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CHEMICAL PROPERTIES OF THE TROPICAL BAMBOO CULMS: NATURE OR NURTURE? INSIGHTS FROM *GIGANTOCHLOA SCORTECHINII, DENDROCALAMUS PENDULUS* AND THEIR HYBRID SPECIES IN PENINSULAR MALAYSIA

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The most sought–after timber bamboo species in Peninsular Malaysia, *Gigantochloa scortechinii* (Buluh semantan, GS), is directly harvested from forests due to a lack of large-scale plantations. GS was confused with its hybrid species (×*Gigantocalamus malpenensis*, GM), resulted from natural hybridisation with another wild common species, *Dendrocalamus pendulus* (Buluh akar, DP). This study assessed the similarity and distinctiveness of chemical constituents in DP, GM and GS. On the basis of hybrid intermediacy, we assumed that a chemical property is likely to be heritable if its level in GM is intermediate between those of DP and GS. Culms of all species were collected from the logged-over forests in Perak. Culm dimensions, density and moisture were measured for each species. Based on the Technical Association of the Pulp and Paper Industry (TAPPI) standards of testing methods, the contents of cellulose, hemicellulose, lignin, ash and solvent extractives were analysed for 18 samples (six for each species) using ANOVA and Tukey's test. DP culms are the longest and they have significantly longer ($p < 0.05$) internodes, smaller diameter and thinner walls than those of GM and GS. GS has a relatively high cellulose content (58.38 ± 1.19%, crystallinity index = 78.30%). Cellulose, hemicellulose and lignin were significantly ($p < 0.05$) different between DP and GS by 6.31%, 5.70% and 6.27%, respectively. Whereas, those of GM were intermediate, implying that they are heritable characteristics. Lignocellulose contents are rather consistent within each of these species, that is low relative standard deviation (RSD), while ash content and solvent extractives exhibit higher intra-species variation, possibly attributed to stronger environmental influences than genetics. Based on its chemical properties, we suggested that prospective biomaterials for biofuels, chemicals, pulps and fabrics can be derived from GS.

Keywords: Buluh akar, Buluh semantan, ×*Gigantocalamus malpenensis*, Peninsular Malaysia, physical characteristics, chemical composition

INTRODUCTION

The woody bamboos (Arundinarieae and Bambuseae of Bambusoideae, Poaceae) are characterised by their culm woodiness, which is attributed to the abundance of the lignocellulosic content. In their natural habitats, bamboo plays important roles in preventing soil erosion and rehabilitating degraded sloping lands (Azmy 1999, INBAR 2021). Bamboos are suggested to be useful in mitigating climate change by sequestering atmospheric carbon, attributed to their vigorous growth, effective carbon fixation and tolerance to extreme climates (Zhou et al. 2005). The carbon stock capability of the Moso bamboo forest (including the above ground, underground and soil carbon) in its optimal climatic conditions was estimated to be 101–289 t C ha^{-1}, comparable to those of the broad-leaved and tropical forests (262.5 t C ha^{-1} and 230.4 t C ha^{-1}, respectively; Lou et al. 2010). Since ancient times, many woody bamboo species have been cultivated by tropical Asian communities such as those from India, China, Japan and Southeast Asia, for their cultural and economic importance. Culms and branches are used to make household tools, utensils, furniture and building structures. In the modern green industries, bamboo is appreciated as a wood substitute for its woody characteristics and fast growth rate. Studies have shown that bamboo fibre-reinforced composites exhibit promising values in making various engineered products such as fencing and flooring (Aguinsatan et al. 2019, Kamruzzaman et al. 2008, Sulastiningsih et al. 2008).

Although Malaysia is blessed with diverse bamboo resources, many local species were reported to have low commercialisation status. Due to the inconsistent supply of bamboo culms and hence low market demand, or vice versa, bamboo processing technology is not well-developed in this country (Azmy & Appanah 1998, Joest 2017). Until now, applications of these bamboos are largely limited to cottages and small-scale industries, such as making farm cages, agricultural baskets, incense sticks and handicrafts. On the other hand, the manufacturing of commercial bamboo products such as house furniture, strip-based flooring, windows scaffolds, and fencing walls, to name a few, mainly depends on imported bamboo materials (INBAR 2021, Joest 2017). The economically important bamboo species in Malaysia include *Bambusa blumeana*, *B. vulgaris*, *B. heterostachya*, *Dendrocalamus asper*, *Gigantochloa scortechinii*, *G. levis*, *G. ligulata*, *G. wrayi*, *Schizostachyum brachycladum*, *S. grande* and *S. zollingerii*, among others (Azmy 1999, Hisham et al. 2006, Nordahlia et al. 2008).

There have been extensive studies on the chemical properties of the useful bamboo species. Knowledge of the chemical properties of bamboo culms can aid species selection for specific applications such as construction, textiles and paper production. In addition, the bamboo species with promising chemical values may be suitable for selective propagation (Hisham et al. 2006). Based on various publications from years 2013–2021, the main chemical constituents of the important sympodial (10 species) and monopodial (four species) bamboos were summarised as follows: cellulose (33.80–54.60%), hemicellulose (13.26–25.75%), lignin (18.36–38.47%), hot water extracts (0.36–9.23%), alcohol toluene extracts (1.57–8.29%), ash (0.20–3.05%) and moisture (3.80–18.16%) (Figure 1 and Table 1). Comparing the sympodial to the monopodial bamboos, cellulose was observed to be present in higher amount while lignin was

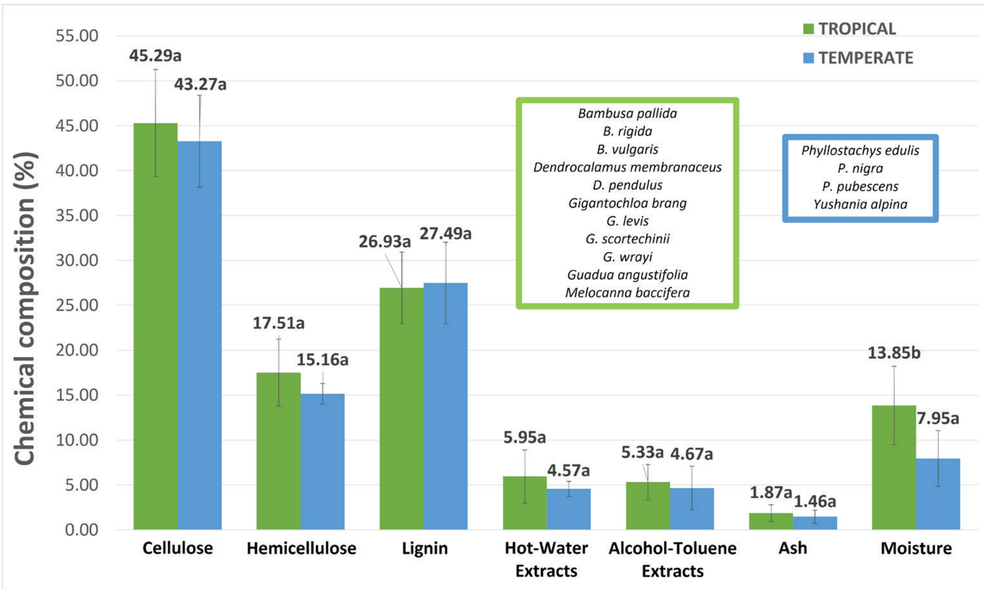

Figure 1 Clustered bar chart for the bamboo chemical properties compiled from the past studies. Data of 14 species of bamboos (green bars for tropical bamboos, blue bars for temperate bamboos) from 11 publications were re-analysed. The mean values are shown above their respective bars and the letters next to them indicate whether the differences are significant ($p = 0.05$) between the tropical and temperate groups (refer to Table 1 for the data and their sources)

