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Allometric Model for Estimating Above-ground Biomass and Carbon Stock of *Bambusa vulgaris* var. *striata*

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Abstract

Bamboo, one of the non-timber forest products, is promising in climate change mitigation strategy due to its ability to remove CO_2 from the atmosphere through photosynthesis. However, the allometric model to estimate the biomass and carbon of bamboo is still limited. The research aimed to develop the allometric model using the diameter as the predictor. The materials for destructive sampling were 30 culms of yellow ampel bamboo (Bambusa vulgaris var. striata). A power model was used to analyze data in order to develop an allometric model. Furthermore, data validation was used to leave-one out cross-validation (LOOCV), and assessing the difference between predicted and observed values used a t-test. The results showed that bamboo biomass was allocated in culms, branches, and leaves at 48.14, 27.66, and 24.20%, respectively. Moreover, the percentage carbon content of culms, branches, and leaves was 55.64%, 50.67%, and 48.48%, respectively. The best allometric model to estimate total biomass was lnWD = -1.846 + 2.218 lnD and to estimate carbon stock was lnC = -2.504 + 2.225 lnD. In conclusion, the diameter at 60 cm from the base (D_{60}) was the best predictor, and adding the predictor length of culm did not improve the allometric model significantly. Moreover, the predictor $D_0 – D_{bh}$ (1.3 m) did not differ significantly in estimating above-ground biomass and carbon stock. Furthermore, for practical purposes, the D_{bh} is recommended for use in measuring bamboo diameter in the field.

Keywords: *carbon accounting, climate change mitigation, yellow bamboo, non-timber forest product*

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Introduction

Climate change issues have attracted the attention of stakeholders and researchers worldwide. In 2021, the outcome of the 26th Climate Change Conference in Glasgow, United Kingdom, was that the parties agreed to take collective actions and partnerships to cut greenhouse gas emissions (GHG). One promising strategy to remove GHG from the atmosphere is increasing the number of timber and non-timber plants to absorb the CO_2 for their photosynthesis process.

Bamboo is one of the promising non-timber plants that can contribute to removing CO_2 from the atmosphere. Yuen et al. (2017) estimated that the total ecosystem carbon from 70 bamboo species was 94–392 MgC ha^{-1}, and the worldwide bamboo forest cover was 31.5 million ha. Moreover, bamboo also plays a vital role in regulating water, improving soil properties, and providing livelihood products (Huy et al., 2019). However, the distribution of native bamboo is limited to Asia, America, and Africa (Ahmad et al., 2021). Moreover, based on the author's knowledge, the research articles on bamboo allometry that were indexed by the Scopus database have only been carried out in Cameroon (Kaam et al., 2024), China (Gao et al., 2016), Colombia (Camargo García et al., 2023), Ethiopia (Yebeyen et al., 2022), Ghana (Amoah et al., 2020), India (Kaushal et al., 2022), Indonesia (Prayogo et al., 2021), Japan (Inoue et al., 2019), Laos (Xayalath et al., 2019), Mexico (Ordóñez-Prado et al., 2024), Taiwan (Li et al., 2024), and Vietnam (Huy et al., 2019).

Moreover, the allometric models for bamboo have been developed for specific and mixed species. For instance, the allometric model of *Oxytenanthera abyssinica* (Ethiopian lowland bamboo) and *Oldenania alpina* (highland bamboo) in Ethiopia (Gurmessa et al., 2016; Yebeyen et al., 2022), *Bambusa procera* in tropical forest of Viet Nam (Huy et al., 2019), *Chimonobambusa quadrangularis* in Japan (Inoue et al., 2019), *B. vulgaris* in Ghana (Amoah et al., 2020), and *B. vulgaris* in Cameroon (Kaam et al., 2023). Furthermore, allometric models for mixed bamboo species also have been developed for thorny bamboo (*B. stenostachya*), makino bamboo (*Phyllostachys makinoi*), moso bamboo (*P. pubescens*), and ma bamboo (*Dendrocalamus latiflorus*) in Taiwan (Li et al., 2016; 2024), and seven bamboo species (*B. balcoa, B. bambos, B. vulgaris, B. nutans, Dendrocalamus hamiltonii, D. stocksii,* and *D. strictus*) in India (Kaushal et al., 2022). Not only is there an allometric of biomass, but the linear and non-linear regression also has been applied to

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estimate the leaf area of *B. vulgaris* using the predictors' height, diameter at breast height, length of leaf, and width of leaf (Montelatto et al., 2021).

Allometric models to estimate wood biomass have mainly used predictors for diameter and height. Additionally, much research on bamboo biomass has used predictors of diameter at breast height (Zhang et al., 2014; Li et al., 2016; Huy et al., 2019). However, the bamboo allometric model has been developed in some cases with multi-predictor diameter and height (Singnar et al., 2021; Ordóñez-Prado et al., 2024). Based on the authors' knowledge, the diameter at breast height is not suitable for developing an allometric model for all species. For instance, the multi-stem species, such as willow and gliricidia, have used a diameter of 30 cm from the base (D_{30}) as the predictor on the allometric model to estimate biomass and carbon stock (Mulyana et al. 2020). Thus, the use of diameter at breast height (*Dbh*) depends on the characteristics of species that will be developed in the allometric model.

