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Comparative study of carbon sequestration potential of various bamboo species in entisols of Sub-montane zone of Maharashtra

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Abstract
Bamboo with the vigorous growth and its ability to thrive in varied climatic conditions probably can replace woods in sequestering carbon. The various bamboo species evidently unrivaled the efficiency of bamboo to capture and store carbon. A field experiment on the carbon sequestration potential of various bamboo species was initiated at Zonal Agricultural Research Station, Kolhapur, Sub-montane Zone Maharashtra during 2022-23. The present investigation was initiated with an objective to evaluate the comparative carbon sequestration potential of different bamboo after 12 years of bamboo plantation. The experiment comprised of six bamboo species as treatment *viz. Bambusa tulda*, *Bambusa balcooa*, *Bambusa bambos*, *Dendrocalamus asper*, *Dendrocalamus strictus*, *Melocanna baccifera*. Each bamboo species was having four replicated plots i.e. four replications. The soil of experimental site was shallow and lighter type belonging to Entisols having moderate undulating topography with small ridges and valleys and steep slopes ranging from 5 to 6.5 percent.
The bamboo species *Dendrocalamus strictus* resulted significantly highest above ground biomass in all bamboo components such as culm biomass (89.48 t ha^{-1}), branches (27.90 t ha^{-1}) and leaves (1.34 t ha^{-1}) over respective bamboo components of all the other species. Similarly, the below ground biomass (32.05 t ha^{-1}) was also found to be significantly superior in *Dendrocalamus strictus*. In context of soil carbon density, the bamboo species *Dendrocalamus strictus* recorded highest though non-significant value of 21.13 t C ha^{-1}. In most of the total carbon stock contributing parameter the bamboo species *Bambusa tulda* stood next to *Dendrocalamus strictus*. The summation of total biomass carbon stock and soil carbon density put forth that the bamboo species *Dendrocalamus strictus* emerged as most efficient species of bamboo that can thrive well in the existing climatic condition and showed significantly highest total carbon stock to the tune of 90.90 t C ha^{-1} over all the other bamboo species followed by *Bambusa tulda*. It is therefore concluded that the species *Dendrocalamus strictus* is most potential bamboo species to sequester highest amount of atmospheric carbon as compared to all the other species grown in Sub-montane conditions of Maharashtra.

Keywords: Carbon sequestration, bamboo species, entisols, Sub-montane zone

1. Introduction
Climate change poses a major threat as it leads to an increase in the concentration of greenhouse gases, primarily carbon dioxide, in the atmosphere. According to the fifth assessment report of Inter-governmental Panel on Climate Change the elevated level of greenhouse gases causes the Earth's temperature to rise, if the current pace of greenhouse gas emissions persists, it's probable that global temperatures will rise by more than 4°C compared to pre-industrial levels by the year 2100 (IPCC 2013). Such an increase in temperature carries significant risks, including the widespread extinction of various species, global and regional food shortages, and limitations on typical human endeavors and resulting in various disruptions to the natural world. Therefore, it is imperative to take swift actions to remove carbon from the atmosphere. The method used for it is carbon sequestration. Carbon sequestration is the process of capturing and storing atmospheric carbon dioxide (CO_2) in different forms, such as biomass, soil, or underground reservoirs. Carbon sequestration can help mitigate the effects of climate change by reducing the amount of CO_2 in the atmosphere.

Trees function as the vital sinks for atmospheric carbon i.e. carbon dioxide, since 50 percent of their standing biomass is carbon itself. Importance of forested areas in carbon sequestration is already accepted, and well documented (Ravindranath *et al*., 1997) [3]. Among all the trees one of the potential sources of carbon sequestration is bamboo, a fast-growing and versatile plant that can store carbon in its culms, leaves, roots, and products. Bamboo plants can act as efficient carbon sinks, as they can absorb about 24.31 t CO_2/ha per year on average (Yiping *et al*., 2010) [1]. Bamboo can also reduce carbon emissions by displacing the use of wood and fossil fuels for various purposes, such as construction, furniture, energy, and paper. Bamboo products can have a long lifespan and retain the carbon sequestered by the plant (Suhaily *et al*., 2013) [2]. However, the carbon sequestration potential of bamboo may vary depending on the species, soil type, climate, and management practices so the furthermore in this study, we aim to compare the carbon sequestration potential by different bamboo species in entisols of sub-montane zone of Maharashtra.