Table 1 Chemical properties compiled from past studies (chemical composition and locations of sampling for 14 species of tropical and temperate bamboos from 11 publications).

Reference	Species	Cell-ulose (%)	Hemi-cellulose (%)	Lignin (%)	Hot- Water Extracts (%)	Alcohol-Toluene Extracts (%)	Ash (%)	Mois-ture (%)	Tribe	Location of sampling
Brahma & Brahma (2017)	*Bambusa pallida*	38.94	13.26	18.36	7.88	6.16	1.10	5.38	Bambuseae	India
Chaurasia et al. (2016)	*Melocanna baccifera*	47.00	14.78	26.40	5.80	2.40	1.90	4.83	Bambuseae	India
Depuydt et al. (2019)	*Dendrocalamus membranaceus*	54.60	17.10	31.20	0.36	NA	2.7	NA	Bambuseae	Vietnam
Depuydt et al. (2019)	*Guadua angustifolia*	50.60	16.80	31.90	6.20	NA	0.35	NA	Bambuseae	S America
Depuydt et al. (2019)	*Phyllostachys nigra*	53.70	15.20	29.50	4.20	5.50	0.20	7.50	Arundinarieae	Belgium
Haile et al. (2018)	*Yushania alpina*	46.05	NA	27.44	4.05	7.7	1.84	6.1	Arundinarieae	Ethiopia
Haile et al. (2018)	*Yushania alpina*	46.23	NA	28.41	4.12	8.29	2.7	5.59	Arundinarieae	Ethiopia
Haile et al. (2018)	*Yushania alpina*	46.5	NA	28.49	3.95	5.80	2.09	5.3	Arundinarieae	Ethiopia
Huang et al. (2014)	*Bambusa rigida*	42.75	25.75	24.51	6.32	6.10	2.72	NA	Bambuseae	SW China
Huang et al. (2014)	*Bambusa rigida*	43.32	24.27	29.35	6.86	6.65	3.05	NA	Bambuseae	SW China
Lee et al. (2018)	*Phyllostachys edulis*	38.09	16.10	21.51	3.47	4.32	0.77	6.50	Arundinarieae	Taiwan
Lee et al. (2018)	*Phyllostachys edulis*	45.39	14.23	38.47	3.96	6.39	1.48	6.64	Arundinarieae	Taiwan
Ogunsanwo et al. (2015)	*Bambusa vulgaris*	45.12	19.18	24.30	NA	NA	NA	NA	Bambuseae	Nigeria
Sánchez-Echeverri et al. (2014)	*Guadua angustifolia*	46.30	16.64	23.86	2.46	NA	1.44	NA	Bambuseae	Colombia
Sánchez-Echeverri et al. (2014)	*Guadua angustifolia*	50.26	18.52	26.33	1.42	NA	2.93	NA	Bambuseae	Colombia

Continued

Table 1 Continued

Wahab et al. (2013)	*Gigantochloa brang*	51.58	15.60	24.83	8.30	NA	1.25	NA	Bambuseae	W Malaysia
Wahab et al. (2013)	*Gigantochloa levis*	33.80	14.70	26.50	9.23	NA	1.29	NA	Bambuseae	W Malaysia
Wahab et al. (2013)	*Gigantochloa scortechinii*	46.87	14.10	32.55	8.00	NA	2.83	NA	Bambuseae	W Malaysia
Wahab et al. (2013)	*Gigantochloa wrayi*	37.66	16.90	30.04	8.62	NA	0.88	NA	Bambuseae	W Malaysia
Xu et al. (2014)	*Phyllostachys pubescens*	40.05	14.82	24.41	6.03	2.22	1.08	NA	Arundinarieae	E China
Xu et al. (2014)	*Phyllostachys pubescens*	38.46	15.23	25.31	5.63	1.57	1.63	NA	Arundinarieae	E China
Zhan et al. (2021)	*Phyllostachys edulis*	39.71	13.55	24.70	5.30	2.00	0.85	8.14	Arundinarieae	SC China
Zhan et al. (2021)	*Phyllostachys edulis*	38.52	16.97	26.64	4.98	2.87	1.94	9.64	Arundinarieae	SC China

NA = not available (properties that were not assessed by the respective researchers) lower (Figure 1). These studies are important for culm treatment technologies, as high-temperature steaming, oil heating and acid/alkaline treatments were reported to have a significant impact on the chemical, physical and thermal properties of bamboo fibres and parenchyma cells, as well as on their resistance to pests and fungi (Ogunsanwo et al. 2015, Sánchez-Echeverri et al. 2014, Zhan et al. 2021). However, the past studies have mainly focussed on the economically-important and cultivated species, but not the forest species.

The present study aims to assess and compare the physical and chemical properties of two common forest bamboos in Peninsular Malaysia, *Dendrocalamus pendulus* (DP) and *Gigantochloa scortechinii* (GS), and their hybrid, ×*Gigantocalamus malpenensis* (GM), in a hybrid zone in Sungai Siput, Perak. This natural hybrid species was first reported to exist as isolated individual clumps in Tapah, Perak and as a hybrid zone population at the fringe of Ulu Gombak Forest Reserve, Selangor (Goh et al. 2011). Its third population was discovered in Sungai Siput and was assessed recently for its population genetics and confirmed as the F1 population (Kong et al. 2022). An intermediate phenotype is expected for the F1 hybrid, in which equal genetic influence is received from each parental species. On this basis, it was hypothesised that the property(ies) of GM that is/are at the intermediate level of those of its parental species are the potential heritable traits. On the contrary, the non-intermediate characteristics may indicate those more affected by the environmental variation. There have been relatively more extensive studies on GS because of its economic importance in Malaysia. For instance, the effects of culm age and physical treatments on the chemical constituents of GS were investigated by Abd. Latif et al. (1994) and Hisham et al. (2006). Chemical composition of four *Gigantochloa* species cultivated in Malaysia was assessed by Wahab et al. (2013). However, DP and GM have not been studied in this aspect.