Morphologically, bamboo culms have different characteristics than trees with single or multi-stem culms. Commonly, bamboo in the Indonesia region has wood and hollow culm (Damayanti et al., 2019; Widjaja et al., 2020). Furthermore, Clark et al. (2015) explained that bamboo culms (stems) are usually hollow and segmented, whereas tree stems are solid and not segmented. The research aimed to elaborate on the predictor that can accurately predict biomass and carbon.

Methods

The research site was conducted in the private forest at five villages in the sub-district (*Kapanewon*) Pakem, Sleman District, Special Region Province of Yogyakarta, Indonesia. Geographically, Sleman District was located at E110°13′00″–E110°33′00″ and S7°34′51″–S7°47′03″. According to Badan Pusat Statistik Kabupaten Sleman (2021), Sleman District is divided into five villages, namely Hargobinangun, Purwobinangun, Candibinangun, Harjobinangun, and Pakembinangun. The altitude of *Kapanewon* Pakem is 500–1,000 m asl, with an average temperature, precipitation, and humidity of 21.6 °C, 246.33 mm month^{-1}, and 82.75%, respectively. The Sleman District government has designated bamboo as a superior non-timber forest product by issuing Sleman Major Decree Number 306/Kep.KDH/A/2013 on bamboo as a priority non-timber forest product for Sleman District and Number 59.1/Kep/KDH/A/2021 on bamboo as a priority products for Sleman District.

Primary data on bamboo dimensions (diameter, culm thickness, total length of culm, and fresh-cut weight) were collected using destructive sampling. Referring to Li et al. (2016), we harvested 30 yellow bamboo culms and weighed the biomass of culm, branches, and leaves. The bamboo's biomass, diameter, and length are measured in detail by cutting the bamboo culms based on their internodes (Mulyana & Reorita, 2022a; 2022b). Especially for the culm, we also measured the diameter of the culm at 0, 30, 60, 90, and 130 cm from the base (Figure 1). The biomass of fallen culms was separated into three groups: stems, branches, and leaves. Generally, the research on bamboo biomass has grouped above-ground biomass into culms, branches, and leaves (Yuen et al., 2017).

The data-collecting stages were bamboo inventory, getting permission from the bamboo owner, and destructive sampling. Bamboo inventory was conducted to collect initial data at the location of *B. vulgaris* var. *striata* at five villages in *Kapanewon* Pakem, Sleman Regency, Yogyakarta. After getting permission, selected bamboo was cut down and measured at the diameter of 0, 30, 60, 90, and 130 cm (*Dbh*). Due to the morphology, the bamboo shows an arch pattern on the top side; the bamboo culm has been cut into internodes. The total culm length was the summation of internode one until internode *n* (Figure 1) as shown in Equation *[1]*.

$$L = \sum_{i=1}^{n} L_i \qquad [1]$$

note: L is the total length of the culm (m), L_i is the length of the culm at section i (m), and n is the number of sections.

Small sample sizes (n<30) to develop an allometric model have been conducted in research on predicting above-ground biomass and carbon. For instance, Inoue et al. (2019) used 20 samples of square bamboo (*C. quadrangularis*) in Japan, and Stas et al. (2017) used 25 samples to develop a local allometric model for the old secondary forest on limestone in Indonesia.

Detailed measurement of percent carbon content (PCC) for bamboo is vital in estimating carbon stock (Zhang et al., 2014). Each bamboo sample was divided into three sub-samples (leaves, branches, and stem). Specifically for bamboo culm, samples were collected from the bottom, middle, and top of the culm to represent the entire bamboo culm. Furthermore, the samples (leaves, branches, and stem) were taken to the laboratory at the Department of Forest Product Technology, Faculty of Forestry, Universitas Gadjah Mada for the drying process. The dried weight of the culms, branches, and leaves was analyzed in the Soil laboratory, Faculty of Agriculture, Universitas Gadjah Mada, Indonesia, to determine the percentage carbon content.

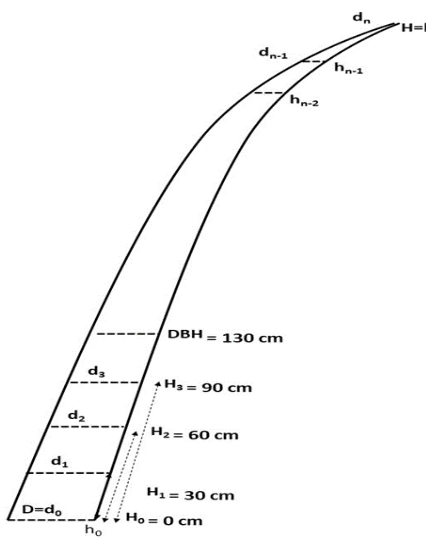

Figure 1 Illustration for measuring the diameter and total length of bamboo culm.

