{-1}), CuB (38.08 Mg.ha^{-1}), and TAGB (51.14 Mg.ha^{-1}), as well as no significant differences with the TAGB of *B. bambos*(63.14 Mg.ha^{-1}).

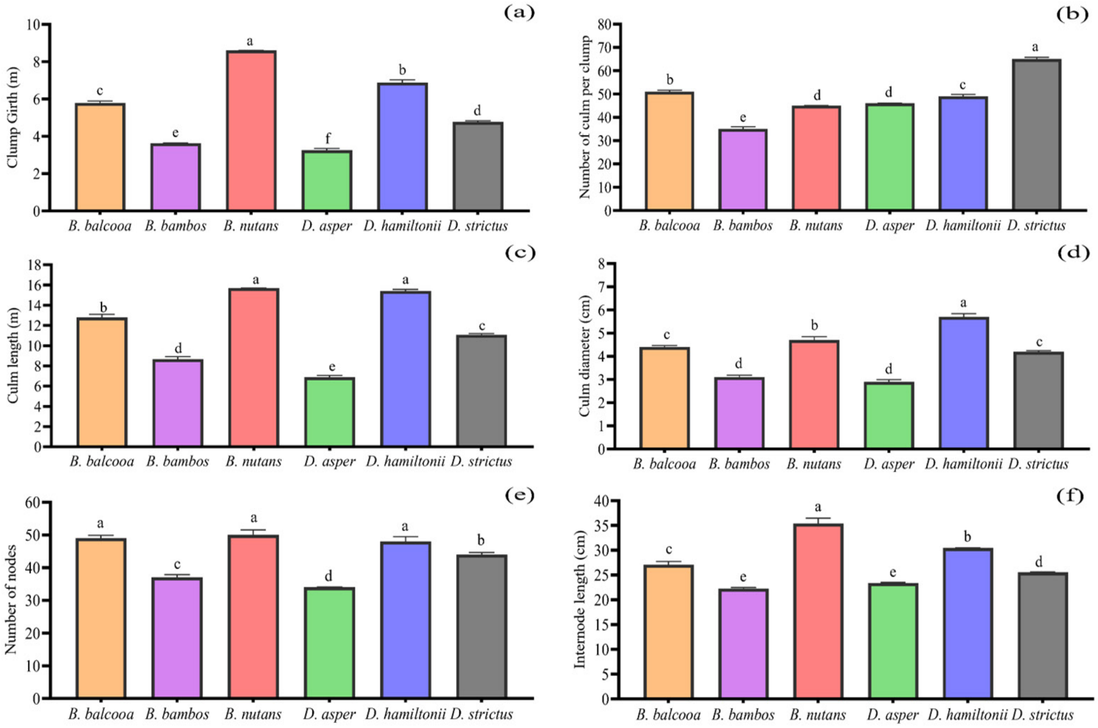


Figure 2. Variations in growth parameters: a) clump girth (m), b) number of culms, c) culm length (m), d) culm diameter (cm), e) number of nodes, and f) internode length (cm) for six bamboo species. Means followed by different letters are significantly different ($p<0.05$). The error bar signifies the mean standard deviation.

Nutrient uptake

In this research, the nutrient uptake, *i.e.,* nitrogen (N), phosphorus (P), and potassium (K) by various growth components (Figure 3) of the six bamboo species exhibited significant differences ($p<0.05$). Regarding the nutrient uptake by leaves, Tukey's HSD test revealed that the highest N (0.25 Mg.ha^{-1}), P (0.07 Mg.ha^{-1}), and K (0.36 Mg.ha^{-1}) uptake was recorded by *D. hamiltonii*, which remained statistically on par with the N (0.24 Mg.ha^{-1}) and P (0.06 Mg.ha^{-1}) uptake by leaves of *B. nutans.* Significant variations in the nutrient uptake by branches were also observed in bamboo species, with the highest N (0.42 Mg.ha^{-1}), P (0.07 Mg.ha^{-1}), and K (0.46 Mg.ha^{-1}) uptake being recorded by *B. nutans*, followed by *D. hamiltonii* (N: 0.28 Mg.ha^{-1}, P: 0.06 Mg.ha^{-1}, K: 0.34 Mg.ha^{-1}), whereas the lowest N (0.06 Mg.ha^{-1}), P (0.01 Mg.ha^{-1}), and K (0.06 Mg.ha^{-1}) uptake was recorded by *D. asper*. As for the nutrient uptake by culms, *D. hamiltonii* showed the highest N (1.78 Mg.ha^{-1}), P (0.35 Mg.ha^{-1}), and K (2.34 Mg.ha^{-1}) uptake values, followed by the N (1.34 Mg.ha^{-1}), P (0.25 Mg.ha^{-1}), and K (1.57 Mg.ha^{-1}) culm uptake of *B. nuatns.* The lowest N, P, and K uptake values reported by culms correspond to *D. asper* (0.22, 0.04, and 0.28 Mg.ha^{-1}) which was insignificantly different from the N (0.23 Mg.ha^{-1}), P (0.05 Mg.ha^{-1}), and K (0. Mg.ha^{-1}) culm uptake of *B. bambos*. Among the bamboo species, the overall total aboveground nutrient uptake also varied significantly ($p<0.05$). The highest total aboveground N, P, and K uptake (2.31, 0.47, and 3.04 Mg.ha^{-1}) was observed in *D. hamiltonii*, followed by *B. nutans* (2.00, 0.38, and 2.36 Mg.ha^{-1}).

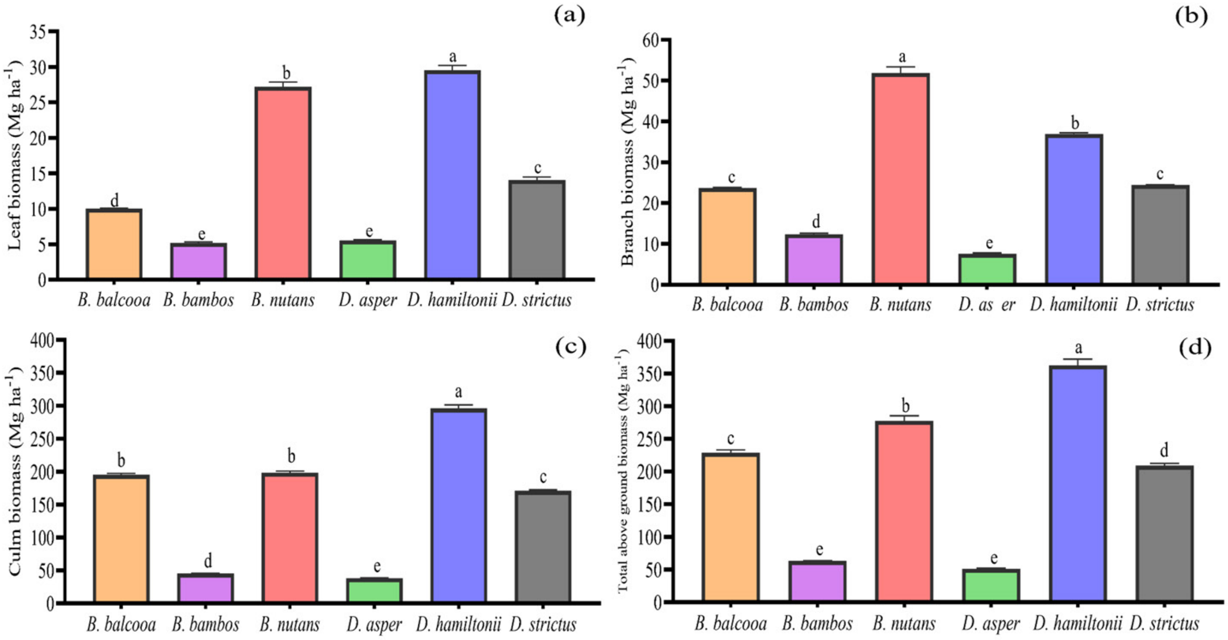


Figure 3. Variations in above ground biomass a) leaf biomass, b) branch biomass, c) culm biomass, and d) total aboveground biomass for six bamboo species. Means followed by different letters are significantly different ($p<0.05$). The error bar signifies the mean standard deviation.

