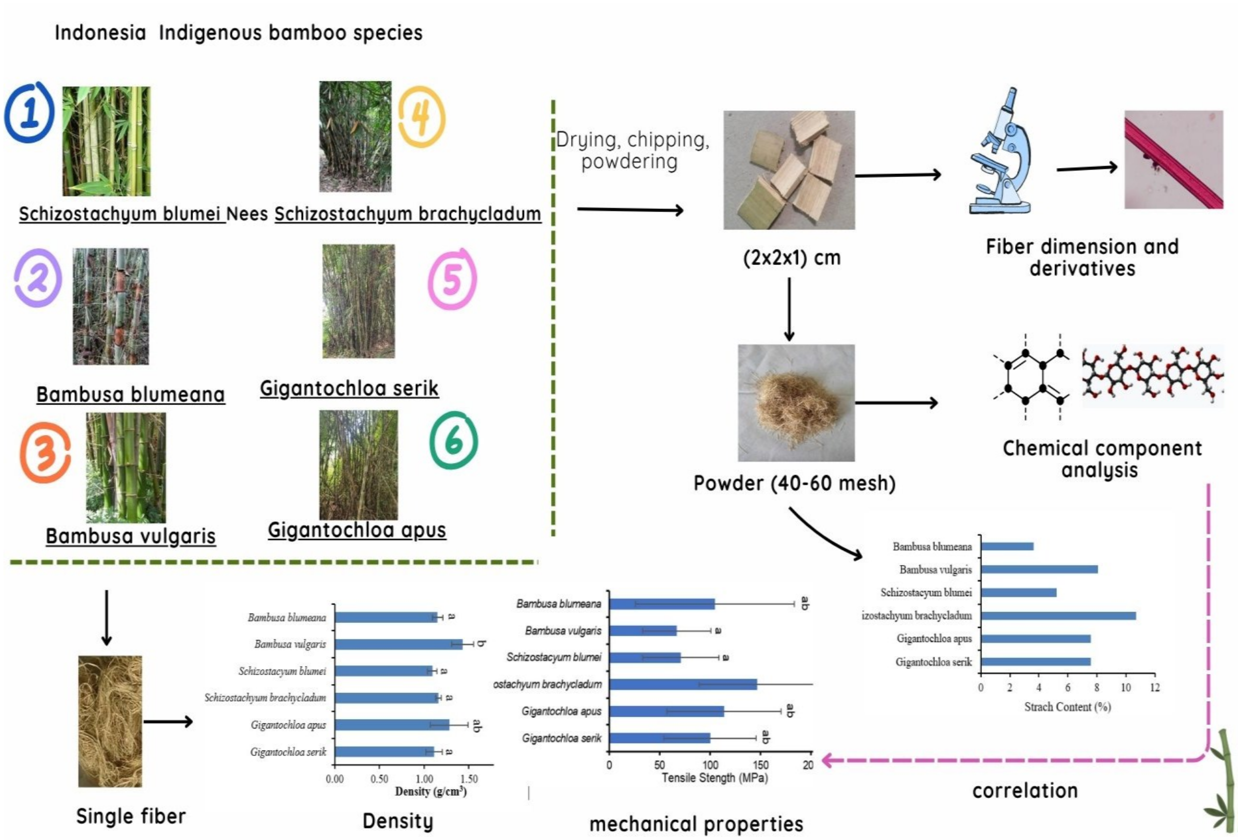
Comparative Analysis of Fiber Characteristics and Chemical, Physical, and Mechanical Properties of Six Indigenous Bamboo Species from Indonesia

Sarah Augustina,[a,*] Riana Anggraini,[b] Ika Yuliandari,[b] Antalina Florida br Marpaung,[b] Feby Savva Charisma,[b] Muhammad Rasyidur Ridho,[a,b] Pati Kemala,[a] Seng Hua Lee,[c,d] Apri Heri Iswanto,[e] Petar Antov,[f,*] and Widya Fatriasari,[a,*]

*Corresponding author: sara012@brin.go.id (S.A.); widy003@brin.go.id (W.F.); p.antov@ltu.bg (P.A.)