2. Material and Methods

2.1 Experimental site and location

The Sub-montane zone of Maharashtra is characterized by shallow and lighter type soil mostly belonging to Entisols having moderate undulating topography with small ridges and valleys and steep slopes ranging from 5.0 to 6.5%. A long-term experiment on different bamboo species was addressed to control soil erosion due to small and medium gullies. However, several researchers reported that the bamboo plantation has the potential to sequester huge amounts of atmospheric carbon by virtue of its biomass. In order to evaluate the carbon sequestration of different bamboo species having varied physiological characteristics, a study was initiated to evaluate the carbon sequestration potential of an existing bamboo plantation having six different species after 12 years of plantation. The present investigation was done on Carbon Sequestration Potential of Various Bamboo Species in Entisols of Sub-montane Zone of Maharashtra which was initiated at the Zonal Agricultural Research Station Farm, Shenda Park, Kolhapur, Maharashtra.

2.2 Climate

The agro-climatic region to which the study area of belongs is the Sub-montane Zone of Maharashtra. Geographically, Kolhapur is situated at an elevation of 605 meters above mean sea level on 160 42’ 17.24” N North latitude and 740 14’ 10.74” East longitudes. The average annual rainfall of Kolhapur is 1019.5 mm. Out of the total annual precipitation, 75 percent gets received during the period from June to September from the South-West monsoon, while the remaining quantity (25%) is received mostly in the month of October and November from the North-East monsoon. The annual average maximum and minimum temperature ranged between 35-28 °C respectively. Precipitation is the lowest in February, most precipitation falls in July. The average temperatures vary during the year by 5.7 °C. The climate of the study area is semi-arid tropical and characterized by hot summer (March to May) and dryness in other months except in rainy months (June to September).

2.2.1 Experimental details

A field experiment focuses on carbon sequestration of different bamboo species planted in September 2010, featuring six distinct bamboo species: *Bambusa tulda*, *Bambusa balcooa*, *Bambusa bambos*, *Dendrocalamus asper*, *Dendrocalamus strictus*, and *Melocanna baccifera* was started after 12 years of plantation. The experimental layout followed a Randomized Block Design (RBD), with each treatment replicated four times. The chosen field exhibited a slope ranging from 5.0 to 6.5%, and a standardized planting distance of 5.0 × 5.0 m was employed.

The methodology for estimating bamboo biomass involved several key steps. First, a representative clump was selected from each replication, and culms were identified and felled. The culms were then dissected into leaves, branches, and stem components. The total fresh weight (TFW) of each component was recorded using an electronic weighing balance. Subsamples were collected, transported to the laboratory, and dried in an electric oven at 80 °C for 72 hours until constant weight was achieved, allowing for the determination of dry matter.

2.2.2 Estimation of Bamboo Biomass

2.2.2.1 Estimation of aboveground biomass

The average dry weight (ADW) of each above-ground culm component was calculated using the formula:

$$\text{ADW (kg culm}^{-1}) = \frac{\text{TFW (kg)} \times \text{SDW (kg)}}{\text{SFW (kg)}}$$

TFW = Total fresh weight; SDW = Subsample dry weight; SFW = Subsample dry weight

The standing biomass (SB) for leaves, branches, and stem was calculated by multiplying the number of culms per clump by the average dry weight of each component. The above-ground biomass per clump (AGBPC) was then calculated by summing the standing biomass of each above-ground component, and the above-ground biomass per hectare (AGBPH) was obtained by multiplying the above-ground biomass per clump by the number of clumps per hectare (400) and dividing by 1000:

$$\text{AGBPH (t ha}^{-1}) = \frac{\text{AGBPC} \times 400}{1000}$$

For belowground biomass estimation, the root biomass per culm (BGBPC) was calculated using a non-destructive method:

$$\text{BGBPC (t ha}^{-1}) = \text{AGBPC} \times 0.27$$

Total biomass per clump (TBPC) and total biomass per hectare (TBPH) were calculated by summing the biomass of above and below-ground clump components, including stem, branches, leaves, and roots.