Soil physicochemical properties

In the bamboo plantations, there was a significant reduction regarding soil properties (Table 1), *i.e.*, soil porosity (POR), soil electrical conductivity (EC), soil organic carbon (SOC), available soil nitrogen (ASN), available soil phosphorus (ASP), and available soil potassium (ASK), as well as an increase in soil parameters like bulk density (BD), particle density (PD), and pH, as the soil depth increased ($p<0.05$).

In the soil layer (0-40 cm), the highest BD (1.36 g.cm^3) was observed in the control plots, followed by *D. asper* (1.23 g.cm^3), whereas the lowest value was observed in *D. hamiltonii* (1.07 g.cm^3). Similarly, the open plots exhibited the highest PD (2.84 g.cm^3), but no significant difference was observed in the different bamboo species. The soil pH of the control plots was found to be slightly alkaline while also exhibiting the highest value (7.75), whereas the lowest soil pH was recorded in *D. asper* (6.66), on par with *B. bambos* (6.83) and *D. hamiltonii* (6.81). The highest soil POR was recorded in *D. hamiltonii* (59.00%), close to those of *B. nutans* (58.20 %), *B. bambos* (58.10 %), and *B. balcooa* (56.30 %). The highest soil EC was observed in *D. strictus* (0.54 ds m^{-1}), followed by *B. balcooa* (0.49 ds m^{-1}). The highest SOC (1.54 %) was recorded in *D. hamiltonii*, also followed

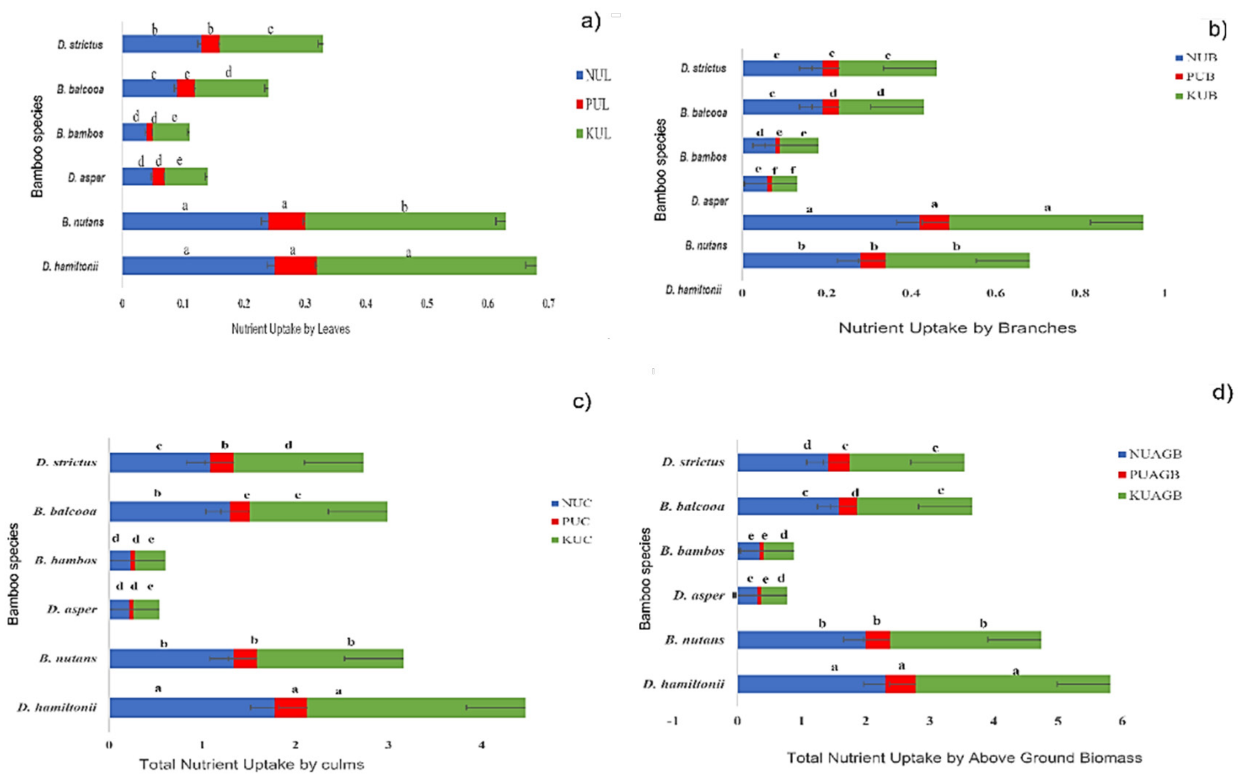


Figure 4. Variations in total nutrient uptake by a) leaves, b) branches, c) culms, and d) aboveground biomass for six bamboo species. Means followed by different letters are significantly different (p<0.05). The error bar signifies the mean standard deviation.

Note: NUL: nitrogen uptake by leaves; PUL: phosphorus uptake by leaves; KUL; potassium uptake by leaves; NUB: nitrogen uptake by branches; PUB: potassium uptake by branches; KUB; potassium uptake by branches; NUC; nitrogen uptake by culms; PUC: phosphorus uptake by culms; KUC: potassium uptake by culms; NUAGB: nitrogen uptake by aboveground biomass; PUAGB: phosphorus uptake by aboveground biomass; KUAGB: potassium uptake by aboveground biomass.

by *B. balcooa* (1.40 %). The open plots had the lowest soil POR (52.20 %), EC (0.34 ds m^{-1}), and SOC (0.74 %). Among the bamboo species, the highest ASN (228.29 kg.ha^{-1}) and ASK (216.72 kg.ha^{-1}) were recorded in *D. hamiltonii*, on par with the ASN (223.28 kg.ha^{-1}) and ASK (211.68 kg.ha^{-1}) of *B. balcooa.* In contrast, the open plots had the lowest ASN (169.96 kg.ha^{-1}) and ASK (172.54 kg.ha^{-1}). Regarding ASP, there was no significant variation between the bamboo species and the open plot.

Tukey's HSD test also revealed that, in the 40-80 cm soil layer, the open plots had the highest soil BD (1.45 g.cm^{3}), and *D. hamiltonii* showed the lowest value (1.21 g.cm^{3}). As for the soil POR, *D. hamiltonii* exhibited the highest value (56.40 %), and the lowest was recorded in the open plots (50.20 %) and *D. asper* (52.10 %), which exhibited no significant difference. The highest soil EC (0.36 ds m^{-1}) was observed in *D. strictus*, on par with *B. balcooa* (0.35 ds m^{-1}). Among the bamboo species, *D. hamiltonii* exhibited the highest SOC (0.72 %), followed by *B. bambos* (0.65 %), the highest ASN (173.73 kg.ha^{-1}), followed by *D. strictus* (164.32 kg.ha^{-1}), and the highest ASP (14.78 kg.ha^{-1}) in the 40-80 cm soil layer, while the open plots had the lowest SOC (0.40 %), ASN (144.25 kg.ha^{-1}), and ASP (10.49 kg.ha^{-1}). However, there was no significant difference in the soil PD, pH, and ASK between the bamboo species and the open plots.

Table 1. Soil physicochemical properties of six bamboo species in 14-year-old plantation and a control plot in the Terai region of the Central Himalayas.