The statistical analysis was performed using R software at a significant level of 5%. The descriptive analysis was applied to describe the characteristics of data, including minimum, maximum, mean, and standard deviation. In this study, the allometric models were developed by regression analysis. According to Inoue et al. (2019), Huy et al. (2019), and Xayalath et al. (2019), the allometric models to estimate the above-ground biomass of bamboo are as shown in Equations *[2]* to *[4]*.

$$Y = \beta_0 D^{\beta_1} \quad [2]$$

$$Y = \beta_0 L^{\beta_1} \quad [3]$$

$$Y = \beta_0 (D^2 L)^{\beta_1} \quad [4]$$

note: Y is dried weight biomass or carbon (kg), D is the diameter (cm), L is the length of the culm (m), and β_0 and β_1 are intercepts.

The development of an allometric model using non-linear regression causes heteroscedasticity (Altanzagas et al., 2019). Furthermore, avoiding the heteroscedasticity from the development of an allometric model using non-linear regression, in this study we followed Sadono et al. (2021; 2022) by using natural log-transformation to convert non-linear regression into linear regression. The linear regression models for the Equations *[2]* to *[4]* are shown in Equations *[5]* to *[7]*

$$\ln Y = \ln a + b \ln D \quad [5]$$

$$\ln Y = \ln a + b \ln L \quad [6]$$

$$\ln Y = \ln a + b \ln (D^2 L) \quad [7]$$

note: $\ln Y$ was the predicted value of above-ground biomass or carbon stock in the logarithmic unit, a and b were the fitted parameters. In addition, the correction factor (CF) is needed to correct the systematic bias from the antilog transformation. The equation of CF is as shown in Equation *[8]*.

$$CF = \exp\left(\frac{RMSE^2}{2}\right) \quad [8]$$

note: *CF* is the correction factor, *RMSE* is the root means square error from each allometric model.

Leave-one-out cross-validation (LOOCV) was applied to validate the allometric equations. The LOOCV has been practiced in validating the allometric model by Wirabuana et al. (2021; 2024) in Indonesia and Altanzagas et al. (2019) in Mongolia. The best model was chosen based on the highest value of adjusted coefficient determination (R^2_{adj}) and the lowest values of root mean square error (*RMSE*), mean absolute bias (*MAB*), and Akaike information criterion (*AIC*).

A comparative analysis was conducted on the performance of the best bamboo allometric model, which was then evaluated in relation to existing bamboo allometric models. At the level of individual bamboo culm, the model's bias and coefficient of variation in aboveground biomass on harvested bamboo culms are examined (Chave et al. 2014; Stas et al. 2017). Additionally, Stas et al. (2017) explain that bias was defined as the deviation between predicted (allometric model) and observed value of the felled bamboo, expressed as a percentage of the observed value aboveground biomass. Moreover, in comparative analysis, low bias and coefficient of variance are considered (Stas et al. 2017). According to Chave et al. (2014), the formulas for calculating bias and coefficient of variance are as shown in Equations *[9]* to *[12]*.

$$Bias\ (j) = \frac{[B_{est}(j) - B_{obs}(j)]}{B_{obs}(j)} \quad [9]$$

$$RSE(j) = \sqrt{\frac{1}{N_j\,p} \sum_{i\epsilon lj} [AGB_{est}(i,j) - AGB_{obs}(i,j)]^2} \quad [10]$$

$$MAGB(j) = \frac{1}{N_j} \sum_{i\epsilon lj} AGB_{obs}(i,j) \quad [11]$$

$$CV(j) = \frac{RSE(j)}{MAGB(j)} \quad [12]$$

note: $B_{est}(j)$ is the estimated value of aboveground biomass bamboo-*j*, $B_{obs}(j)$ is the observed value of aboveground biomass bamboo-*j*, *RSE* is the residual standard error of aboveground biomass of bamboo, *MAGB* is the mean aboveground biomass of bamboo, and *CV* is the coefficient of variance.

Results

The diameter, culm length, and fresh-weight biomass of fallen bamboo culm were varied. The diameter of 30 samples ranged from 2.50 to 8.77 cm, and the culm length was 3.10–11.90 m (Table 1). Referring to the Indonesia bamboo map and toolkit bamboo identification, the diameter of bamboo *B. vulgaris* ranged from 5 cm to 10 cm (Damayanti et al. 2019; Widjaja et al. 2020). The culm diameter generally decreases from D_0 until D_{bh} and reaches zero value at the top of the culm (Figure 1). While the culm length varies among the diameters, some culms with big diameters have a short culm length. In contrast, the small culm diameter shows a longer culm length.