To estimate total biomass carbon storage, the carbon content in aboveground biomass was calculated using the formula.

$$\text{TCAGB (t C ha}^{-1}) = \frac{\text{TSB} \times \text{\% stem C}}{100} + \frac{\text{TLB} \times \text{\% Leaf C}}{100}$$

TCAGB = Total carbon in above-ground bamboo biomass
TSB = Total stem biomass
TLB = Total leaves biomass

The total carbon content in below-ground bamboo biomass (t C ha⁻¹) was estimated using the formula

$$TCBGB = \frac{TRB \times \%\ root\ C}{100}$$

TCBGB = Total carbon in below-ground bamboo biomass
TRB = Total root biomass

The total biomass carbon stock (TBCS) was then calculated by summing the total carbon content in above and below-ground biomass.

$$TBCS\ (t\ C\ ha^{-1}) = TCAGB\ (t\ C\ ha^{-1}) + TCBGB\ (t\ C\ ha^{-1})$$

TCAGB = Total carbon in above-ground bamboo biomass
TCBGB = Total carbon in below-ground bamboo biomass

For mean soil organic carbon density, the weight of soil (Mg) was calculated using the formula:

Weight of soil (Mg) = Bulk density × Volume of 1 hectare

The carbon density (t C ha^{-1}) was calculated using the formula.

Carbon density (t C ha^{-1}) = Weight of soil × % SOC

Table 1: Total Biomass as Influenced by Different Bamboo Species

Tr. No.	Treatment/ Bamboo species	Bamboo biomass components				Total Biomass
		Above Ground Biomass			Below Ground Biomass	
		Culm	Branches	leaves	Roots	
		-----------------------------t ha^{-1}-------------------------------				
T_1	*B. tulda*	64.73	21.46	1.28	23.27	110.74
T_2	*B. balcooa*	42.00	13.89	0.86	15.32	72.08
T_3	*B. bambos*	24.18	6.29	0.89	8.47	39.82
T_4	*D. asper*	13.83	4.75	0.46	5.14	24.19
T_5	*D. strictus*	89.48	27.90	1.34	32.05	150.77
T_6	*M. baccifera*	11.90	1.47	0.21	3.67	17.25
	General mean	41.02	0.66	0.84	14.65	69.14
	SEm ±	2.14	1.99	0.07	0.77	3.61
	CD at 5%	6.46	1.99	0.22	2.31	10.88

Where, SOC is the soil organic carbon

The mean soil carbon density was then calculated by averaging values from two depths (0-15 cm and 15-30 cm). Finally, the total carbon stock in different bamboo species was estimated by adding the total biomass carbon stock (TBCS) and mean soil carbon density. The total carbon storage (t C ha⁻¹) was calculated by the formula:

Total carbon storage = TBCS + Mean soil carbon

2.2.3 Statistical Analysis

The data obtained from our experiment underwent thorough statistical analysis using the "Analysis of variance" (ANOVA) technique. This method, as outlined by Panse and Sukhatme (1985) [4], involved the construction of an ANOVA table. This statistical approach was crucial for examining the variations in the experimental data and drawing meaningful conclusions from the results.

3. Results and Discussion

3.1 Total Biomass as Influenced by Different Bamboo Species

In this study, the AGB of each bamboo species was analyzed, considering culm, branches, leaves, and root biomass. The results, detailed in Table 1, indicate significant variations in component biomass among different bamboo species.

3.1.1 Above-ground Biomass (AGB)

The component-wise AGB, presented in Table 1, highlights that *Dendrocalamus strictus* exhibited the highest biomass for culms (89.48 t ha⁻¹), branches (27.90 t ha⁻¹), and leaves (1.34 t ha⁻¹). *Bambusa tulda* recorded the second-highest component-wise biomass (64.73 t ha⁻¹ culm, 21.46 t ha⁻¹ branches, and 1.28 t ha⁻¹ leaves), while *Melocanna baccifera* displayed the lowest AGB values (11.90 t ha⁻¹ culm, 1.47 t ha⁻¹ branches, and 0.21 t ha⁻¹ leaves).