Species	Soil depth (cm)	BD (g.cm^3)	PD (g.cm^3)	POR (%)	PH	EC (ds m^{-1})	SOC (%)	ASN (kg.ha^{-1})	ASP (kg.ha^{-1})	ASK (kg.ha^{-1})
balcooa	0-40	1.16±0.01^{Ccd}	2.65± 0.02^{Cb}	56.30± 0.61^{Aabc}	7.01± 0.15^{Cbc}	0.49± 0.01^{Ab}	1.40± 0.03^{Ab}	223.28± 5.32^{Aab}	22.62± 0.52^{Aa}	211.68± 4.61^{Aa}
	40-80	1.32± 0.02^{Bb}	2.78± 0.08^{Ba}	52.50± 1.57^{Bb}	7.36± 0.09^{Ba}	0.35± 0.01^{Ba}	0.42± 0.01^{Be}	157.42± 2.57^{Bc}	12.65± 0.24^{Bd}	117.60± 0.64^{Bc}
	80-120	1.52± 0.03^{Aa}	2.91± 0.05^{Aa}	47.60± 0.13^{Cc}	7.69± 0.17^{Aa}	0.25± 0.01^{Ca}	0.13± 0.01^{Ce}	123.55± 0.76^{Cb}	8.17± 0.03^{Cc}	96.32± 2.42^{Cb}
B. bambos	0-40	1.14± 0.01^{Cd}	2.70± 0.07^{Bb}	58.10± 1.82^{Aab}	6.83± 0.11^{Ccd}	0.39± 0.01^{Ac}	1.31± 0.04^{Ac}	203.58± 1.52^{Ac}	19.48± 0.58^{Aab}	185.92± 4.68^{Ac}
	40-80	1.34± 0.01^{Bb}	2.82± 0.07^{Aba}	52.50± 0.71^{Bb}	7.39± 0.01^{Ba}	0.26± 0.01^{Bb}	0.65± 0.01^{Bb}	149.27± 0.40^{Bd}	13.88± 0.33^{Bb}	117.60± 0.72^{Bc}
	80-120	1.46± 0.03^{Ab}	2.91± 0.03^{Aa}	50.00± 1.57^{Bab}	7.70± 0.11^{Aa}	0.21± 0.01^{Cc}	0.18± 0.01^{Cb}	137.98± 2.44^{Ca}	9.63± 0.20^{Ca}	105.84± 2.88^{Ca}
B. nutans	0-40	1.13± 0.02^{Cd}	2.70± 0.03^{Bb}	58.20± 0.90^{Aab}	6.90± 0.05^{Cc}	0.38± 0.01^{Acd}	1.33± 0.03^{Ac}	209.90± 5.86^{Ac}	19.96± 0.35^{Aab}	196.74± 3.61^{Ab}
	40-80	1.33± 0.02^{Bb}	2.88± 0.08^{Aa}	53.80± 1.50^{Bb}	7.43± 0.23^{Ba}	0.26± 0.01^{Bb}	0.50± 0.01^{Bd}	157.42± 1.82^{Bc}	12.99± 0.08^{Bcd}	124.32± 2.11^{Bab}
	80-120	1.55± 0.03^{Aa}	2.97± 0.08^{Aa}	47.70± 0.16^{Cbc}	7.72± 0.15^{Aa}	0.24± 0.01^{Cab}	0.16± 0.01^{Cc}	137.35± 3.74^{Ca}	8.73± 0.22^{Cb}	100.24± 2.32^{Cab}
D. asper	0-40	1.23± 0.02^{Cb}	2.71± 0.03^{Cb}	54.60± 0.71^{Acd}	6.66± 0.24^{Cd}	0.37± 0.01^{Ade}	1.18± 0.03^{Ad}	204.46± 3.06^{Ac}	19.82± 0.57^{Aab}	202.16± 4.54^{Ab}
	40-80	1.36± 0.03^{Bb}	2.84± 0.08^{Ba}	52.10± 0.35^{Bbc}	7.36± 0.16^{Ba}	0.26± 0.01^{Bb}	0.59± 0.01^{Bc}	155.54± 1.38^{Bc}	12.99± 0.03^{Bcd}	124.32± 3.05^{Bab}
	80-120	1.55± 0.03^{Aa}	2.96± 0.01^{Aa}	47.70± 1.33^{Cbc}	7.86± 0.10^{Aa}	0.22± 0.01^{Cc}	0.12± 0.01^{Cf}	132.96± 3.89^{Ca}	8.73± 0.02^{Cb}	98.56± 3.29^{Cb}
D. hamil-tonii	0-40	1.07± 0.02^{Ce}	2.61± 0.06^{Cb}	59.0± 0.80^{Aa}	6.81± 0.08^{Ccd}	0.36± 0.01^{Ae}	1.54± 0.01^{Aa}	228.29± 1.24^{Aa}	23.85± 0.68^{Aa}	216.72± 0.01^{Aa}
	40-80	1.21± 0.02^{Bc}	2.77± 0.05^{Ba}	56.40± 0.08^{Ba}	7.46± 0.03^{Ba}	0.27± 0.01^{Bb}	0.72± 0.01^{Ba}	173.73± 4.37^{Ba}	14.78± 0.35^{Ba}	127.68± 2.95^{Ba}
	80-120	1.41± 0.02^{Ab}	2.90± 0.02^{Aa}	51.40± 0.31^{Ca}	7.89± 0.13^{Aa}	0.24± 0.01^{Cab}	0.15± 0.01^{Cd}	138.61± 2.92^{Ca}	9.29± 0.07^{Ca}	101.92± 2.57^{Cab}
D. strictus	0-40	1.18± 0.01^{Cc}	2.68± 0.06^{Cb}	56.01± 1.71^{Abc}	7.13± 0.02^{Cb}	0.54± 0.01^{Aa}	1.29± 0.02^{Ac}	218.88± 1.49^{Ab}	21.81± 0.26^{Aa}	201.60± 5.08^{Ab}
	40-80	1.34± 0.01^{Bb}	2.83± 0.04^{Ba}	52.60± 1.15^{Bb}	7.46± 0.05^{Ba}	0.36± 0.01^{Ba}	0.59± 0.01^{Bc}	164.32± 1.79^{Bb}	13.43± 0.07^{Bbc}	122.08± 2.74^{Bbc}
	80-120	1.54± 0.03^{Aa}	2.96± 0.08^{Aa}	47.80± 0.75^{Cbc}	7.69± 0.08^{Aa}	0.23± 0.01^{Cb}	0.21± 0.01^{Ca}	136.77± 4.47^{Ca}	8.79± 0.29^{Cb}	99.12± 2.23^{Cb}
Control plot	0-40	1.36± 0.01^{Ca}	2.84± 0.07^{Aa}	52.20± 0.96^{Ad}	**7.75± 0.09**^{Aa}	0.34± 0.01^{Af}	0.74± 0.02^{Ae}	169.96± 4.86^{Ad}	16.46± 0.22^{Ab}	172.54± 1.64^{Ad}
	40-80	1.45± 0.02^{Ba}	2.92± 0.06^{Aa}	50.20± 0.31^{Ac}	7.69± 0.08^{Aa}	0.24± 0.01^{Bb}	0.40± 0.01^{Bf}	144.25± 3.53^{Bd}	10.49± 0.01^{Be}	122.64± 0.58^{Bb}
	80-120	1.58± 0.02^{Aa}	2.00± 0.03^{Bb}	47.40± 1.55^{Bc}	7.50± 0.24^{Aa}	0.21± 0.01^{Cc}	0.13± 0.01^{Ce}	132.96± 1.81^{Ca}	8.50± 0.21^{Cbc}	98.56± 1.01^{Cb}

These values correspond to the mean ± standard deviation (n = 4). Different lower-case letters indicate significant differences in the soil characteristics of bamboo species and the control plot in the same soil layer. Different capital letters indicate significant differences in the soil characteristics of different soil layers for the same treatment (ANOVA and LSD test, $p<0.05$). BD: bulk density; PD: particle density; EC: electrical conductivity; POR: soil porosity; ASN: available soil nitrogen; ASP: available soil phosphorous; and ASK: available soil potassium.