The research was conducted during the rainy season (March–April 2021), when leaves sprouted. The above-ground biomass allocation of yellow *ampel* bamboo was mainly distributed in culms, followed by branches and leaves (Figure 2). Bamboo grew very well in the rainy season because the temperature, water availability, and nutrient status favored the growth (Yuen et al., 2017). Whereas the biomass allocation on *B. vulgaris* from Ghana was leaf, branches, and stem were 1.82% (0.557 kg culm^{-1}), 4.67% (1.430 kg culm^{-1}), and 93.51% (28.643 kg culm^{-1}), respectively (Amoah et al., 2020).

Table 1 Statistic summary of *Bambusa vulgaris* var. *striata* samples

Value	Diameter (cm)					Length	Dry-weight biomass (kg culm^{-1})		
	D_0	D_{30}	D_{60}	D_{90}	Dbh	(m)	Leave	Branches	Stem
Min	2.50	2.42	2.7	2.7	2.74	3.10	0.16	0.16	0.48
Max	8.50	8.77	8.31	8.05	8.15	11.90	3.52	3.74	7.81
Mean	5.51	5.44	5.39	5.32	5.31	7.37	1.80	2.06	3.57
SD	1.72	1.69	1.57	1.51	1.55	2.63	0.96	1.08	2.57

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Based on Figure 2, the biomass was dominantly allocated in the stem or culm of bamboo, followed by biomass in branches and leaves. The dominant pattern of bamboo biomass in culm was also found in thorny bamboo in Taiwan, which was culm (78.8–94.10%), branches (2.67–18.49%), and leaves (0.44–8.92%) (Li et al., 2016). A similar result was also found in Ethiopia, in which the biomass distribution of *Oxytenanthera abyssinica* was 75.95% in culm, 13.29% in branches, and 10.76% in leaves (Gurmessa et al., 2016). In the bamboo forest at the Columbian Andes Mountain, the biomass of bamboo was allocated in culm around 67% (Camargo García et al., 2023).

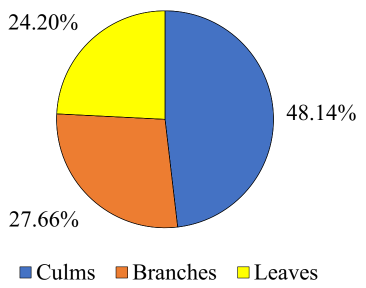

Figure 2 Biomass allocation in *Bambusa vulgaris* var. *striata*.

The result indicated that the moisture content in the culm, branches, and leaves was 103.93%, 63.31%, and 87.20%, respectively. Moreover, the percentage carbon content (PCC) of *B. vulgaris* var. *striata* in the culms, branches, and leaves was 55.64 ± 0.07%, 50.67 ± 0.48%, and 48.48 ± 0.10%, respectively. It was similar to Zhang et al.'s (2014) result that the PCC of moso bamboo (*Phyllostachys pubescens* Mazel ex Houz.) ranged from 41.67 to 51.58% and the PCC value in culm and branches was higher than in leaves. Moreover, we have visualized the relationship between predictors (diameter and total length) and the total dried weight biomass. The scatterplot of diameter and dried weight biomass has a pattern, while the total length of culm and dried weight biomass has a random pattern (Figure 3).