DOI: 10.15376/biores.20.4.8493-8514

GRAPHICAL ABSTRACT



Comparative Analysis of Fiber Characteristics and Chemical, Physical, and Mechanical Properties of Six Indigenous Bamboo Species from Indonesia

Sarah Augustina,[a,*] Riana Anggraini,[b] Ika Yuliandari,[b] Antalina Florida br Marpaung,[b] Feby Savva Charisma,[b] Muhammad Rasyidur Ridho,[a,b] Pati Kemala,[a] Seng Hua Lee,[c,d] Apri Heri Iswanto,[e] Petar Antov,[f,*] and Widya Fatriasari,[a,*]

Bamboo is a versatile, sustainable resource used in industries such as construction, furniture, textiles, and paper. Its species vary in properties, influencing their suitability for specific applications. This research aimed to perform a comparative analysis of the fiber characteristics and chemical properties of Indonesian bamboo species from the genera *Gigantochloa*, *Schizostachyum*, and *Bambusa*. Pearson's correlation analysis was performed to quantify associations among fiber characteristics, chemical composition, and mechanical performance. The results indicated that *Bambusa* presented the greatest fiber density, whereas *Gigantochloa* presented superior fiber dimensions, and *Schizostachyum* presented intermediate values. The mechanical properties of the fibers were inversely related to density. *Bambusa* showed the highest fiber dimensions, followed by *Schizostachyum*, whereas *Gigantochloa* presented the lowest scores, with the exception of the flexibility ratio. All the species, notwithstanding their variation, satisfied the criteria for fiber quality class II. The *Bambusa* species presented the highest contents of holocellulose, α-cellulose, and hemicellulose, followed by *Gigantochloa* and *Schizostachyum*. The highest concentration of starch was found in *Schizostachyum*, followed by *Gigantochloa*, and then *Bambusa*. Notably, *G. serik*, *S. brachycladum*, and *B. blumeana* have demonstrated considerable potential for pulp and paper applications, similar to traditional pulpwood species.

DOI: 10.15376/biores.20.4.8493-8514

Keywords: Bamboo fiber; Chemical properties; Fiber quality; Mechanical properties; Pearson's correlation; Physical properties

Contact information: a: Research Center for Biomass and Bioproducts, BRIN, Jl. Raya Bogor km 46, Bogor 16911, Indonesia; b:Department of Forestry, Faculty of Agriculture, University of Jambi, Jl. Lintas Jambi Ma, Bulian, Muaro Jambi, 36361, Indonesia; c: Department of Wood Industry, Faculty of Applied Sciences, Universiti Teknologi MARA Pahang Branch Jengka Campus, 26400 Bandar Tun Razak, Pahang, Malaysia; d: Institute for Infrastructure Engineering and Sustainable Management (IIESM), Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia; e: Pusat Unggulan IPTEK (PUI) Bambu, Universitas Sumatera Utara, Kampus USU 2 Bekala, Pancur Batu, 20353 Deli Serdang, Indonesia; f: Faculty of Forest Industry, University of Forestry, 1797 Sofia, Bulgaria;
**Corresponding authors: sara012@brin.go.id (S.A.); widy003@brin.go.id (W.F.); p.antov@ltu.bg (P.A.).*

INTRODUCTION

As versatile and sustainable natural resources within the subfamily Poaceae, bamboos are commonly termed ‘tree grasses’ and categorized as nonwood forest products. Bamboo consists of approximately 1,642 species that are naturally distributed across tropical, subtropical, and tropical monsoon regions, excluding Europe and Antarctica (Clark *et al.* 2015; Zhao *et al.* 2022). The species are categorized into three primary tribes: Arundinarieae (temperate bamboo, 546 species), Bambuseae (tropical bamboo, 812 species), and Olyreae (herbaceous bamboo, 124 species) (Clark *et al.* 2015). These tribes vary considerably in anatomical, chemical, and mechanical characteristics, which directly affect their suitability for specific industrial applications. Indonesia is estimated to harbor approximately 11.5% of the world's bamboo species, encompassing approximately 161 species across 20 genera. The majority are found in Sumatera (75 species), Java (60 species), Papua (30 species), Sulawesi (23 species), Kalimantan (22 species), Bali (19 species), Lesser Sunda Islands (14 species), and the Moluccas (13 species) (Widjaja 2000, 2014). Species from the Bambuseae tribe are prevalent in Indonesia, mainly found in lowland areas with tropical and humid climates, secondary forests, valleys, and rivers or streams (Widjaja 2000; Clark *et al.* 2015). The Bambuseae tribes are located primarily in the western regions of Indonesia and are predominantly represented by the genera *Bambusa*, *Gigantochloa*, and *Dendrocalamus*; conversely, the eastern regions are characterized by the genera *Schizostachyum*, *Dinochloa*, *Nastus*, and *Racemobambos* (Widjaja 2000). The application of these bamboo species relies on the essential properties intrinsic to each species, *e.g.*, their fiber attributes and chemical composition.