3.1.2 Below-ground Biomass (BGB)

The BGB, representing root biomass, mirrored the AGB trends and represented in table 1. *D. strictus* had the highest BGB (32.05 t ha⁻¹), followed by *B. tulda* (23.27 t ha⁻¹), and *M. baccifera* exhibited the lowest BGB (3.67 t ha⁻¹).

3.1.3 Total Biomass

Combining AGB and BGB resulted in a similar pattern, as shown in Table 1. *D. strictus* recorded the highest total biomass at 150.77 t ha⁻¹, followed by *B. tulda* at 110.74 t ha⁻¹, while *M. baccifera* had the lowest total biomass at 17.25 t ha⁻¹.

The observed biomass accumulation variations can be attributed to factors such as genetic characteristics, plant age, soil conditions, climate, and topography. *D. strictus*, in particular, emerged as a prominent species in the Entisols of the Sub-montane Zone (SBZ) of Maharashtra, displaying the highest AGB, BGB, and overall total biomass (Reddy *et al.*, 2022; Singh *et al.*, 2002) [5, 6]. The higher AGB and BGB in *D. Strictus* could be attributed to better adaptability and suitable genetic makeup of this particular species for the climatic conditions and soil type of SBZ. Similarly, Nath *et al.* (2015) [7] reported the AGB and BGB of *D. strictus* were significantly higher than those of *B. tulda* and *M. baccifera* in a subtropical forest of Northeast India. The findings were also comparable with study of Singh *et al.* (2002) [6] in which they found that AGB, BGB and total biomass of *D. strictus* were higher than those of *B. balcooa* and *D. asper*. The results are also in line with the findings of Ji *et al.* (2020) [8] who reported higher AGB and BGB in 7 year old *D. strictus*. The outcomes of highest AGB and BGB in *D. strictus* were also analogous to the results of Kumar *et al*. (2023) [9]; Dhruba and Jyothi (2020) [17]; Tariyal *et al*. (2013) [12]; Pathak *et al*. (2015) [13]; Devi *et al*. (2013) [14].

3.2 Total Carbon Content, Soil Carbon Density and Total Carbon Stock as Influenced by Different Bamboo Species

The variations in plant biomass carbon stock among different bamboo species result from diverse factors such as growth rates, stem characteristics, root systems, leaf properties, climate, topography, and environmental conditions. The data, presented in Table 4 and illustrated in Figure 1, depict distinct levels of carbon storage within various bamboo species.

3.2.1 Carbon Content in Bamboo Components

Analyzing carbon concentration in various bamboo components which is presented in table 2, *Bambusa balcooa* exhibited higher concentrations in culms (46.70%), branches (46.23%), and leaves (44.08%). On the other hand, *Bambusa tulda* demonstrated lower concentrations in culms (48.29%), branches (48.09%), and leaves (44.47%). In terms of root carbon concentration, *Melocanna baccifera* had higher values (44.45%), while *Dendrocalamus asper* displayed the lowest (41.88%).These variations can be attributed to factors like genetic characteristics, soil conditions, and environmental influences on bamboo growth. The overall mean carbon concentrations were 47.28% for culms, 47.04% for branches, 44.18% for leaves, and 43.38% for roots. The significance of culms in carbon content aligns with findings by researchers such as Reddy *et al*. (2022) [5] and Devi *et al*. (2018) [15]. The study is similar to Reddy *et al*. (2022) [5], revealed non-significant differences in carbon content among bamboo species, reflecting uniform environmental and climatic conditions. The overall carbon content in bamboo stalks, estimated at 45%, was consistent with Aarthi *et al*. (2021) [18] and supported the order of carbon content in bamboo components: culm > branches > leaves > roots. This sequence is in line with studies by Baruah *et al*. (2020) [10], Nath *et al*. (2009) [16], and Devi *et al*. (2018) [15], further emphasizing the significance of culms in carbon storage.