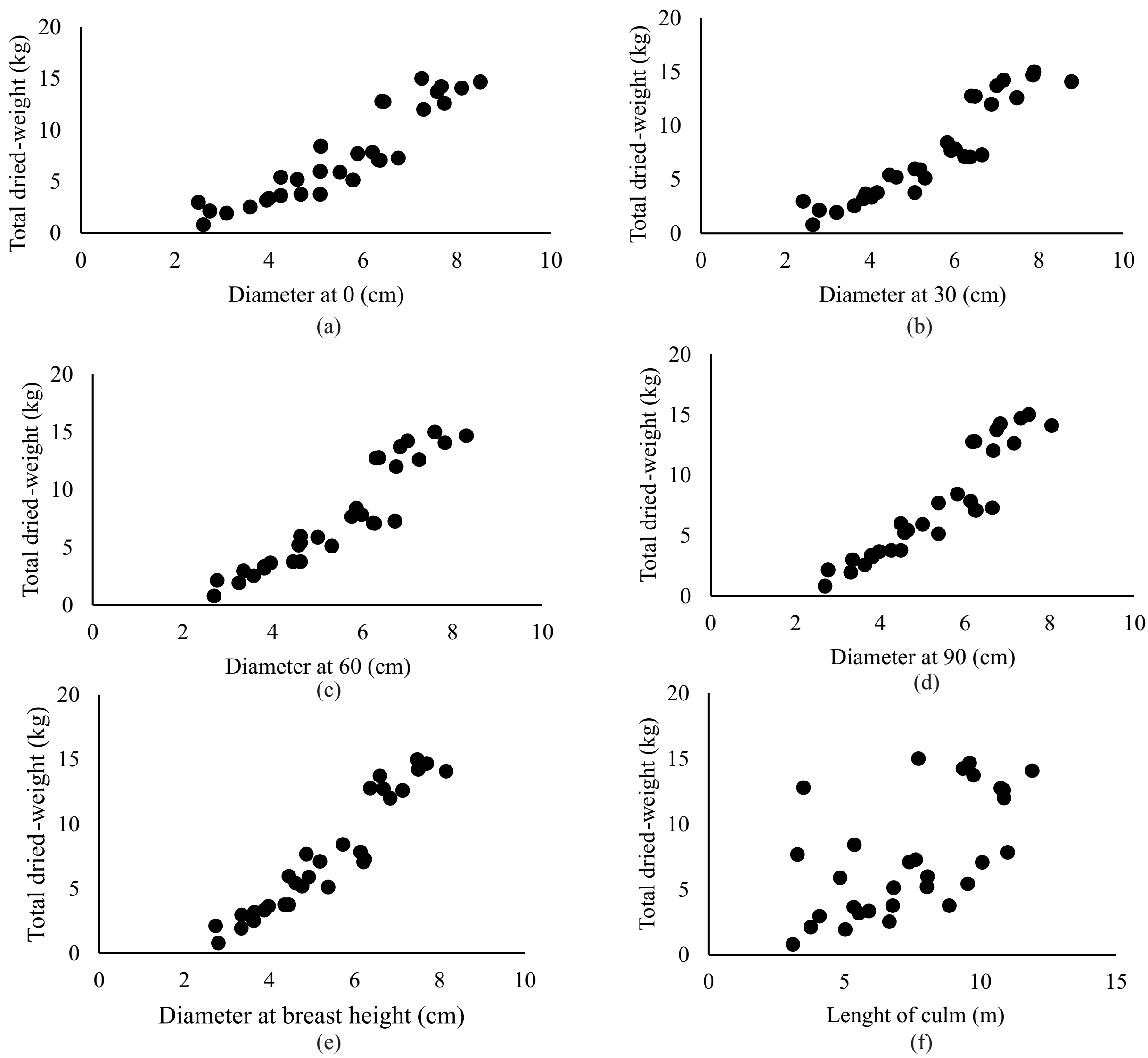

Figure 3 Relationship among total dried weight, diameter, and length of culm.

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Biomass equations of yellow *ampel* bamboo (*B. vulgaris* var. *striata*) with the diameter (*D*) as a predictor have shown better estimation than the predictor of the length of the culm (*L*). The values of the coefficient of determination for diameter were higher than the length of the culm. Some allometric models to estimate the biomass of bamboo showed that the coefficient of determination ranged from 0.883 to 0.998 (Table 2).

Scatter plot graphs have been developed to elaborate the relationship between the observed value and predicted values. Predicted values have resulted from the equations (Table 2), dried weight biomass, or total above-ground carbon. Figure 4 shows the pattern of diameter predictors (D_0, D_{30}, D_{60}, D_{90}, and D_{bh}), total length culm predictors, and combination diameters and total length culm (multi-predictors) to estimate dried weight biomass and total above-ground carbon.

The predicted values with the diameter predictors have resulted in near and narrow to the observed values. Meanwhile, the predicted values of total length culm predictors show more significant bias than those of diameter predictors. Moreover, multi-predictors also showed a bias from the observed value (Figure 4).

According to Table 2, the result showed that the predictor of diameter can be considered to estimate dried weight biomass or total above-ground carbon compared to the total culm length predictor. Diameter at breast height (1.3 m) has been used to develop a generic allometric model to estimate the above-ground biomass of mixed bamboo species in Columbia (Camargo García et al., 2023), Indonesia (Prayogo et al., 2021), Laos (Xayalath et al., 2019), and Taiwan (Li et al., 2024). Compared to other allometric models, the local model has shown a similar pattern in estimating above-ground biomass (Figure 5).

Discussion

Allometric model to estimate biomass and carbon The biomass and carbon allometric model developed from predictor diameter has shown a better value of coefficient determination and lower error than predictor length (Table 2). It also found in Ethiopian lowland bamboo (*Oxytenanthera abyssinica*), predictor diameter ($\ln TAGB = 10.97 + 1.68 \ln D$; $RSE = 0.172$; $R^2 = 0.82$) has shown better estimation on total above-ground biomass than predictor of total height ($\ln TAGB = -1.788 + 1.403 \ln H$; $RSE = 0.191$; $R^2 = 0.77$) (Gurmessa et al., 2016). In Indonesia, the biomass allometric model for six bamboo species (*Gigantochloa apus, Dendrocalamus asper, B. vulgaris, Schizostachyum zollingeri, Gigantochloa atter,* and *Schizostachyum brachycladum*) is $DW = 0.6396 Dbh^{1.6162}$ ($R^2 = 0.776$) and $DW = 0.3128 H^{1.4492}$ ($R^2 = 0.4289$) (Prayogo et al., 2021). The other bamboo biomass equations also strengthened the research findings that the diameters were better than the total length of the culm to estimate the biomass (Table 3).