MATERIALS AND METHODS

Sample collection and preparations

Bamboo culm sampling was performed in October 2020 in the Pos Piah-Pos Poi area, Sungai Siput, Perak, where a bamboo population genetic study was undertaken by Kong et al. (2022). All bamboo clumps are considered to have persisted in the same macrohabitat with little environmental variation. Field identification of *D. pendulus* (DP) and *G. scortechinii* (GS) was based on vegetative characters described in Wong (1995). The bamboo hybrid, ×*G. malpenensis* (GM) was identified based on the description by Goh et al. (2011). Culm sampling was based on the culm age estimated in the field with assistance of the experienced harvesters from SEAD Industries (as acknowledged). The culms of 2–5 years old can be distinguished from those young and older by visually judging their freshness and colouration, and presence of lichen patches on the culm surface, as stated in the technical manual by INBAR (2004). For each species, two bamboo culms of different clumps were harvested at mid culm (about 2.5–4.0 m height from ground).

For estimating the physical characteristics, the bamboo culms were cut into square pieces of 20 × 20 × 3.2 mm (l × w × d) samples for density and equilibrium moisture content (EMC) measurements. Whole culms were sectioned into 150 mm lengths of internode (those without node) for testing maximum load (in Newton, N). Uncut whole culms were used for measurements of the culm dimensions (culm diameter, wall thickness, lengths of internode and full culm).

For chemical analyses and X-ray powder diffraction (XRD), the bamboo culms were pulverised into fibre powder (~250 μm), dried at 90 ºC till constant weight and stored in dry sealed bags. The pulverised fibre powder was subdivided for each culm to be analysed as laboratory triplicates.

Physical characteristics

The six samples (two from each species) were triplicated into 18 replicates, which were then individually used to analyse each physical property. The basic physical properties of bamboo culms were determined by following the British Standards (BS) ISO 22157 (BS 2019). The culm diameter (including the culm wall) and wall thickness were measured using Vernier callipers, while internode length and full culm length were measured using a measuring tape. The short round culms were aligned (parallel to the fibre grain) on the centroid of loading plates of the Automatic Compression Test Machine (Unit Test Scientific, Autocon 2000, Malaysia) with the capacity of 400–5000 kN and compressed at 10 mm min^{-1}. The EMC was determined by oven-drying the bamboo samples at 103 ± 2 ºC till constant weight. The bamboo samples were weighed and then immersed into distilled water to measure volume differences, for calculation of base density as follows:

$$\text{Base density (g cm}^{-3}\text{)} = m / v_f - v_0 \quad (1)$$

where m is the sample mass, v_f is the post-immersed sample volume and v_0 is the initial sample volume.

Chemical analyses and X-ray powder diffraction (XRD)

A total of six samples (two from each species) were triplicated into 18 replicates, which were then used to analyse each chemical property and XRD of bamboo. All pulverised bamboo samples were chemically analysed using analytical-grade solvents and reagents. To calculate chemical constituents on a dry-weight basis, the moisture content of each sample was primarily determined by oven-drying at 103 ± 2 ºC following the description in Technical Association of the Pulp and Paper Industry (TAPPI) T 264 cm–07 (TAPPI 2007b). The bamboo samples were then defatted by performing hot-water extraction via T 207 cm–01 (TAPPI 2001) and followed by 95% ethanol-toluene (2:1) extraction using Soxhlet apparatus via T 204 cm–17 (TAPPI 2007a). The defatted dry residue was used as a starting material for cellulose and lignin determination. Defatted samples were incubated in 10:1 (v/v) acetic nitric reagent (80% acetic acid, 65% nitric acid) for an hour and filtered to obtain a yellow-coloured liquid (as the extracted hemicellulose-lignin fraction) and the insoluble bamboo cellulose fibre. The cellulose fibre residues were washed in distilled water and centrifuged to obtain a clear and colourless supernatant. The cellulose content was determined colorimetrically after digestion in 67% sulphuric acid and reacted with the anthrone reagent (Updegraff 1969). The contents of hemicellulose were determined gravimetrically by first incubating the defatted samples in 5% sodium hydroxide for 2 hours, then filtering and acidifying with acetic acid. The hemicellulose fractions were precipitated with 95% ethanol, washed and centrifuged with absolute ethanol and diethyl ether, and lastly, oven-dried at 105 ˚C till constant weight. A modified T 222 om–02 method for lignin (Klason method) was used to isolate the insoluble lignin using 72% sulphuric acid for at least 2 hours to digest the cellulose fraction and dilute the acid to continue to digest excessive hemicellulose and acid-soluble lignin (TAPPI 2006). Lastly, the ash levels of bamboo samples were determined by incinerating the lignin residue in a furnace at 550 ºC until a white ash was formed (TAPPI 2007b).

X-ray powder diffraction (XRD) was used as an additional cellulose measurement method. Pulverised bamboo samples were scanned using an X-ray diffractometer (Shimadzu, LabX XRD–6100, Japan) (λ=1.54 Å) at 40 kV with a scattering angle (2θ, 2˚ min^{-1}) ranging from 10˚ to 40˚ (Ahtee et al. 1983). The crystallinity index (CI) was calculated as follows:

$$\%\,\text{Crystallinity Index (CI)} = (I_{002} - I_{am}) / I_{002} \times 100\% \quad (2)$$

where I_{002} is the intensity for the crystalline segment (2θ=22˚) and I_{am} is the amorphous segment (2θ=18˚).

Data analysis

Descriptive statistics of the chemical properties were computed using Statistical Package for the Social Sciences (SPSS) version 16 (SPSS Inc., Chicago). The coefficient of variation (CV) or relative standard deviation (RSD) was determined to indicate data set variability, as follows:

$$\text{RSD} = s / \bar{x} \quad (3)$$

where s is sample standard deviation and $\bar{x}$ is sample mean. The variation of RSD < 0.1000 is considered small. For each parameter, One-Way Analysis of Variance (ANOVA) was performed at a 95% confidence level to assess significant differences among samples for the three species. Tukey's honesty significance test was performed to evaluate the significant differences between the species-pairs.

RESULTS

Physical characteristics

Physical properties of DP, GM and GS were presented in Table 2. The EMC and maximum loads for the three species ranged between 9.57–10.29% and 62300–66500 N, respectively. Where DP has the lowest EMC of 9.57 ± 2.07% and highest maximum load of 66500 ± 13331 N, while GM has the highest EMC of 10.29 ± 0.78% and lowest maximum load of 62300 ± 9861 N. In addition, DP has the highest full culm length (16.25 ± 0.35 m) and internode length (51.32 ± 1.03 cm), while GS has the greatest culm diameter (10.98 ± 0.45 cm), culm wall thickness (6.50 ± 0.55 mm) and density (0.67 ± 0.06 g cm^{-3}). For the hybrid, GM, these characteristics were at the intermediate levels (Table 2).