The cellular composition of bamboo culm primarily comprises parenchyma cells (50%), fiber cells (40%), and vascular bundles—which include vessels and sieve tubes accompanied by companion cells (about 10%) (Camargo Caicedo *et al.* 2025). Fiber cells represent the second most significant tissue following parenchyma cells and are composed of elongated sclerenchyma cells with tapered, frequently bifurcated ends. They are generally located encircling vascular bundles as protective sheaths or as discrete strands (Camargo Caicedo *et al.* 2025). The morphology and attributes of these fiber cells vary significantly across different bamboo species (Siam *et al.* 2019). Fei *et al.* (2016) reported notable variations in the fiber morphology of four Chinese bamboo species—*Gigantochloa brang*, *Gigantochloa levis*, *Gigantochloa scortechinii*, and *Gigantochloa wrayi*—specifically with respect to fiber length, diameter, cell wall thickness, and lumen size. Maulana *et al.* (2022) reported that *Dendrocalamus* species (*D. asperellus* and *D. giganteus*) possess longer fibers than *Bambusa* species (*B. vulgaris* var. vulgaris and *B. vulgaris* var. striata). Compared with other plant fibers, bamboo fibers exhibit superior mechanical properties, notably high stiffness and tensile strength, along with favorable elongation (Hakeem *et al.* 2015; Chin *et al.* 2020; Gao *et al.* 2022). Bamboo fibers have densities between 0.6 and 1.4 g/cm^3, tensile strengths of approximately 391 to 1000 MPa, and Young’s moduli ranging from 11 to 30 GPa (Petroudy 2017; Gao *et al.* 2022).

In addition to fiber characteristics, the chemical composition—specifically, cellulose, hemicellulose, lignin, other extractives, and ash content—affects the processing behavior of bamboo and is crucial for assessing its potential applications. The primary chemical components of bamboo include cellulose (45 to 55%), hemicellulose (15.3 to 32.0%), lignin (17.3 to 32.5%), with minor component i.e pectin (0.5 to 1.5%), extractives (1.6 to 13.0%), and ash (0.6 to 5.9%) (Moradbak *et al.* 2016; Rocky and

Thompson 2021; Rusch *et al.* 2023). Significant variation exists in the chemical compositions of different bamboo species. The species *B. blumeana* and *B. vulgaris*, possess comparable cellulose contents, with *B. vulgaris* demonstrating marginally higher lignin and extraction levels than *B. blumeana.* Moreover, compared with *Bambusa* species, *Gigantochloa* species present greater levels of cellulose, lignin, and extractive substances (Rusch *et al.* 2023).

The fiber characteristics and chemical compositions are interrelated, affecting the suitability of bamboo for diverse applications. Komuraiah *et al.* (2014) found that the cellulose content is positively correlated with the mechanical properties of bamboo fibers, specifically the tensile strength and density (R = 0.71 and 0.60, respectively). They also observed that cellulose content affects the specific strength, specific Young's modulus, and fiber length (R = 0.38, 0.37, and 0.29, respectively) (Komuraiah *et al.* 2014). Unlike cellulose content, lignin content is inversely correlated with mechanical properties (Komuraiah *et al.* 2014). Elevated lignin levels are typically correlated with increased rigidity and brittleness, potentially detrimental to the overall mechanical properties of bamboo fibers. Furthermore, Komuraiah *et al.* (2014) reported that the hemicellulose content is significantly correlated with the specific Young's modulus, specific strength, diameter, and moisture absorption (R = 0.69, 0.50, 0.07, and 0.42, respectively).

Conducting a comparative analysis of fiber characteristics and chemical properties was found to be both intriguing and demanding. Comprehending these variations is crucial for enhancing species selection for particular applications and augmenting product efficacy. This study examined the fiber characteristics, including density, mechanical properties, fiber dimensions, and fiber derived dimensions, alongside the chemical composition—specifically, cellulose, hemicellulose, lignin, extractives, ash and strach content—of various indigenous bamboo species in Indonesia, namely, *Gigantochloa apus*, *Gigantochloa serik*, *Schizostachyum brachycladum*, *Schizostachyum blumei*, *Bambusa vulgaris*, and *Bambusa blumeana*.