The research findings were similar to those of Huy et al. (2019), where the predictor diameter was better than the predictor combination between diameter and total length of culm. Moreover, the predictor of the total length of bamboo

Table 2 Statistic summary of *Bambusa vulgaris* var. *striata* samples

Model*	Predictor	ln*a*	*b*	R^2_{adj}	SEE	MAB	RMSE	AIC	CF
$\ln DW = \ln a + b \ln D$	D_0	-1.423	1.942	0.850	0.283	3.698	0.283	-1.579	1.041
	D_{30}	-1.463	1.980	0.861	0.272	3.699	0.272	-1.250	1.038
	D_{60}	-1.846	2.218	0.908	0.221	3.699	0.221	-2.304	1.025
	D_{90}	-1.910	2.272	0.901	0.229	3.700	0.229	-2.275	1.027
	D_{bh}	-1.880	2.257	0.904	0.226	3.698	0.226	-2.299	1.028
$\ln DW = \ln a + b \ln L$	L	-0.337	1.102	0.337	0.594	3.698	0.594	-1.065	1.193
$\ln DW = \ln a + b \ln D^2L$	D_0, L	4.340	0.642	0.766	0.352	3.698	0.352	-1.262	1.064
	D_{30}, L	3.768	0.657	0.780	0.342	3.062	0.752	-1.300	1.327
	D_{60}, L	4.612	0.705	0.803	0.322	3.699	0.323	-1.785	1.054
	D_{90}, L	4.636	0.707	0.787	0.337	3.700	0.337	-1.722	1.058
	D_{bh}, L	5.583	0.693	0.776	0.345	4.734	1.091	-1.680	1.814
$\ln C = \ln a + b \ln D$	D_0	-2.077	1.947	0.848	0.285	2.436	0.285	-2.744	1.042
	D_{30}	-2.117	1.985	0.859	0.275	2.433	0.275	-2.872	1.038
	D_{60}	-2.504	2.225	0.908	0.222	2.450	0.222	-3.026	1.025
	D_{90}	-2.568	2.279	0.900	0.231	2.451	0.231	-2.938	1.027
	D_{bh}	-2.538	2.265	0.904	0.227	2.446	0.227	-2.980	1.026
$\ln C = \ln a + \mathrm{b} \ln L$	L	-0.980	1.101	0.333	0.597	2.440	0.597	-1.061	1.195
$\ln C = \ln a + \mathrm{b} \ln D^2L$	D_0, L	3.697	0.643	0.763	0.356	2.437	0.356	-2.088	1.065
	D_{30}, L	3.768	0.657	0.777	0.346	2.437	0.346	-2.172	1.062
	D_{60}, L	3.972	0.707	0.801	0.327	2.446	0.327	-2.197	1.055
	D_{90}, L	3.994	0.708	0.784	0.340	2.446	0.340	-2.112	1.060
	D_{bh}, L	3.942	0.694	0.773	0.348	2.440	0.348	-2.062	1.063

Note: * indicated that the model significance (*p*-value) was <0.05, *DW* is dried weight biomass (kg), *C* is total above-ground carbon (kg), D_n is the diameter at height n cm from the base (cm), *L* is the length of culm (m), a and b are fitted parameters, R^2_{adj} is coefficient determination, *SEE* is the standard error of the estimate, *MAB* is the mean of absolute bias, and *RMSE* is root mean square error.