In the 80-120 cm soil layer, the variations in soil BD, PD, pH, EC, ASN, ASP, and ASK were not statistically significant, except for SOC, whose highest value was recorded in *D. strictus* (0.21 %), followed by *B. bambos* (0.18%), whereas the lowest was reported by *D. asper* (0.12 %) (Tukey's HSD test).

Soil microbial population

The soil microbial population exhibited significant variations between the bamboo species and the open plot ($p<0.05$). The highest fungi count was observed in *B. nutans* (101.20 $\times 10^4$ cfu.g^{-1}), which did not differ significantly from that of *D. hamiltonii* (100.47 $\times 10^4$ cfu.g^{-1}), followed by *D. strictus* (97.14 $\times 10^4$ cfu.g^{-1}) and *B. bambos* (95.61 $\times 10^4$ cfu.g^{-1}). The open plot had the lowest fungi count (54.40 $\times 10^4$ cfu.g^{-1}). Among the different bamboo species, the highest actinomycetes count was reported by *D. hamiltonii* (54.16 $\times 10^5$cfu.g^{-1}), followed by *B. nutans* (51.33 $\times 10^5$cfu.g^{-1}), and the lowest value was recorded in the open plot (30.45 $\times 10^5$cfu.g^{-1}). Similarly, the bacterial count was significantly higher in *D. hamiltonii* (68.30 $\times 10^6$cfu.g^{-1}), followed by *B. nutans* (65.11$\times 10^6$cfu.g^{-1}), and it was minimal in open plots (36.22 $\times 10^6$cfu.g^{-1}).

DISCUSSION

Growth parameters and biomass

In this research, the variations in the growth parameters of the six different bamboo species, which grew under similar environmental conditions, may be indicative of their unique genetic makeup (Kaushal *et al.*, 2020b), as well as due to internal factors such as the plant's origin, species type, and resilient system. All bamboo species in the plantations are sympodial and are prone to growing centrifugally, *i.e.*, growing from the center outwards. Due to the varying adaptive potentials of these bamboo species with regard to their surroundings and environment, numerous external factors may have an impact on the growth rate (Hassan *et al.*, 2022).

The variation in the clump girth, *i.e.*, the measurement of the enclosing boundary of the cluster of bamboo poles, depends on the mortality and recruitment of new culms in the bamboo clumps (Franklin *et al.*, 2010; Iyer, 2019). Chen *et al.* (2022) argued that internodal length is affected by the growth of fiber and parenchyma cells in the bamboo culm. Similarly, Chen (2021) suggested that this aspect is dependent on the function of intercalary meristem present at the base of the internode, which increases the internodal length by elongation of the meristematic cells. This could be the case of *B. nutans* in this research. Similar findings were reported by Singh *et al.* (2018) and Gaikwad *et al.* (2021), who recorded the highest clump girth and internodal length of *B.nutans* in bamboo plantations. Likewise, Kaushal *et al.* (2020b) reported the highest clump girth for *B. nutans* (15.40 m) and the lowest one for *D. asper* (5.10 m) in 12-year-old bamboo plantations, which is consistent with our findings.

The culm length growth of the bamboo species, which shows a substantial association with the aboveground biomass according to the adaptive potential regarding the given environmental conditions (Noguchi & Yoshida, 2005), corroborates the highest culm length reported by *B. nutans*, which was followed by *D.*

hamiltonii. Similarly, Singh *et al*. (2018) recorded the significant growth (8.70 m) of *B. nutans* in the central plains of India, which was lower than that reported in this study. Likewise, the study by Kanwal (2011) attributed the highest culm height to *B. nutans* over eight other bamboo species in the central Himalayan zone of India.

Large-diameter bamboo culms are increasingly in demand as sustainable raw materials for the wood industries (Zhang *et al*., 2013), which depends on the growth of ground and vascular tissue in the intermediate layer of bamboo culms (Xie *et al*., 2014; Wang *et al*., 2022). This might be the reason for the higher culm diameter growth of *D. hamiltonii* in our study. Similar findings were published by Pattanaik and Hall (2014) and Zhan *et al*. (2016), who observed a greater diameter growth in *D. hamiltonni* in the east Khasi hills of Meghalaya, India (7.16 cm) and in the Yunnan province, China (10-18.5 cm). These values are higher than ours. Likewise, Kaushal *et al*. (2020b) reported a great culm diameter growth for *D. hamiltonii* over other bamboo species in the central Himalayan region.

In the bamboo species, the aggregation of culms per clump was dependent on the activity of the adventitious buds present on the rhizome, which ultimately develop into new culm recruits (Zhao-Hua *et al*., 2005). Likewise, Li *et al*. (2021) found that the number of culms per clump is positively correlated with the vitality and growth of the belowground rhizome, which varies from species to species and is determined by capacity of a bamboo species to adapt to a given environment, which might be the reason for the higher culm density per clump in *D. strictus*. Similarly, Kittur *et al*. (2016) recorded 75 culms per clump of *D. strictus* in a seven-year-old bamboo plantation in the humid climate of India, which is comparable to our findings.

The variations in the aboveground growth parameters, *i.e.*, the leaves, branches, and culm of the bamboo species, is dependent on species' characteristics and their ability to compete for limited resources. Similarly, different bamboo species have distinct phylogenetic, morphological, and physiological features, as well as distinct biomass allocation strategies to optimize resource uptake (Mensah *et al*., 2016). Oli & Kandel (2005) and Puangchit *et al*. (2019) recorded the branch biomass (12.24 t. ha^{-1}; 10 t. ha^{-1}) of *B. nutans* in the eastern Terai region of Nepal and in the reserve forest of Myanmar, with values lower than those of our findings. Similarly, Kaushal *et al*. (2022) observed the highest branch biomass in *B. nutans* in the foothills of western Himalaya. Likewise, in comparison with our study, Shanmughavel & Francis (2003) recorded higher values for the culm (431.66 Mg. ha^{-1}) and the total aboveground biomass (623.05 t. ha^{-1}) of *D. hamiltonii* in wastelands of Coimbatore, India.

Nutrient uptake

Various factors such as species, age, developmental phase, soil fertility, climatic factors, and other variables have a general impact on the uptake, accumulation, and distribution of nutrients throughout the various plant parts (Ovington, 1965). According to Kim *et al*. (2018), the variations in the nutrient uptake by different biomass components of bamboo species can be linked to their response to soil nutrition and their propensity to accumulate various amounts of dry matter in different parts. Similarly, resource allocation and their utilization by various structural and functional organs for habitat adaptation might be another feasible explanation for the observed variations in nutrient uptake (Guo *et al*., 2021).

Many researchers (Singh & Kochhar, 2005; Singh & Rai, 2012; Kumar *et al*., 2006) have documented the nutrient uptake by different biomass components of various bamboo species. Like any other plant species, the primary organ for organic matter production is the leaf, while branches and stems serve as storage organs, particularly in older bamboos (Wu *et al*., 2009). The differences in nutrient uptake by the leaves of the bamboo species could be ascribed to their specific photosynthesis strategy, which is influenced by genetic variability (Luo *et al*., 2021). Our findings are consistent with those of Gaikwad *et al*. (2021), who recorded the highest N uptake by leaves and the highest P and K uptake by branches in a two-year-old *B. nutans* plantation in semi-arid tracts of Madhya Pradesh, India. Likewise, Kumari & Bharadwaj (2017) recorded the N and P uptake of *D. hamitonii* leaves (0.19 Mg. ha^{-1-}; 0.02 Mg. ha^{-1}) in the subtropical climate of Himachal Pradesh, values lower than those of our findings.