Chemical properties

Comparison of the chemical properties of DP, GM and GS was shown in the bar chart in Figure 2 (refer to Tables 3, 4 and 5 for the full dataset). The main constituents in the three studied bamboos were 50.18–60.29% cellulose, 11.12–20.28% hemicellulose and 21.02–30.11% lignin compounds while the minor constituents were 6.20–9.05% hot-water extracts, 4.75–6.67% alcohol-toluene extracts and 1.88–3.03% ash compounds (Figure 2). DP has the highest content of lignin (28.55 ± 0.78%) and hot-water extracts (8.26 ± 0.40%), while GM has the highest content of alcohol-toluene extracts (5.91 ± 0.45%), and GS contains the highest content of cellulose (58.38 ± 1.19%), hemicellulose (18.84 ± 1.01%) and ash (2.84 ± 0.16%).

Figure 3 shows the cellulose contents of DP, GM and GS contain crystallinity index (CI) of 75.90%, 76.90% and 78.30%, respectively. As shown in the boxplots, cellulose, hemicellulose and lignin contents have the least data variation within species (0.020 < RSD < 0.0879). While the intraspecies data variations observed for hot-water extracts, alcohol toluene extracts, and ash ranged from 0.0503 to 0.1313.

ANOVA results shows that the differences among DP, GM and GS ("among groups") were significant for lignocelluloses and ash content (Table 4). GS has significantly ($p<0.05$) higher contents of cellulose and hemicellulose, while having lower lignin content than those of DP (Figure 2). The boxplot shows the content of cellulose, hemicellulose and lignin of GM, the hybrid species, which appeared to be intermediate between those of its parental species, DP and GS (Figure 3).

DISCUSSION

Chemical properties

Cellulose and ash levels in DP, GM and GS appear to be higher than the averaged values reported in Figure 1 for tropical and temperate bamboos in past studies (Brahma & Brahma 2017, Chaurasia et al. 2016, Depuydt et al. 2019, Haile et al. 2020, Huang et al. 2014, Lee et al. 2018, Ogunsanwo et al. 2015, Sánchez-Echeverri et al. 2014, Wahab et al. 2013, Xu et al. 2014, Zhan et al. 2021). For other chemical properties, the levels are similar to the average data from past studies.

DP and GS contain significantly different levels of lignocelluloses, where GM was found to show intermediate values between the three. This shows that the cellulose, hemicellulose and lignin contents in the hybrid species are equally influenced by each parental species, implying that the three properties may be attributed to genetic factors. Similarly, a tropical bamboo hybrid species in South-West China, *Bambusa changningensis*, has also demonstrated an intermediate level of cellulose compared to its parental species (Zhuo et al. 2023). Past studies have suggested that the biosynthesis of lignocelluloses was regulated by genes in some plants. Persson et al. (2005) reported that the cellulose biosynthesis of plants has been related to the genes of cellulose synthase, while Xu et al. (2017) highlighted the importance of regulating the 4-coumarate: coenzyme A ligase gene in monolignol (early form of lignin) biosynthesis pathways.

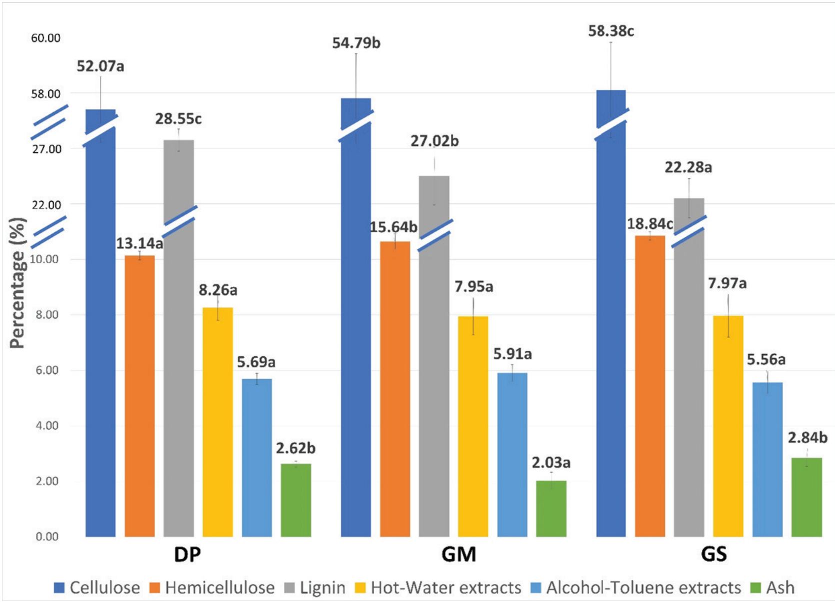

Figure 2 Clustered bar chart for chemical properties of DP, GM and GS. The mean values are shown above their respective bars. The Tukey's honesty significant test results for each category of chemical properties are summarised as the letters next to the mean values. Different letters for a chemical property in different species indicate significant difference ($p < 0.05$)