Table 2: Carbon content in different bamboo components

Tr. No.	Treatment/ Bamboospecies	Carbon content in bamboo components			
		AGB			BGB
		Culm	Branches	leaves	Roots
		(%)			
T_1	*B. tulda*	46.70	46.23	44.08	44.13
T_2	*B. balcooa*	48.29	48.09	44.47	43.17
T_3	*B. bambos*	47.60	47.40	43.85	43.98
T_4	*D. asper*	46.93	46.73	44.40	41.88
T_5	*D. strictus*	47.38	47.20	44.18	42.68
T_6	*M. baccifera*	46.78	46.60	44.11	44.45
	General mean	47.28	47.04	44.18	43.38
	S.Em ±	0.46	0.48	0.39	0.65
	CD at 5%	NS	NS	NS	NS

3.2.2 Above and Below Ground Biomass Carbon Stock

Total biomass carbon stock (TBCS) combines above ground biomass carbon stock (AGBCS) and below ground biomass carbon stock (BGBCS). *Dendrocalamus strictus* showed significantly higher values in AGBCS components, with culm, branches, and leaves at 42.34, 13.15, and 0.59 t C ha^{-1} respectively. In comparison, *Melocanna baccifera* displayed the lowest values at 5.57, 0.69, and 0.09 t Cha^{-1} for culm, branches, and leaves. For BGBCS, *D. strictus* had the highest root carbon stock at 13.68 t C ha^{-1}, followed by *Bambusa tulda* at 10.27 t C ha^{-1}, while *Melocanna baccifera* recorded the lowest at 1.62 t C ha^{-1}. The overall TBCS pattern followed the same trend, with *D. strictus* recording the highest value at 69.77 t C ha^{-1}, followed by *B. tulda* at 50.98 t C ha^{-1}, and *M. baccifera* at 7.97 t C ha^{-1}.

3.2.3 Soil Organic Carbon Density

Assessing soil carbon potential, the study considered soil organic carbon (SOC) density at 0-15 cm and 15-30 cm depths. Although non-significant, *D. strictus* displayed the highest SOC density at both depths (23.57 and 18.69 t C ha^{-1}), followed by *D. asper*. The mean SOC density (0-30 cm) was highest in *D. strictus* (21.13 t C ha^{-1}), followed by *D. asper*.

Table 3: Soil carbon density as influenced by different bamboo species

Tr. No.	Treatment/ Bamboo species	SOC density		Mean SOC density
		0-15 cm	15-30 cm	0-30 cm
		(t C ha^{-1})		
T_1	*B. tulda*	21.68	16.10	18.89
T_2	*B. balcooa*	21.97	16.34	19.16
T_3	*B. bambos*	22.73	17.35	20.04
T_4	*D. asper*	23.19	17.65	20.42
T_5	*D. strictus*	23.57	18.69	21.13
T_6	*M. baccifera*	22.90	16.70	19.80
	General mean	22.67	17.14	19.91
	SEm ±	0.80	0.78	0.72
	CD at 5%	NS	NS	NS

3.2.4 Total Carbon Stock: The total carbon stock, combining TBCS and SOC density which is represented in table 5 and graphically in figure 2, highlighted *D. strictus* as the most efficient species, with a significant highest total carbon stock (TCS) of 90.90 t C ha^{-1}. *B. tulda* ranked second with 69.87 t C ha^{-1}, while *M. baccifera* recorded the least at 27.77 t C ha^{-1}.

These findings emphasize *D. strictus* potential for total carbon sequestration, influenced by species characteristics, age, soil properties, and climate (Reddy *et al*., 2022) [5]. who reported highest biomass carbon stock in 7 years old *D. strictus*. The outcomes of highest AGBCS and BGBCS in *D. strictus* were also analogous to the results of Kumar *et al*., (2023) [9]; Dhruba and Jyothi (2020) [17]; Pathak *et al*., (2015) [13]; Devi *et al*., (2013) [14]. The highest amount of AGBCS and BGBCS was observed by the Tariyal *et al*. (2013) [12] in which *D. strictus* had the highest carbon stock than the *B. balcooa*. The research results were additionally in similar with Nath *et al*. (2015) [7] who reported that the AGBCS and BGBCS of *D. strictus* were significantly higher than those of *B. tulda* and *M. baccifera* in a subtropical forest of Northeast India.