The maximal nutrient uptake by culms is attributed to bamboo species with a high biomass production and nutrient export potential via culm harvesting (Singh & Rai, 2012), which corroborates the high nutrient uptake by the culms of *D. hamiltonii* in our plantation. Similar findings were published by Kumari & Bharadwaj (2019) who reported the total N (0.21 t. ha^{-1}), P (0.03 t. ha^{-1}), and K (0.19 t. ha^{-1}) uptake by *D. hamiltonii* in ten-year-old bamboo plantations, with values lower than those of our findings. Likewise, Gaikwad *et al*. (2021) observed lower values of total N (0.45 t. ha^{-1}), P (0.04 t. ha^{-1}), and K (0.37 t. ha^{-1}) uptake by *B. nutans* in comparison with our study.

Soil physicochemical properties

There are significant differences regarding the impact of different bamboo species on soil physicochemical properties and the microbial population. The soil BD, which has a substantial impact on soil fertility, water flow, and gas penetration, is impacted by a variety of factors, including the aboveground biomass, compaction, and the plant species' rooting system, among others (Nawaz *et al*., 2013). The reduced soil BD in the 0-40 cm soil layer of our bamboo plantations is most likely due to an increased root dispersion, which can loosen the soil (Zhou & Shangguan, 2007). The rooting systems of different bamboo species may be the reason for the differences in soil BD (Cao *et al*., 2011). In the 0-40 and 40-80 cm soil layers, *D. hamiltonii* reported the lowest soil BD, which could be attributed to higher production of fine roots and aboveground biomass, litterfall rate, and decomposition (Seobi *et al*., 2005; Udawatta *et al*., 2009). Kaushal *et al*. (2020a) reported higher fine root production and litterfall as well as a lower soil BD under *D. hamiltonii* in comparison to other bamboo species. The slight decrease in soil particle density when compared to the control plot might be due to maximal root spread in the upper soil layer, which generates channels in the soil and might have accelerated the downward movement of finer soil particles (silt and clay), thus reducing soil particle density as suggested by El-amin *et al*. (2001). Similarly, Selassie & Ayanna (2013) and Pandey (2019) observed a decline in soil particle density with the addition of soil organic matter in bamboo plantations.

Soil porosity is the proportion of pore space in a given volume of soil, which is determined by the soil BD, organic matter, and particle shape and size, among others (Robinson *et al*., 2022). The smaller pore space in the 40-80 and 80-120 cm soil layers when compared to the 0-40 cm level of the bamboo plantations could be attributed to reductions in root distribution, biomass, total root length, and the root area per unit of soil volume (Kodešová *et al*., 2006; Hao *et al*., 2019). Arunachalam & Arunachalam (2002) and Kumar *et al*. (2021) estimated the soil pore space under different bamboo species. Similarly to our study, Patra *et al*. (2022) observed maximum values for soil porosity under *D. hamiltonii* in the northwestern Himalayan region. The slightly more acidic nature of the 0-40 cm soil layer in comparison with the 40-80 and 80-120 cm levels may be explained by the presence of litterfall, which causes more humus to accumulate. The decomposition of this humus may have resulted in organic acids, causing a decrease in the soil pH (Kumar *et al*., 2022; Qian *et al*. 2021)

The electrical conductivity of the soil is determined by its particle size, dispersion, porosity, water retention, and temperature (Bai *et al*., 2013). The enhanced electrical conductivity of the 0-40 cm soil layer under the bamboo plantations might be due to a better water retention, as a result of the larger pore space (Bai *et al*., 2013; Fu *et al*., 2021). Likewise, the decomposition of litterfall, which leads to the leaching of bases under the bamboo species, could be a plausible explanation for the increased soil electrical conductivity (Kim *et al*., 2018; Gaikwad *et al*., 2021; Kumar *et al*., 2022). The higher soil organic carbon in the 0-40 cm soil layer under the bamboo plantations could be due to the species' rapid growth rate, resulting in the continuous addition of litterfall to the soil (Lei *et al*., 2019; Kaushal *et al*., 2020b; Benbi *et al*., 2015). Similarly, the dense mat-like root systems of rhizomatous bamboo species, along with their small and finer roots in the upper soil layer, may contribute to more stable soil aggregates, less soil erosion, and an increase in the organic carbon content of the soil (Qiao *et al*., 2016; Dong & Kou, 2022). Likewise, variations in above- and belowground biomass production, as well as the disintegration rate, could be valid explanation for the high soil organic carbon content under *D. hamiltonii*.

The addition of soil organic matter and nutrient return through litterfall, as well as the extensive fibrous interconnected root structure of bamboo plantations, have the potential to reduce the surface water flow velocity and increase the retention of more nutrients in the soil, which would otherwise be lost due to erosion (Shiau *et al*., 2017). This could be the reason for the greater availability of soil N, P, and K under the bamboo plantations in comparison to the control plot. Singh and Singh (2006) posited that bamboo species that allocate more biomass to the foliage are likely to have more nutrient-rich litterfall and enhanced soil fertility, which may be the reason for the higher soil nutrient availability under *D. hamiltonii*. Similarly to our study, Kanwal *et al*. (2011) reported the ASP (24.84 kg.ha^{-1}) and ASK (191 kg.ha^{-1}) values of the 0-40 cm soil layer in a six-year-old *D. hamiltonii* plantation in the Central Himalayas.

Soil microbial population

The greater microbial populations found under the bamboo plantations in comparison with the control plot could be attributed to litterfall, which is a carbon and nitrogen source for the soil. This would boost soil enzymatic activities and soil organic carbon, consequently increasing microorganism diversity in the soil (Tian *et al*., 2007; Chang *et al*., 2019). Researchers such as Xue *et al*. (2017) and Zhang *et al*. (2020) have suggested a positive relationship between the ASN, the SOC, and the diversity of soil microorganisms. Likewise, bamboo roots exude various metabolic products, which attract diverse soil microflora into the rhizosphere (Trivedi *et al*., 2020; Zheng & Lin, 2020), which might be a plausible explanation for the higher microbial population under the bamboo plantations. Similarly to our study, Kaushal *et al*. (2020b) revealed that *D. hamiltonii* had the highest actinomycetes count (8.4 ×10^5cfu. g^{-1}) compared to other species in a ten-year-old bamboo plantation. On contrary, Arunachalam & Arunachalam (2002) reported the lowest bacterial (7.080 ×10^5cfu. g^{-1}) and fungal (22.53 ×10^3 cfu. g^{-1}) soil count under *D. hamiltonii* among other bamboo species in the humid tropics of India.

CONCLUSIONS

For homogeneous climate conditions, this study revealed that the aboveground growth characteristics of several bamboo species can vary, indicating their adaptive and production potential, which is an important indicator for species selection in plantations. *B. nutans* and *D. hamiltonii*, due to their larger and thicker culm walls, can act as excellent sustainable building materials, as they can support great loads. These species also accumulated the highest amount of total aboveground biomass, making them excellent raw materials for bio-energy, pulp, paper, and paperboard production, as well as a more effective terrestrial carbon sink for climate change mitigation. The assessment of nutrient uptake by bamboo species is critical for optimizing soil nutrient management in order to enchance the plantation output potential. *D. hamiltonii* performed best in improving the soil physicochemical properties and enhancing the soil microbial population. Thus, it is suitable for the restoration of fallow lands in the Terai region of the Central Himalayas.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge Dr. D. K. Dwiedi from the G. B. Pant University of Agriculture and Technology, Pantnagar, for proofreading the article. We would also like to extend our appreciation to Dr. José Gutiérrez, the style editor of Colombia Forestal, for all of his hard work in making the manuscript accurate.