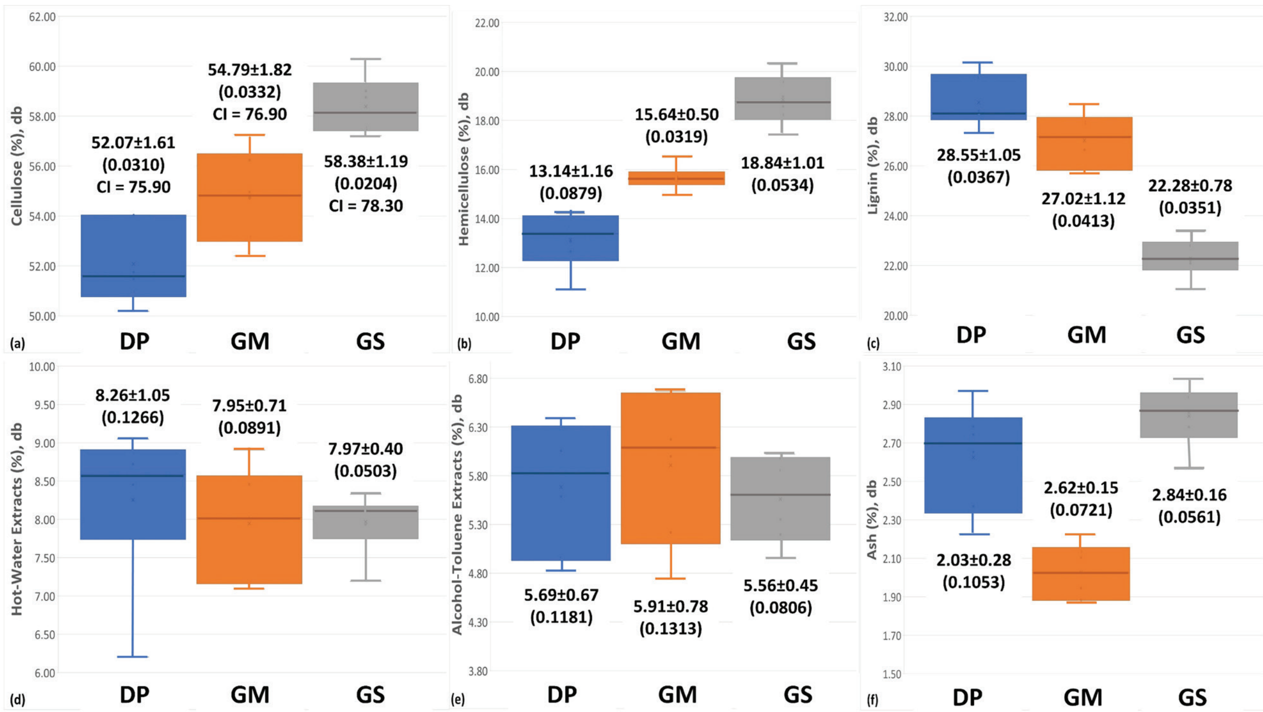

Figure 3 Boxplots for (a) cellulose, (b) hemicellulose, (c) lignin, (d) hot-water extracts, (e) alcohol-toluene extracts, and (f) ash contents of DP, GM and GS. Crystallinity index (CI) of each bamboo species was provided in (a). Values of means ± standard deviations with relative standard deviations (RSD) in parenthesis are shown above or below their respective boxplots

For the contents of alcohol-toluene extracts, hot-water extracts and ash of GM which are not at the intermediate levels compared to its parental species, we suggest that they could be influenced by the environmental factors such as microhabitat and soil nutrients. This may also

Table 2 Means and standard deviations of the physical properties for DP, GM and GS.

Physical properties	Mean ± standard deviation		
	DP (n = 6)	GM (n = 6)	GS (n = 6)
Maximum load (N)	66500 ± 13331	62300 ± 9861	65383 ± 9703
EMC (%)	9.57 ± 2.07	10.29 ± 0.78	9.58 ± 0.84
Full culm length (m)	16.25 ± 0.35	10.93 ± 0.29	11.08 ± 0.42
Internode length (cm)	51.32 ± 1.03	39.75 ± 1.41	35.63 ± 0.61
Density (g cm^{-3})	0.50 ± 0.07	0.62 ± 0.06	0.67 ± 0.06
Culm diameter (cm)	8.80 ± 0.35	9.93 ± 0.63	10.98 ± 0.45
Wall thickness (mm)	4.33 ± 0.52	5.50 ± 1.05	6.50 ± 0.55

be the explanation for their relatively large RSD values. This means that these three properties may show high variability even within the same species.

The abundance of cellulose (58.40%) with a high fraction of crystalline materials (78.30%) in GS due to an increase in cellulose chain order and also may be associated with a reduced lignin content. Cellulose or alpha-cellulose consists of glucose monomers, and it links through β-1,4-glycosidic bonds into a linear chain. Individual cellulose chains are stacked up via hydrogen bonding resulting in an unbranched, rigid and strong crystalline structure. Lignin is a complex, branched structure polymer with aliphatic chains which mainly consists of aromatic-based monomers—coniferyl, sinapyl and *p*-coumaryl alcohols (Chaurasia et al. 2016, Haile et al. 2020). The crystalline characters of cellulose will influence the behaviour of acid/enzymatic hydrolysis into smaller molecules. While hemicellulose is heterogeneous, it has a weaker structure than cellulose because it is built of xylose, mannose, arabinose, galactose and rhamnose, among others, that forms branching. The low polymerisation of hemicellulose degrades quickly as compared to the structurally well-oriented alpha-cellulose, which can withstand high temperatures and only decompose at 300–400 ºC (Depuydt et al. 2019, Huang et al. 2014, Wahab et al. 2013).

The high cellulose content and crystallinity index of GS may have resulted in its relatively high load-bearing capacity (maximum load > 65000 N) (Table 2). Celluloses are primary components of wood with load-bearing capability due to a high degree of intermolecular bonding. Their rigid structures are reinforced by high crystalline materials and hemicelluloses that form matrices to connect the fibres. The rigidity of cellulose fibres contributes to an increased stiffness to resist deformation during more enormous mechanical stress such as pressing and pulling loads (Bako et al. 2020, Gomes Neto et al. 2021, Sá Ribeiro et al. 2017). This can have a positive impact on the fibre properties by increasing the culm hardness, and hence may result in an improved culm strength. While the fraction of crystalline material in woody plants are mostly contributed by cellulose, it was reported that hemicellulose and lignin in the amorphous region may still affect the XRD value (Ahtee et al. 1983). For instance, certain molecules with similar structural properties to some hemicellulose monomers such as xylan and mannan, compose molecules that appear as crystalline ordered arrangements in a repeating pattern, typically forming a solid with distinct structural properties (Ahtee et al. 1983). The low contents of cellulose in DP have resulted in a lesser crystalline material than GM and GS, as the hemicellulose fraction may be bound with a variety of molecules that are non-crystalline in nature, further enhancing the amorphous background and lower CI.

Optimal selection of fibres is usually based on the following criteria: high cellulose content for good strength and flexibility, high hemicellulose content for enhancing bonding between cellulose fibres and low lignin content to avoid brittleness during processing but still providing rigidity (Depuydt et al. 2019, Huang et al. 2014). For applications, bamboo culms with lignocellulose moieties of celluloses > 50% and lignin < 30% (and > 10% hemicellulose) have achieved the specific characteristics of potential raw material to be extracted for fibreboard making, which ordinarily contains 33–51% cellulose, 20–35% hemicellulose and 20–30% lignin as these are converted into

Table 3 Physical and chemical properties of DP, GM and GS (sample codes and updated labels for this study were also listed)