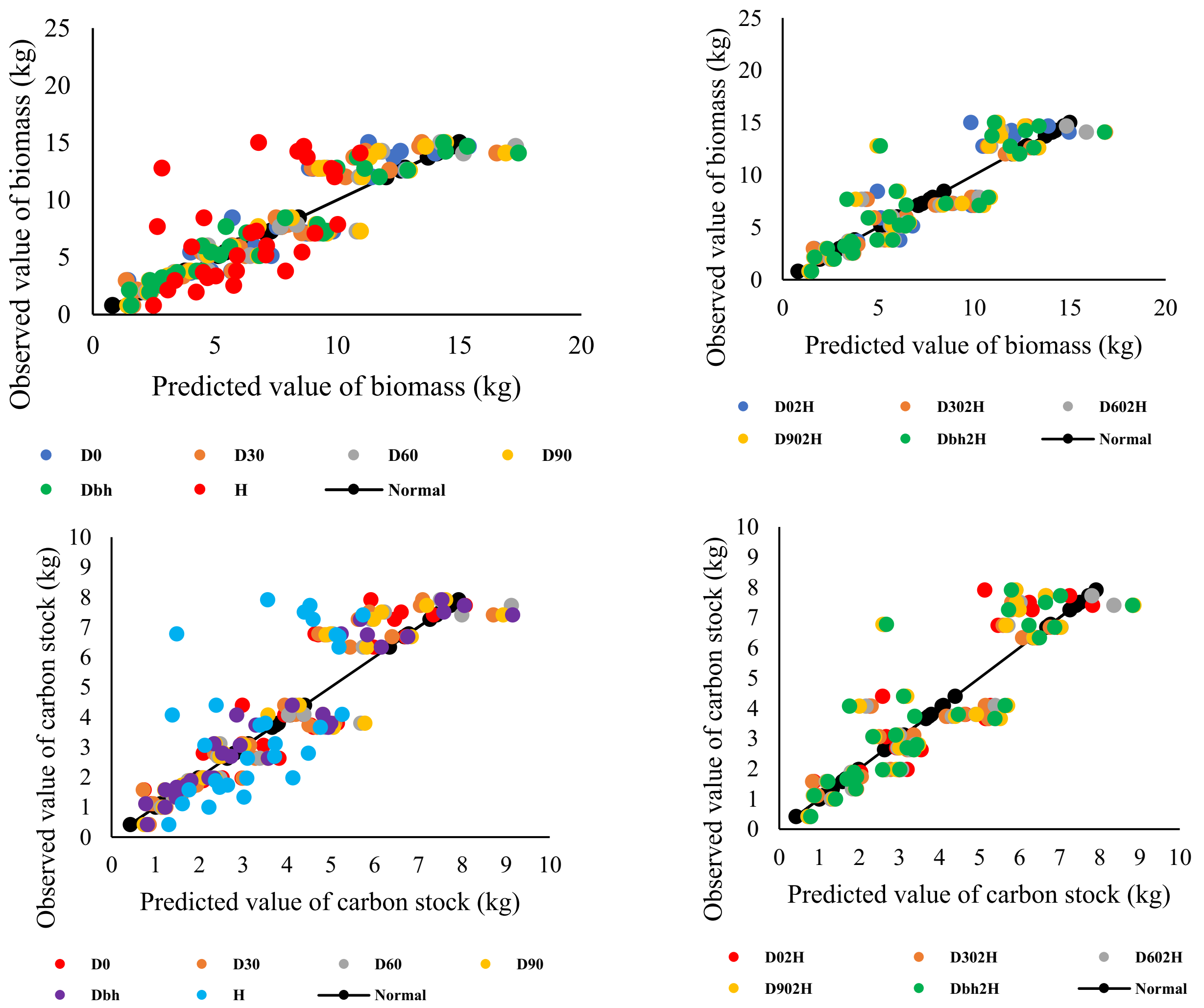

Figure 4 Observed and predicted value of biomass with single and multi-predictors.

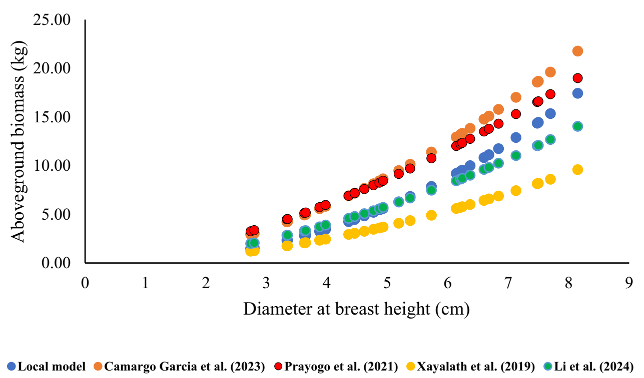

Figure 5 Estimating aboveground biomass of *Bambusa vulgaris* var. *striata* through different allometric model.

was less accurate due to the difficulty of measuring the total length of bamboo (Yuen et al. 2017; Huy et al. 2019). The bamboo growth has shown astonishing productivity, with the maximum height reached at 40 days or initial early growth (Yen, 2016). Furthermore, Yen and Lee (2011) explained that the bamboo's diameter and height did not increase after the initial early growth.

The difficulty of measuring bamboo height can be seen in Figure 1, where the bamboo has formed an arch at the top area. In this research, to minimize the uncertainty value of the height of bamboo, we have cut the bamboo culm by its internodes and then measured the total length of bamboo by summing the total length of internodes.

Comparison among diameters on estimating biomass and total carbon The previous section explained that the diameter predictor was better than the total length of the culm predictor in estimating biomass and carbon. According to Table 1, the minimum, average, and maximum diameter values at 0, 30, 60, 90, and D_{bh} were in the same range. Additionally, the average difference between D_0 and D_{bh} (D_{bh} minus $D_{0)}$ was 0.4 cm. The difference of 0.4 cm resulted in the difference in dried weight and total above-ground carbon, which was 0.02 and 0.01 kg, respectively. Furthermore, the predicted value has shown an underestimation from the actual value of less than 5% for all diameter predictors (D_0, D_{30}, D_{60}, D_{90}, and D_{bh}).