AUTHOR CONTRIBUTIONS

N.Sh., N.S. and S.N.R. were responsible for the conception and design of this study, as well as for acquisition of the data. Data analysis and/or interpretation was carried out by M.Y. and B.J. N.Sh. and D.K. were responsible for drafting and revising the manuscript.

REFERENCES

Akinlabi, E. T., Anane-Fenin, K., & Akwada, D. R. (2017). *Bamboo: The multipurpose plant*. Springer.

Alemayehu, A., Mulatu, Y., Eshete, N., & Terefe, M. (2015). Growth performance and biomass accumulation of four different introduced bamboo species in South-Western Ethiopia. *Growth*, *5*(3), 5-10.

Arce, J. J. C. (2019). *Forests, inclusive and sustainable economic growth and employment*. United Nations.

Arunachalam, A., & Arunachalam, K. (2002). Evaluation of bamboos in eco-restoration of 'jhum'fallows in Arunachal Pradesh: Ground vegetation, soil and microbial biomass. *Forest Ecology and Management, 159(3)*, 231-239. Https://doi.org/10.1016/S0378-1127(01)00435-2

Bai, W., Kong, L., & Guo, A. (2013). Effects of physical properties on electrical conductivity of compacted lateritic soil. *Journal of Rock Mechanics and Geotechnical Engineering*, *5*(5), 406-411. Https://doi.org/10.1016/j.jrmge.2013.07.003

Benbi, D. K., Brar, K., Toor, A. S., & Singh P. (2015). Total and labile pools of soil organic carbon in cultivated and undisturbed soils in northern India. *Geoderma, 237*, 149-158. Https://doi.org/10.1016/j.geoderma.2014.09.002

Blake, G. R., & Hartge, K. H. (1986). *Methods of soil analysis*. American Society of Agronomy.

Bower, C. A., & Wilcox, L. V. (1965). *Methods of soil analysis*. American Society of Agronomy.

Cao, S. X., Chen, L., Shankman, D., Wang, C. M., Wang, X. B., & Zhang, H. (2011) Excessive reliance on afforestationin China's arid and semi-arid regions, Lessons in ecological restoration. *Earth Science Review, 104*, 240-245. Https://doi.org/10.1016/j.earscirev.2010.11.002

Chang, E. H., Tian, G., Shiau, Y. J., Chen, T. H., & Chiu, C. Y. (2019). Influence of thorny bamboo plantations on soil microbial biomass and community structure in subtropical badland soils. *Forests, 10(10),* 854. Https://doi.org/10.3390/f10100854

Chen, X. (2021). Variations in patterns of internode and branch lengths for several bamboo species. *Plant Biosystems, 155(6)*, 1088-1099. Https://doi.org/10.1080/11263504.2020.1829729

Chen, M., Lin, G., Ramakrishnan, M., Fei, Z., Kunnummal, K. V., Yulong, D., & Chen, J. (2022). Rapid growth of Moso bamboo (*Phyllostachys edulis*): Cellular roadmaps, transcriptome dynamics, and environmental factors. *The Plant Cell, 34*(10), 3577-3610. Https://doi.org/ 10.1093/plcell/koac193

Chhonkar, P. K., Bhadraray, S., Patra, A. K., & Purakayastha T. J. (2007). *Experiments in soil biology and biochemistry*. Westville Publishing House.

Danielson, R. E., & Southerland, P. L. (1986). *Porosity*. American Society of Agronomy, Soil Science Society of America.

Dong, L., & Kou, M. (2022). Soil Aggregate stability and carbon density in three plantations in the Loess Plateau, China. *Forests*, *13(7)*, 1096. Https://doi.org/10.3390/f13071096

El-Amin, E. A., Diab, I. E., & Ibrahim, S. (2001). Influence of Eucalyptus cover on some physical and chemical properties of a soil in Sudan. *Communications in Soil Science and Plant Analysis, 32*(13-14), 2267-2278. https://doi.org/10.1081/CSS-120000282

Farooq, T. H., Shakoor, A., Wu, X., Li, Y., Rashid, M. H. U., Zhang, X., & Yan, W. (2021). Perspectives of plantation forests in the sustainable forest development of China. *Forest-Biogeosciences and Forestry*, *14(2)*, 166-174. https://doi.org/10.3832/ifor3551-014

Franklin, D. C., Prior, L. D., Hogarth, N. J., & McMahon, C. R. (2010). Bamboo, fire and flood: Consequences of disturbance for the vegetative growth of a clumping, clonal plant. *Plant Ecology*, *208(2)*, 319-332. Https://doi.org/10.1007/s11258-009-9709-x

Fu, Y., Horton, R., & Heitman J. (2021). Estimation of soil water retention curves from soil bulk electrical conductivity and water content measurements. *Soil and Tillage Research*, *209,* 104948. Https://doi.org/10.1016/j.still.2021.104948

Gaikwad, A. S., Thite, M., & Rananavare, S. I. A. (2021). Effect of different bamboo species on growth attributing characters grown on Entisol of semi-arid climate. *The Pharma Innovation Journal*, *10(12)*, 1980-1985. Https://doi.org/10.22271/tpi.2021.v10.i12Saa.9910

Goh, Y., Yap, S. P., & Tong, T. Y. (2020). Bamboo: The emerging renewable material for sustainable construction. *Encyclopedia of Renewable and Sustainable Materials, 2*, 365-376. Https://doi.org/10.1016/B978-0-12-803581-8.10748-9

Guo, Z., Zhuang, M., Yang, L., Li, Y., Wu, S., & Chen, S. (2021). Differentiated mineral nutrient management in two bamboo species under elevated CO_2 environment. *Journal of Environmental Management, 279*, 111600. Https://doi.org/10.1016/j.jenvman.2020.111600

Hao, M., Zhang, J., Meng, M., Chen, H. Y., Guo, X., Liu, S., & Ye, L. (2019). Impacts of changes in vegetation on saturated hydraulic conductivity of soil in subtropical forests. *Scientific Reports, 9(1),* 8372. Https://doi.org/10.1038/s41598-019-44921-w

Hassan, N. H. M., Abdullah, N., Kelanda, D. N. A., & Perumal, M. (2022). Early field growth performance of ten selected bamboo taxa: The case study of Sabal bamboo pilot project in Sarawak, Malaysia. *Biodiversitas, 23(6),* 2882-2892. Https://doi.org/10.13057/biodiv/d230614

Iyer, R. (2019). *Sustainability-based evaluation of bamboo harvest in Pachgaon* [Doctoral dissertation, Department of Biology, IISRE]. http://dr.iiserpune.ac.in:8080/xmlui/bitstream/handle/123456789/3018/Rahul%20_Iyer_20141154_Thesis_final.pdf?sequence=1&isAllowed=y

Jackson, M. L. (1958). *Soil chemical analysis*. Asia Publishing House.

Jackson, M. L. (1967). *Soil chemical analysis*. Prentice Hall.

Kanwal, M. S. (2011). Influence of different bamboo species on growth, carbon sequestration potential and soil properties in tarai region of northern india [Master's thesis, G. B. Pant University of Agriculture and Technology, Department of Agronomy.