Sample code	Label	Species	C	CI	H	L	HWE	ATE	A	EMC	ρ	I	D	W	F_{max}
D02a	DEN5	DP	51.75	75.90	14.20	28.01	9.05	6.29	2.23	10.15	0.58	51.50	8.70	4.00	61300
D02b	DEN5	DP	50.18	75.90	14.09	29.53	8.86	6.06	2.74	12.10	0.45	50.40	8.50	4.00	68200
D02c	DEN5	DP	50.96	75.90	12.66	28.06	8.72	6.39	2.97	7.80	0.46	51.70	8.40	4.00	70100
D03a	DEN6	DP	54.04	75.90	13.69	28.21	6.20	5.59	2.79	7.48	0.60	49.80	8.80	5.00	63100
D03b	DEN6	DP	51.47	75.90	13.06	30.11	8.45	4.96	2.65	8.08	0.50	51.90	9.10	5.00	66400
D03c	DEN6	DP	54.04	75.90	11.12	27.35	8.25	4.83	2.37	11.79	0.41	52.60	9.30	4.00	69900
H01a	HYB6	GM	56.24	76.90	15.56	25.73	8.91	6.00	2.14	9.13	0.67	39.80	9.80	6.00	63400
H01b	HYB6	GM	53.17	76.90	15.52	27.78	8.03	6.67	1.88	10.83	0.57	38.90	9.50	5.00	65700
H01c	HYB6	GM	54.70	76.90	14.94	26.64	8.02	6.17	1.88	10.48	0.55	37.40	9.20	7.00	52100
H02a	HYB7	GM	57.26	76.90	15.64	25.85	7.18	5.22	1.94	9.87	0.64	40.80	10.70	4.00	56100
H02b	HYB7	GM	54.96	76.90	15.71	28.44	7.09	4.75	2.10	10.09	0.63	40.40	10.70	6.00	66700
H02c	HYB7	GM	52.40	76.90	16.49	27.69	8.46	6.64	2.22	11.36	0.69	41.20	9.70	5.00	69800
G01a	GIG2	GS	59.01	78.30	17.43	21.02	8.33	5.20	2.87	9.87	0.66	35.10	10.40	7.00	69300
G01b	GIG2	GS	57.47	78.30	20.28	23.36	8.12	5.35	2.86	8.08	0.60	35.40	11.70	6.00	65600
G01c	GIG2	GS	60.29	78.30	19.58	22.08	7.19	4.97	2.56	9.72	0.62	35.90	10.80	6.00	66400
G02a	GIG3	GS	58.76	78.30	18.97	22.19	8.12	5.98	2.94	10.02	0.70	36.00	11.10	7.00	58200
G02b	GIG3	GS	57.55	78.30	18.23	22.80	7.93	5.86	2.78	9.29	0.78	36.50	10.70	7.00	61400
G02c	GIG3	GS	57.22	78.30	18.57	22.25	8.12	6.02	3.03	10.51	0.66	34.90	11.20	6.00	71400

C = cellulose (%), CI = CI (%), H = hemicellulose (%), L = lignin (%), HWE = hot-water extracts (%), ATE = alcohol-toluene extracts (%), A = ash (%), EMC = EMC (%), ρ = density (g cm-3), I = internode length (cm), D = culm diameter (cm), W = wall thickness (mm), Fmax = maximum load (N)

Table 4 ANOVA of the chemical properties of DP, GM and GS (mean differences in different species are significant at $p < 0.05$)

		Sum of Squares	df	Mean Square	F	Sig.
Cellulose (%), db	Between Groups	120.223	2	60.111	24.597	0.000*
	Within Groups	36.657	15	2.444		
	Total	156.880	17			
Hemicellulose (%), db	Between Groups	98.224	2	49.112	56.745	0.000*
	Within Groups	12.982	15	0.865		
	Total	111.206	17			
Lignin (%), db	Between Groups	127.962	2	63.981	64.956	0.000*
	Within Groups	14.775	15	0.985		
	Total	142.736	17			
Hot-Water Extracts (%), db	Between Groups	0.353	2	0.177	0.301	0.745^{ns}
	Within Groups	8.808	15	0.587		
	Total	9.161	17			
Alcohol-Toluene Extracts (%), db	Between Groups	0.367	2	0.183	0.438	0.653^{ns}
	Within Groups	6.277	15	0.418		
	Total	6.644	17			
Ash (%), db	Between Groups	2.131	2	1.066	25.923	0.000*
	Within Groups	0.617	15	0.041		
	Total	2.748	17			

* = significant difference, ns = no significant difference

Table 5 Multiple comparisons of Tukey's significant test on chemical properties of DP, GM and GS (mean differences in different species are significant at $p < 0.05$)

Dependent Variable		Bamboo species (I)	Bamboo species (J)	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
							Lower Bound	Upper Bound
Cellulose (%), db	Tukey HSD	DP	GS	-6.31000*	0.90255	0.000	-8.6544	-3.9656
			GM	-2.71500*	0.90255	0.023	-5.0594	-0.3706
		GM	GS	-3.59500*	0.90255	0.003	-5.9394	-1.2506
			DP	2.71500*	0.90255	0.023	0.3706	5.0594
		GS	DP	6.31000*	0.90255	0.000	3.9656	8.6544
			GM	3.59500*	0.90255	0.003	1.2506	5.9394
Hemicellulose (%), db	Tukey HSD	DP	GS	-5.71*	0.480	0.00000	-4.9445	-5.9045
			GM	-2.51*	0.480	0.00083	-1.9045	-2.8645
		GM	GS	-3.20*	0.480	0.00007	-2.56	-3.52
			DP	2.51*	0.480	0.00083	2.8645	1.9045
		GS	DP	5.71*	0.480	0.00000	5.9045	4.9445
			GM	3.20*	0.480	0.00007	3.52	2.56

Continued

Table 5 Continued

Lignin (%), db	Tukey HSD	DP	GS	6.26167*	0.11706	0.192	-0.5191	0.0891
			GM	1.52333*	0.57300	0.045	0.0350	3.0117
		GM	GS	4.73833*	0.57300	0.000	3.2500	6.2267
			DP	-1.52333*	0.57300	0.045	-3.0117	-0.0350
		GS	DP	-6.26167*	0.57300	0.000	-7.7500	-4.7733
			GM	-4.73833*	0.57300	0.000	-6.2267	-3.2500
Hot-Water Extracts (%), db	Tukey HSD	DP	GS	0.28667	0.44242	0.796	-0.8625	1.4358
			GM	0.30667	0.44242	0.771	-0.8425	1.4558
		GM	GS	-0.02000	0.44242	0.999	-1.1692	1.1292
			DP	-0.30667	0.44242	0.771	-1.4558	0.8425
		GS	DP	-0.28667	0.44242	0.796	-1.4358	0.8625
			GM	0.02000	0.44242	0.999	-1.1292	1.1692
Alcohol-Toluene Extracts (%), db	Tukey HSD	DP	GS	0.12333	0.37348	0.942	-0.8468	1.0934
			GM	-0.22167	0.37348	0.826	-1.1918	0.7484
		GM	GS	0.34500	0.37348	0.634	-0.6251	1.3151
			DP	0.22167	0.37348	0.826	-0.7484	1.1918
		GS	DP	-0.12333	0.37348	0.942	-1.0934	0.8468
			GM	-0.34500	0.37348	0.634	-1.3151	0.6251
Ash (%), db	Tukey HSD	DP	GS	-0.21500	0.11706	0.192	-0.5191	0.0891
			GM	0.59833*	0.11706	0.000	0.2943	0.9024
		GM	GS	-0.81333*	0.11706	0.000	-1.1174	-0.5093
			DP	-0.59833*	0.11706	0.000	-0.9024	-0.2943
		GS	DP	0.21500	0.11706	0.192	-0.0891	0.5191
			GM	0.81333*	0.11706	0.000	0.5093	1.1174

composite materials (Chaurasia et al. 2016). Improvement in hemicellulose content could be considered by culm treatment, to increase bonding between cellulose fibres and to high-strength and stable fibreboards.