Table 4: Carbon stock in different component, above ground biomass carbon stock, below ground biomass carbon stock and total biomass carbon stock in different bamboo species

Tr. No.	Treatment/Bamboo species/species	Culm-CS	Branches -CS	Leaves-CS	AGBCS	BGBCS	TBCS
		---(t C ha^{-1})---					
T_1	B. tulda	30.23	9.92	0.56	40.71	10.27	50.98
T_2	B. balcooa	20.28	6.68	0.38	27.34	6.61	33.95
T_3	B. bambos	11.51	2.98	0.39	14.88	3.72	18.60
T_4	D. asper	6.49	2.22	0.21	8.92	2.16	11.08
T_5	D. strictus	42.34	13.15	0.59	56.08	13.68	69.77
T_6	M. baccifera	5.57	0.69	0.09	6.35	1.62	7.97
	General mean	19.40	5.94	0.37	25.71	6.34	32.06
	SEm +	0.94	0.30	0.03	1.25	0.34	1.56
	CD at 5%	2.85	0.90	0.10	3.77	1.03	4.71

The findings were also be comparable with study of Tariyal *et al*. (2013) [12] in which he found that AGBCS, BGBCS and total biomass of *D. strictus* were higher than those of *B. balcooa* and *D. asper*.

Table 5: Soil carbon density as influenced by different bamboo species

Tr. No.	Treatment/Bamboo species	TBSC	SOC density	Total C Stock	Total CO_2 Equivalent
		---(t C ha^{-1})---			
T_1	*B. tulda*	50.98	18.89	69.87	256.42
T_2	*B. balcooa*	33.95	19.16	53.11	194.91
T_3	*B. bambos*	18.60	20.04	38.64	141.81
T_4	*D. asper*	11.08	20.42	31.50	115.61
T_5	*D. strictus*	69.77	21.13	90.90	333.59
T_6	*M. baccifera*	7.97	19.80	27.77	101.93
	General mean	32.06	19.91	51.97	190.71
	SEm +	1.56	0.72	1.63	5.98
	CD at 5%	4.71	NS	4.91	18.01