Kaushal, R., Singh, I., Thapliyal, S. D., Gupta, A. K., Mandal, D., Tomar, J. M. S., & Durai, J. (2020 a). Rooting behaviour and soil properties in different bamboo species of Western Himalayan Foothills, India. *Scientific Reports, 10(1)*, 4966.
Https://doi.org/10.1038/s41598-020-61418-z

Kaushal, R., Tewari, S., Banik, R. L., Thapliyal, S. D., Singh, I., Reza, S., & Durai, J. (2020 b). Root distribution and soil properties under 12-year old sympodial bamboo plantation in Central Himalayan Tarai Region, India. *Agroforestry Systems, 94*, 917-932.
Https://doi.org/10.1007/s10457-019-00459-4

Kaushal, R., Islam, S., Tewari, S., Tomar, J. M. S., Thapliyal, S., Madhu, M., & Durai, J. (2022). An allometric model-based approach for estimating biomass in seven Indian bamboo species in western Himalayan foothills, India. *Scientific Reports, 12(1)*, 7527.
Https://doi.org/10.1038/s41598-022-11394-3

Kim, C., Baek, G., Yoo, B. O., Jung, S. Y., & Lee, K. S. (2018). Regular fertilization effects on the nutrient distribution of bamboo components in a moso bamboo (*Phyllostachys pubescens* (Mazel) Ohwi) stand in South Korea. *Forests, 9(11)*, 671.
Https://doi.org/10.3390/f9110671

Kittur, B. H., Sudhakara, K., Mohan Kumar, B., Kunhamu, T. K., & Sureshkumar, P. (2016). Bamboo based agroforestry systems in Kerala, India: performance of turmeric (*Curcuma longa* L.) in the subcanopy of differentially spaced seven year-old bamboo stand. *Agroforestry Systems, 90*, 237-250.
Https://doi.org/10.1007/s10457-015-9849-z

Kodešová, R., Kodeš, V., Žigová, A., & Šimůnek, J. (2006). Impact of plant roots and soil organisms on soil micromorphology and hydraulic properties. *Biologica, 61(19),* 339-343.
Https://doi.org/10.2478/s11756-006-0185-7

Kumar, B. M., Rajesh, G., & Sudheesh, K. G. (2006). Aboveground biomass production and nutrient uptake of thorny bamboo [*Bambusa bambos* (L.) Voss] in the homegardens of Thrissur, Kerala. *Journal of Tropical Agriculture, 43*, 51-56.

Kumar, R., Thangaraju, M. M., Kumar, M., Thul, S. T., Pandey, V. C., Yadav, S., & Kumar, S. (2021). Ecological restoration of coal fly ash–dumped area through bamboo plantation. *Environmental Science and Pollution Research, 28,* 33416-33432.
Https://doi.org/10.1007/s11356-021-12995-7

Kumar, P. S., Shukla, G., Nath, A. J., & Chakravarty, S. (2022). Soil properties, litter dynamics and biomass carbon storage in three-bamboo species of Sub-Himalayan region of Eastern India. *Water, Air, & Soil Pollution, 233(1)*, 12.
Https://doi.org/10.1007/s11270-021-05477-6

Kumari, Y., & Bhardwaj, D. R. (2017). Distribution of nutrition elements in different bamboos in bamboo based agroforestry plantation: A comparative study. *Journal of Pharmacognosy and Phytochemistry, 6(3)*, 556-561.

Kumari, Y., & Bhardwaj, D. R. (2019). Bioproduction and nutrient cycling in seven bamboo species in subtropical Indian Himalayas. *Journal of Tree Sciences, 38(2)*, 1-12.
http://dx.doi.org/10.5958/2455-7129.2019.00012.8

Lei, Z., Yu, D., Zhou, F., Zhang, Y., Yu, D., Zhou, Y., & Han, Y. (2019). Changes in soil organic carbon and its influencing factors in the growth of *Pinus sylvestris* var. mongolica plantation in Horqin Sandy Land, Northeast China. *Scientific Reports, 9(1),* 16453.
Https://doi.org/10.1038/s41598-019-52945-5

Li, C., Cai, Y., Xiao, L., Gao, X., Shi, Y., Zhou, Y., & Zhou, G. (2021). Rhizome extension characteristics, structure and carbon storage relationships with culms in a 10-year moso bamboo reforestation period. *Forest Ecology and Management, 498*, 119556.
Https://doi.org/10.1016/j.foreco.2021.119556

Liu, R., Yang, X., Gao, R., Hou, X., Huo, L., Huang, Z., & Cornelissen, J. H. (2021). Allometry rather than abiotic drivers explains biomass allocation among leaves, stems and roots of Artemisia across a large environmental gradient in China. *Journal of Ecology, 109(2)*, 1026-1040.
Https://doi.org/10.1111/1365-2745.13532

Lobovikov, M., Paudel, S., Ball, L., Piazza, M., Guardia, M., Wu, J., & Ren, H. (2007). *World bamboo resources: A thematic study prepared in the framework of the global forest resources assessment 2005 (No. 18)*. Food & Agriculture Organization.

Luo, X., Keenan, T. F., Chen, J. M., Croft, H., Colin Prentice, I., Smith, N. G., & Zhang, Y. (2021). Global variation in the fraction of leaf nitrogen allocated to photosynthesis*. Nature Communications, 12(1),* 4866.
Https://doi.org/10.1038/s41467-021-25163-9**.**

Mensah, S., Kakaï, R. G., & Seifert, T. (2016). Patterns of biomass allocation between foliage and woody structure: the effects of tree size and specific functional traits. *Annals of Forest Research, 59(1),* 49-60.
Https://doi.org/ 10.15287/afr.2016.458

Nawaz, M. F., Bourrie, G., & Trolard, F. (2013). Soil compaction impact and modelling. *A review. Agronomy for Sustainable Development, 33*, 291-309.
Https://doi.org/10.1007/s13593-011-0071-8

Noguchi, M., & Yoshida, T. (2005). Factors influencing the distribution of two co-occurring dwarf bamboo species (*Sasa kurilensis* and *S. senanensis*) in a conifer-broadleaved mixed stand in northern Hokkaido. *Ecological Research, 20*, 25-30.
Https://doi.org/10.1007/s11284-004-0009-6**.**

Oli, B. N., & Kandel, C. M. (2005). Biomass estimation of *Bambusa nutans* subspecies *cupulata* grown at Eastern Terai, Nepal. *Banko Janakari*, *15*(2), 34-37.
Https://doi.org/10.3126/banko.v15i2.349

Ovington, J. D. (1965). Organic production, turnover and mineral cycling in woodlands. *Biological Reviews, 40(3)*, 295-336.

Pandey, C. S. (2019). Influence of tree cropping systems on physical properties of salt affected soil. *International Journal of Current Microbiology and Applied Science, 8(4)*, 739-747.
Https://doi.org/10.20546/ijcmas.2019.804.080

Pattanaik, S., & Hall, J. B. (2014). Patterns of morphometric variability in *Dendrocalamus hamiltonii* Munro populations across East Khasi Hills, Northeast India. *Indian Forester, 140(9),* 868-874.

Patra, S., Kaushal, R., Singh, D., Kumar, R., Gadedjisso-Tossou, A., & Durai, J. (2022). Surface soil hydraulic conductivity and macro-pore characteristics as affected by four bamboo species in North-Western Himalaya, India. *Ecohydrology & Hydrobiology*, *22*(1), 188-196.
Https://doi.org/10.1016/j.ecohyd.2021.08.012

Puangchit, L., Hnin, S. M., & Sungkaew, S. (2019). Allometric equations for estimating the aboveground biomass of a 14-Year-old bamboo plantation at moeswe research station, Myanmar. *Journal of Tropical Forest Research*, *3(1)*, 1-19.