The DP, GM and GS bamboos have high levels of hot-water extracts, suggesting the three species may predominantly be deposited with a variety of extractable molecules in their bamboo culms. Hot water extractives in bamboo may include tannins, ligands, flavonoids, starches and pigments, whereas alcohol-toluene extractives contain resin, phenolic substances (terpenoids, sterols), fats, waxes and wood gums (Haile et al. 2020, Wahab et al. 2013). They are non-structural chemical components that are extractable from bamboo cell walls. The hydrophobicity of these extractable compounds in bamboo culms can resist powdery mildew but may also attract pests such as fungi and termites if present in excessive amounts. The results suggest that the bamboo culm with higher extractives may be subjected to suitable chemical treatment to prevent fibre degradation and improve the culm durability for extensive product making and applications (Brahma & Brahma 2017).

Woody plant ashes contain minerals such as calcium, potassium, magnesium, manganese and silica that can influence the fibre properties (surface levelness, smoothness, tearing resistance, etc.). Ash contents in GM are significantly lower (2.03%) than DP and GS, and this causes fewer mineral materials in GM and may result in lesser support to reinforce the fibre structure and a lower culm strength. On the other hand, fibre with low ash content may be favoured in the chemical processing of pulp into rayon and charcoal combustion process because of the interference caused by high alkalinities of minerals in ash content (sintering and forming slag). This issue can be minimised by adding kaolin (Ahtee et al. 1983).

CONCLUSION

In conclusion, our results suggested that the chemical contents may be significantly different even for the closely related tropical bamboo species, implying that species identification is crucial in matching the bamboo materials to their respective industrial applications. Cellulose, hemicellulose and lignin contents were suggested to be heritable, while the other chemical properties (ash, hot-water and alcohol-toluene extractives) in the tropical woody bamboos, could be more influenced by the environment. As such, the lignocellulose contents in each bamboo species may be relatively more consistent across various clumps and populations. Establishing a reference record of the chemical compositions for each useful bamboo species could be meaningful only for the lignocelluloses. Besides, our results suggested that GS comprises high contents of ash and cellulose (coupled with an abundance of crystalline structures), making its fibres suitable for heavy-duty applications. It is noteworthy that the chemical properties of the culm < 3 years old may not have stabilised yet but our present study was unable to differentiate the culm samples at yearly interval. Despite such limitation, our data may still be representative and relevant because this age group is the best that can be estimated by the bamboo harvesters' common experience in the field. Further studies may consider tagging the culms when each of them sprouts. In summary, our results provide important information on the chemical and physical properties of different bamboo species, which aids consideration for species-specific practical applications. This study also calls for additional investigations into the intra-species variations for forest bamboos because their outcrossing nature can possibly lead to significant variations in their genotypes and phenotypes, including the physical and chemical properties.

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REFERENCES

Abd. Latif M, Khoo KC, Jamaludin K & Abd. Jalil HA.1994. Fiber morphology and chemical properties of *Gigantochloa scortechinii*. *Journal of Tropical Forest Science* 6: 397–407.

Aguinsatan RG, Razal RA, Carandang MG & Peralta EK. 2019. Site influence on the morphological, physical and mechanical properties of giant bamboo (*Dendrocalamus asper*) in Bukidnon province, Mindanao, Philippines. *Journal of Tropical Forest Science* 31: 99–107.

Ahtee M, Hattula T, Mangs J & Paakkari T. 1983. An X-ray diffraction method for determination of crystallinity in wood pulp. *Paperi ja Puu Papper och Trä* 8: 475–480.

Azmy HM & Appanah S. 1998. Bamboo resources conservation and utilization in Malaysia. In Rao AN & Rao VR (eds) *Bamboo - Conservation, Diversity, Ecogeography, Germplasm, Resources Utilization and Taxonomy: Proceedings of Training Course Cum Workshop*. 10-17 May 1998, Yunnan.

Azmy HM. 1999. Regeneration of natural stand bamboos of *Gigantochloa scortechinii*. *Journal of Tropical Forest Science* 11: 639–650.

Bako RM, Sariman F, Wullur CW et al. 2020. Optimization of sulfur soaking water on mechanical properties and physical properties of woven petung bamboo (*Dendrocalamus asper* Backer ex Heyne) strips. *E3S Web of Conferences* 190: 00031. https://doi.org/10.1051/e3sconf/202019000031

Brahma S & Brahma BK. 2017. Understanding of bamboo as timber substitute: Chemical and anatomical properties of *Bambusa pallida* Munro of Kokrajhar District, Assam, India. *International Journal of Innovative Science Engineering and Technology* 6: 14462–14467.

BS (BRITISH STANDARD). 2019. ISO 22157 for physical and mechanical testing. *Bamboo structures – determination of physical and mechanical properties of bamboo culms – test methods*. https://www.sis.se/api/document/preview/80009366/.

Chaurasia SK, Singh SP, Naithani S & Srivastava P. 2016. A comprehensive study on proximate chemical composition of *Melocanna baccifera* (Muli bamboo) and it's suitability for pulp and paper production. *Journal of Forestry Research* 5: 168.

Depuydt DEC, Sweygers N, Appels L, Ivens J & Van Vuure AW. 2019. Bamboo fibres sourced from three global locations: A microstructural, mechanical and chemical composition study. *The Journal of Reinforced Plastics and Composites* 38: 397–412. https://doi.org/10.1177/0731684419828532.

Goh WL, Chandran S, Kamiya K & Wong KM. 2011. A natural hybrid between *Dendrocalamus pendulus* and *Gigantochloa scortechinii* (Poaceae: Bambusoideae: Bambuseae) in Peninsular Malaysia. *The Gardens' Bulletin Singapore* 62: 223–238.

Gomes Neto JA, Barbosa NP, Beraldo AL & De Melo AB. 2021. Physical and mechanical properties of the *Bambusa vulgaris* as construction material. *Engenharia Agrícola* 41(2): 119–126. https://doi.org/10.1590/1809-4430-eng.agric.v41n2p119-126/2021.