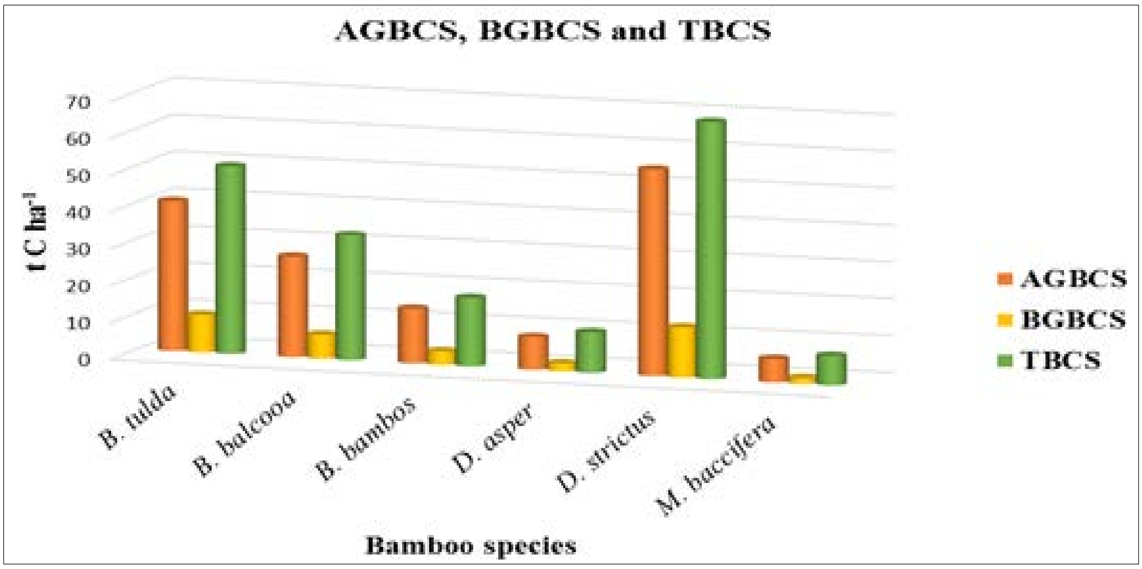

Fig 1: AGBCS, BGBCS and TBCS as influenced by different bamboo species

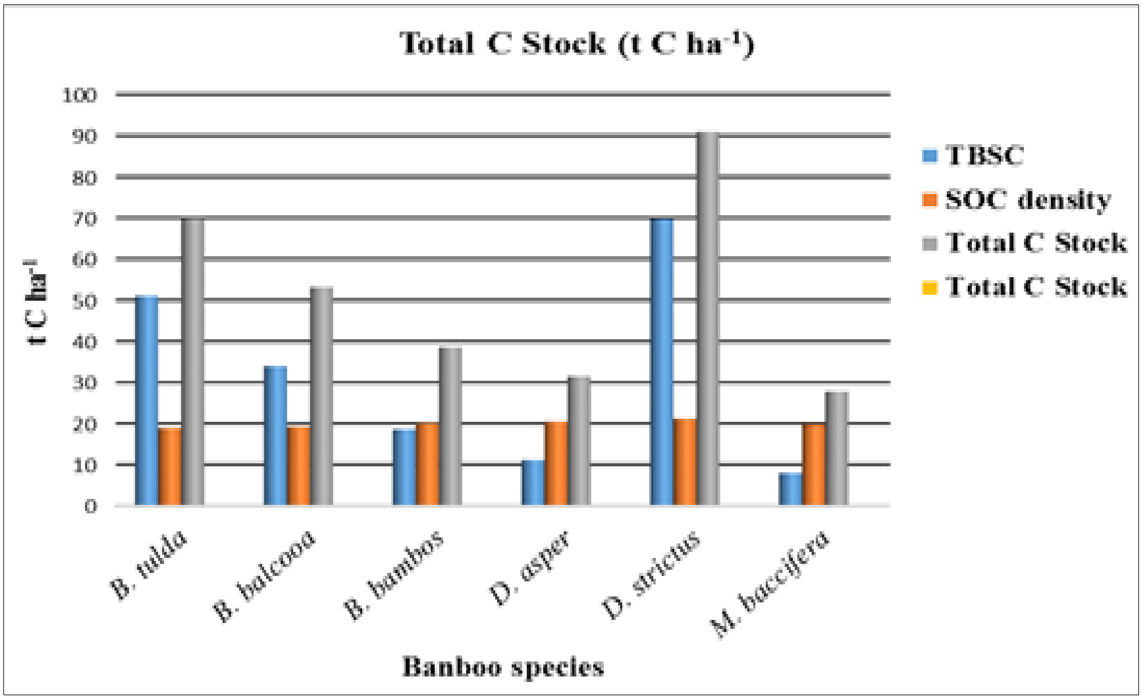

Fig 2: Total C Stock as influenced by different bamboo species

4. Conclusion

The bamboo species D. strictus not only registered maximum carbon storage in above ground (culm, branches and leaves) and below ground (roots) bamboo components but it also exhibited highest soil organic carbon (SOC) density as compared to rest of bamboo species. Nevertheless, the bamboo species, B. tulda recorded the second highest values among the various species in terms of total biomass carbon stock (TBSC) and SOC density. The summation of TBSC and SOC density further gave clear insight to evaluate the carbon sequestration potential of different bamboo species. Hence, it is concluded that thebamboo species D. strictus thrives efficiently in the climatic condition of Sub-montane Zone and emerged as the most potential bamboo species in terms of carbon sequestration after 12 year of bamboo plantation in the Entisols of Sub-montane Zone of Maharashtra.

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