Qian, Z., Sun, X., Gao, J., & Zhuang, S. (2021). Effects of bamboo (*Phyllostachys praecox*) cultivation on soil nitrogen fractions and mineralization. *Forests*, 12(8), 1109.
Https://doi.org/10.3390/f12081109

Qiao, Y., Miao, S., Yue, S., Wu, H., & Han, X. (2016). How 23-year continuous soybean cultivation led to more SOC and thermal energy stored in Mollisol micro-aggregates. *Polish Journal of Environmental Studies*, *25*(3), 1215-1221.
Https://doi.org/10.15244/pjoes/61628

Robinson, D. A., Thomas, A., Reinsch, S., Lebron, I., Feeney, C. J., Maskell, L. C., & Cosby, B. J. (2022). Analytical modelling of soil porosity and bulk density across the soil organic matter and land-use continuum. *Scientific Reports, 12(1)*, 7085.
Https://doi.org/10.1038/s41598-022-11099-7

Seobi, T., Anderson, S. H., Udawatta, R. P., & Gantzer, C. J. (2005). Influence of grass and agroforestry buffer strips on soil hydraulic properties for an Albaqualf. *Soil Science Society of America Journal, 69(3)*, 893-901.
Https://doi.org/10.2136/sssaj2004.0280

Selassie, Y. G., & Ayanna, G. (2013). Effects of different land use systems on selected physico-chemical properties of soils in Northwestern Ethiopia. *Journal of Agricultural Science, 5(4)*, 112.
Https://doi.org/10.5539/jas.v5n4p112

Shanmughavel, P., & Francis, K. (2003). *Biomass accumulation and nutrient distribution in Dendrocalamus hamiltonii* [Conference presentation]. XII World Forestry Congress, Quebec, Canada.

Sharma, M. L., & Nirmala, C. (2015). *Bamboo diversity of India: An update* [Conference presentation]. 10th World Bamboo Congress, Seoul, South Korea.

Shiau, Y. J., Wang, H. C., Chen, T. H., Jien, S. H., Tian, G., & Chiu, C. Y. (2017). Improvement in the biochemical and chemical properties of badland soils by thorny bamboo. *Scientific Reports, 7(1)*, 40561. Https://doi.org/10.1038/srep40561.

Silva, L. N., Freer-Smith, P., & Madsen, P. (2019). Production, restoration, mitigation: a new generation of plantations. *New Forests, 50(2)*, 153-168. Https://doi.org/10.1007/s11056-018-9644-6

Singh, J., Sharma, R., Dhakad, A. K., & Chauhan, S. K. (2018). Defining growth, quality and biomass production of different bamboo species in central plains of Punjab. *Journal of Pharmacognosy and Phytochemistry, 7(5)*, 1328-1332.

Singh, K. A., & Kochhar, S. K. (2005). Effect of clump density/spacing on the productivity and nutrient uptake in *Bambusa pallida* and the changes in soil properties. *Journal of Bamboo Rattan, 4(4)*, 323-334.

Singh, A. N., & Singh, J. S. (2006). Experiments on ecological restoration of coal mine spoil using native trees in a dry tropical environment, India: A synthesis. *New Forests, 31*, 25-39. Https://doi.org/10.1007/s11056-004-6795-4

Singh, K. A., & Rai, A. K. (2012). Nutrient accumulation, distribution and use efficiency in different bamboo plant species in north-eastern hills region of India. *Indian Journal of Agricultural Sciences, 82(2),* 134.

Subbaiah, B. V., & Asija, G. L. (1956). A rapid method for estimation of available N in soil. *Current Science, 25,* 259-260.

Tian, G., Justicia, R., Coleman, D. C., & Carroll, C. R. (2007). Assessment of soil and plant carbon levels in two ecosystems (woody bamboo and pasture) in montane Ecuador. *Soil Science*, *172*(6), 459-468. Https://doi.org/10.1097/ss.0b013e31804fa21a

Trivedi, P., Leach, J. E., Tringe, S. G., Sa, T., & Singh, B. K. (2020). Plant-microbiome interactions: From community assembly to plant health. *Nature Reviews Microbiology, 18(11)*, 607-621. Https://doi.org/10.1038/s41579-020-0412-1

Tu, Z., Chen, L., Yu, X., & Zheng, Y. (2013). Effect of bamboo plantation on rhizosphere soil enzyme and microbial activities in coastal ecosystem. *Journal of Food, Agriculture and Environment, 2(3),* 2333-2338.

Udawatta, R. P., Kremer, R. J., Garrett, H. E., & Anderson, S. H. (2009). Soil enzyme activities and physical properties in a watershed managed under agroforestry and row-crop systems. *Agriculture, Ecosystems & Environment, 131(1-2)*, 98-104. Https://doi.org/10.1016/j.agee.2008.06.001

Walkley, A., & Black, I. A. (1934). An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Science, 37(1)*, 29-38.

Wang, Y., Qiao, G., Xu, J., Jin, K., Fan, M., Ding, Y., & Zhuo, R. (2022). Anatomical characteristics and variation mechanisms on the thick-walled and dwarfed culm of Shidu bamboo (*Phyllostachys nidularia* f. farcta). *Frontiers in Plant Science, 13*, 1-11. Https://doi.org/10.3389/fpls.2022.876658

Watanabe, F. S., & Olsen, S. R. (1965). Test of an ascorbic acid method for determining phosphorus in water and $NaHCO_3$ extracts from soil. *Soil Science Society of America Journal, 29(6),* 677-678.

Wu, J., Xu, Q., Jiang, P., & Cao, Z. (2009). Dynamics and distribution of nutrition elements in bamboos. *Journal of Plant Nutrition, 32(3)*, 489-501. Https://doi.org/10.1080/01904160802679958

Xie, J., Huang, X., Qi, J., Hse, C. Y., & Shupe, T. F. (2014). Effect of anatomical characteristics and chemical components on microwave-assisted liquefaction of bamboo wastes. *BioResources, 9(1),* 1-9.

Xue, L., Ren, H., Li, S., Leng, X., & Yao, X. (2017). Soil bacterial community structure and co-occurrence pattern during vegetation restoration in karst rocky desertification area. *Frontiers in Microbiology, 8,* 2377. Https://doi.org/10.3389/fmicb.2017.02377**.**

Zhan, H., Zhang, L. Y., Niu, Z. H., Wang, C. M., & Wang, S. G. (2016). Chemical properties and fiber morphology of *Dendrocalamus hamiltonii* as potential pulp material. *European Journal of Wood and Wood Products, 74*, 273-276. Https://doi.org/10.1007/s00107-015-0993-y

Zhang, Y. M., Yu, Y. L., & Ji, Y. W. (2013). Effect of thermal treatment on the physical and mechanical properties of *Phyllostachys pubescen* bamboo. *European Journal of Wood and Wood Products*, 71(1), 61-67. Https://doi.org/10.1007/s00107-012-0643-6**.**

Zhang, M. M., Fan, S. H., Guan, F. Y., Yan, X. R., & Yin, Z. X. (2020). Soil bacterial community structure of mixed bamboo and broad-leaved forest based on tree crown width ratio. *Scientific Reports*, 10(1), 6522. Https://doi.org/10.1038/s41598-020-63547-x

Zhao-Hua, L. I., Denich, M., & Borsch, T. (2005). Growth behavior of *Phyllostachys nigra* var. *henonis* (Bambusoideae) in Central China. *Journal of Forestry Research, 16*, 163-168. Https://doi.org/10.1007/BF02856808**.**

Zheng, Y., & Lin, X. (2020). Niche specialization and functional overlap of bamboo leaf and root microbiota. *Frontiers in Microbiology, 11*, 571159. Https://doi.org/10.3389/fmicb.2020.571159

Zhou, Z., & Shangguan, Z. (2007). Vertical distribution of fine roots in relation to soil factors in *Pinus tabulaeformis* Carr. forest of the Loess Plateau of China. *Plant and Soil, 291*, 119-129. Https://doi.org/10.1007/s11104-006-9179-z

BY SA