Haile F, Tsegaye M, Bekalu Y, Tolessa A & Feleke S. 2020. Comparative investigation of chemical composition of the two indigenous bamboo species *Yushania alpina* and *Oxytenanthera abyssinica* grown in the north part of Ethiopia. *Journal of Marine Sciences* 12: 62–66. https://doi.org/10.5829/idosi.wjfms.2020.62.66.

Hisham HN, Othman S, Rokiah H, Latif MA, Ani S & Tamizi MM. 2006. Characterization of bamboo *Gigantochloa scortechinii* at different ages. *Journal of Tropical Forest Science* 18: 236–242.

Huang XY, Xie JL, Qi JQ, Hao JF, Jiang XQ & Hu WH. 2014. Investigation of the physical and mechanical properties and chemical composition of *Bambusa rigida* before and after accelerated aging. *BioResources* 9: 3174–3183.

International Bamboo And Rattan Organization (INBAR). 2004. *Tropical bamboos propagation manual. INBAR publications - technology transfer models.* https://www.inbar.int/wp-content/uploads/2020/05/1491014280.pdf.

International Bamboo And Rattan Organization (INBAR). 2021. *Trade overview 2019: bamboo and rattan commodities in the international market.* INBAR: Beijing, China.

Joest AC. 2017. Malaysian bamboo development: challenges and opportunities. *International Bamboo and Rattan Organization.* https://www.inbar.int/malaysian-bamboo-development-challenges-and-opportunities/.

Kamruzzaman M, Saha SK, Bose AK & Islam MN. 2008. Effects of age and height on physical and mechanical properties of bamboo. *Journal of Tropical Forest Science* 20: 211–217.

Kong HH, Loo KW & Goh WL. 2022. Population genetic assessment of ×*Gigantocalamus malpenensis* K.M. Wong (Poaceae: Bambusoideae: Bambuseae) and implications for bamboo silviculture. *Genetic Resources and Crop Evolution* 70: 1123–1134. http://dx.doi.org/10.1007/s10722-022-01490-8.

Lee C-H, Yang T-H, Cheng Y-W & Lee C-J. 2018. Effects of thermal modification on the surface and chemical properties of moso bamboo. *Construction and Building Materials* 178: 59–71. http://dx.doi.org/10.1016/j.conbuildmat.2018.05.099.

Lou Y, Li Y, Henley KBG & Zhou G. 2010. Bamboo and climate change mitigation. Technical Report No. 32-International Network for Bamboo and Rattan (INBAR), Beijing.

Nordahlia AS, Anwar UMK, Hamdan H, Zaidon A, Paridah MT & Razak OA. 2008. Effects of age and height on selected properties of Malaysian bamboo (*Gigantochloa levis*). *Journal of Tropical Forest Science* 24: 102–109.

Ogunsanwo OY, Terziev N, Panov D & Daniel G. 2015. Bamboo (*Bambusa Vulgaris* Schrad.) from moist forest and derived savanna locations in Southwest Nigeria – properties and gluability. *BioResources* 10: 2823–2835. http://dx.doi.org/10.15376/biores.10.2.2823-2835.

Persson S, Wei H, Milne J, Page GP & Somerville CR. 2005. Identification of genes required for cellulose synthesis by regression analysis of public microarray data sets. *The Proceedings of the National Academy of Science U.S.A.* 102: 8633–8638. https://doi.org/10.1073/pnas.0503392102.

Sá Ribeiro RA, Sá Ribeiro MG & Miranda IPA. 2017. Bending strength and nondestructive evaluation of structural bamboo. *Construction and Building Materials* 146: 38–42. https://doi.org/10.1016/j.conbuildmat.2017.04.074.

SÁnchez-Echeverri LA, Aita G, Robert D & Garcia MER. 2014. Correlation between chemical compounds and mechanical response in culms of two different ages of *Guadua angustifolia* Kunth. *Madera y Bosques* 20: 87–94. http://dx.doi.org/10.21829/myb.2014.202166.

Sulastiningsih IM, Trisatya DR, Indrawan DA, Malik J & Pari R. 2008. Physical and mechanical properties of glued laminated bamboo lumber. *Journal of Tropical Forest Science* 33: 290–297.

TAPPI (Technical Association Of The Pulp And Paper Industry). 2006. *T 222 om−02 for acid-insoluble lignin in wood and pulp.* https://www.tappi.org/content/sarg/t222.pdf.

TAPPI (Technical Association Of The Pulp And Paper Industry). 2007a. *T 204 cm−17 for solvent extractives of wood and pulp.* https://www.tappi.org/content/sarg/t204.pdf.

TAPPI (Technical Association Of The Pulp And Paper Industry). 2007b. *T 264 cm−07 for moisture and ash in wood, pulp, paper and paperboard.* https://www.tappi.org/content/sarg/t211.pdf.

TAPPI (Technical Association Of The Pulp And Paper Industry). 2001. *T 207 cm−01 for water solubility of wood.* http://file.yzimgs.com/175706/2011120520594106.pdf.

Updegraff DM. 1969. Semimicro determination of cellulose in biological materials. *Analytical Biochemistry* 39: 420–424. https://doi.org/10.1016/S0003-2697(69)80009-6.

Wahab R, Mustafa RT, Salam MA, Sudin M, Samsi HW & Rasat MSM. 2013. Chemical composition of four cultivated tropical bamboo in genus *Gigantochloa*. *Journal of Agricultural Science* 5: 66–75. https://doi.org/10.5539/jas.v5n8p66.

Wong KM. 1995. *The morphology, anatomy, biology and classification of Peninsular Malaysian bamboos.* University of Malaya, Kuala Lumpur.

Xu B, Escamilla-Treviño LL, Sathitsuksanoh N et al. 2017. Silencing of 4-coumarate: coenzyme A ligase in switchgrass leads to reduced lignin content and improved fermentable sugar yields for biofuel production. *New Phytologist* 215: 144–156. https://doi.org/10.1111/j.1469-8137.2011.03830.x.

Xu B, Liu S & Zhu T. 2014. Comparison of variations in the chemical constituents of the rhizome and culm of *Phyllostachys pubescens* at different ages. *BioResources* 9: 6745–6755.

Zhan H, Niu Z, Yu L, Li M, Wang C & Wang S. 2021. Dynamic changes of chemical and mechanical properties of moso bamboo (*Phyllostachys edulis*) culms under different storage conditions. *Journal of Renewable Materials* 9: 1031–1043.

Zhou B, Fu M, Xie J, Yang X & Li Z. 2005. Ecological functions of bamboo forest: research and application. *Journal of Tropical Forest Science* 16: 143–147.

Zhuo J, Vasupalli N, Wang Y et al. 2023. Molecular identification of *Bambusa changningensis* is the natural bamboo hybrid of *B. rigida* × *Dendrocalamus farinosus. Frontiers in Plant Science* 14. https://doi.org/10.3389/fpls.2023.1231940.