Table 3 Biomass equations of bamboo

Equation	Region	Species	R^2	References
$DW = 0.328D^{1.790}$	Taiwan	Mixed bamboo	0.691	Li et al. (2024)
$DW = 0.461D^{1.837}$	Columbia	Mixed bamboo	0.632	Camargo García et al. (2023)
$DW = 0.179D^{2.221}$	Laos	Mixed bamboo	0.967	Xayalath et al. (2019)
$DW = 0.309D^{1.897}$	Laos	*Dendrocalamus sinicus*	0.823	Xayalath et al. (2019)
$DW = 1.213D^{1.225}$	Laos	*Dendrocalamus hamiltonii*	0.469	Xayalath et al. (2019)
$DW = 0.218D^{2.281}$	Laos	*Bambusa blumeana*	0.694	Xayalath et al. (2019)
$DW = 0.069D^{2.675}$	Laos	*Thyrsostachys siamensis*	0.913	Xayalath et al. (2019)
$DW = 0.240D^{2.031}$	Laos	*Cephalostachyum pergracile*	0.947	Xayalath et al. (2019)

Note: *DW* is the dried weight of above-ground biomass (kg), *D* is the diameter of bamboo culm (cm), and R^2 is coefficient determination.

Table 4 Comparison among bamboo allometric model to estimate above ground biomass

Allometric model	Location	Bias (%)	CV (%)
Local model	Indonesia	-0.85	18.54
Prayogo et al. (2021)	Indonesia	47.59	37.20
Camargo Garcia et al. (2023)	Columbia	51.20	47.18
Xayalath et al. (2019)	Laos	-35.36	49.62
Li et al. (2024)	Taiwan	-0.22	22.06

Bamboo internodes of *B. vulgaris* have shown a unique pattern. According to Mulyana and Reorita (2022a; 2022b), the mean diameter at base (D_0) was 5.51 cm, D_{bh} was 5.37 cm, and the total length was 7.37 m. The internode length increased gradually at internode numbers 1 to 10 and then decreased gradually until the end (Mulyana & Reorita, 2022a; 2022b). Using diameter predictors (D_0, D_{30}, D_{60}, D_{90}, and D_{bh}) has shown a similarity in estimation, and the bias has also shown less than 5%. Statistically, the predictors D_0 and D_{bh} have shown no significant difference ($t = 0.206$; p-value > 0.05). Furthermore, a predictor between D_0 to D_{bh} could be used to estimate the biomass and carbon of bamboo culm.

According to the technical instruction Number Juknis2/IH/PLA.1/12/2021 on technical instruction for bamboo inventory in forest management units, *Dbh* of bamboo culm is recommended for field measurements because of the difficulties in measuring bamboo diameter at the dense bamboo clump and commonly used in forest measurements (Kementerian Lingkungan Hidup dan Kehutanan, 2021). Moreover, in practice, measuring *Dbh* is more practical and easier to estimate at 1.3 m height than estimating the height of 30, 60, and 90 cm.

Dbh has been applied in some allometric models to estimate above-ground bamboo biomass in Columbia, Indonesia, Laos, and Taiwan (Xayalath et al., 2019; Prayogo et al., 2021; Camargo García et al., 2023; Li et al., 2024). Compared to other allometric models, the local model has shown a good performance in estimating above-ground biomass that is indicated from the low bias and coefficient of variance (Table 4). The allometric model that developed by a single species and small-scale stand was more accurate to estimate the above-ground bamboo biomass than the generic allometric model (Li et al., 2024).

According to Table 4, the generic allometric model for estimating above-ground bamboo biomass shows different bias and coefficients of variance among the models. However, there are similarities among the models. First, the allometric models are fit for a specific site, and collaborative research for a large-scale landscape is needed. Second, for the practical reason, *Dbh* of bamboo is recommended as a predictor of the above-ground biomass allometric model.

Conclusion

This study concluded that the predictor diameter is better than the total length of the culm to estimate dried weight or total above-ground carbon for *B. vulgaris* var. *striata*. Although there was no significant difference among diameter predictors (D_0, D_{30}, D_{60}, D_{90}, and D_{bh}) to estimate dried weight or total above-ground of *B. vulgaris* var. *striata*, the D_{60} has been shown as a promising predictor due to the value of its statistical parameters. The allometric model for D_{60} is $\ln WD = -1.846 + 2.218 \ln D$ to estimate the dried weight biomass of bamboo and $\ln C = 2.504 + 2.225 \ln D$ for total above-ground carbon. However, in practical measurement in the field and commonly used in forestry, the predictor of diameter at breast height (*Dbh*) is recommended to be considered as a predictor to estimate above-ground biomass or carbon stock of *B. vulgaris* var. *striata*.

Recommendation

Our study was limited to *B. vulgaris* var. *striata* from the private forest in Sleman District, Yogyakarta, Indonesia. Our research findings do not reflect all bamboo species in Indonesia because there are different characteristics for each bamboo species. Further research is recommended to collect samples from various bamboo species and/or sites.

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