EXPERIMENTAL

Materials

Fresh bamboo culms, approximately 5 years old, averaging 6.5 cm at diameter breast height (DBH) and 9 m in length, were harvested from six indigenous species—*Gigantochloa apus*, *Gigantochloa serik*, *Schizostachyum brachycladum*, *Schizostachyum blumei*, *Bambusa vulgaris*, *and Bambusa blumeana*—which were collected from Lidung village, Sarolangun subdistrict, Sarolangun Regency, Jambi Province, Indonesia. The culms were manually reduced to chip sizes similar to those used in industry, measuring approximately 20 × 20 × 1 mm. The chips from each species were converted into powder (40- to 60-mesh) for chemical component analysis. Some of the chips were also converted into stick form for further maceration to assess fiber dimension and its derivatives value. For density and mechanical properties, individual fibers were carefully separated manually from fresh bamboo chips using a precision knife and tweezers under controlled conditions to avoid mechanical damage. The separation process involved gently splitting the chips along the natural fiber orientation to preserve fiber integrity, with the average fiber length of around 8 to 10 cm. Only undamaged, intact fibers with no visible signs of tearing or deformation were selected for testing. This approach ensured that the measured mechanical properties accurately reflected the native characteristics of the bamboo fibers.

The chemicals and reagents used in this study included safranin, acetic acid glacial (CH_3COOH), hydrogen peroxide (H_2O_2), sodium hydroxide (NaOH), ethanol (C_2H_6O), benzene (C_6H_6), sodium chlorite (HNO_3), sodium sulfite (Na_2SO_3), and destilled water. These chemicals and reagents were mainly procured from Merck Co., Ltd.

Fiber Characteristics Analysis

Fiber density measurement

The apparent density of individual bamboo fibers was determined *via* Archimedes' principle on the basis of water displacement, following ASTM D3800-17 (2017). Each single fiber was weighed via an analytical balance (±0.0001 g accuracy), and its volume was calculated by immersing the fiber in distilled water and measuring the displaced volume. The density (ρ) was calculated as follows,

$$\rho\ (\text{g/cm}^3) = m/V \tag{1}$$

where m is the mass (g) and V is the displaced volume (cm^3).

Mechanical properties of the fibers

Mechanical properties, including tensile strength and Young's modulus, were assessed *via* single-fiber tensile tests, which were conducted based on ASTM D3822-14 (2020). The analysis began by preparing individual bamboo fibers from each species with a length of approximately 10 cm. Prior to testing, the dimensions of all the samples, including diameter and length, were measured, and the samples were conditioned at ambient temperature (23 ± 2 °C) for 24 h. The latter fiber was mounted between two pieces of cardboard *via* a contact adhesive (Aibon glue). The cardboard, measuring 12 cm in length, was folded on both ends (5 cm each) to support the fiber. The fiber was sandwiched between the cardboard layers, leaving a 2 cm gap at the center for testing. The samples were clamped at both ends on a universal testing machine (UTM, Shimadzu, Japan) with a 10 kN load cell, and the crosshead speed was adjusted at 1 mm/min. The tensile strength (MPa) and Young's modulus (GPa) were calculated via the following equations:

$$\text{Tensile strength (MPa)} = \frac{F}{A} \tag{2}$$

$$\text{Young's Modulus (GPa)} = \frac{\text{tensile strength}}{\text{length at breaking point}} \tag{3}$$

where m is the F (maximal force of bamboo fiber until breaking point) and A is the cross-sectional area of bamboo fiber. All mechanical properties were reported in SI units (MPa for tensile strength and GPa for Young's modulus).

Fiber dimension measurement

Bamboo samples with dimensions of 2 cm × 2 cm × 1 cm were split into small flakes and placed into a test tube. A mixture of 60% acetic acid and 30% hydrogen peroxide was added until all the flakes were submerged. The tube was then heated at 80 °C in a water bath for 3.5 h until the bamboo samples turned pale and softened and the fibers were partially separated. After maceration, the solution was discarded, and the samples were rinsed using distilled water until neutral (free of acid). The fibers were then stained with safranin and left to absorb the dye before microscopic observation of intact fibers.

Fiber dimensions—including fiber length (*L*), fiber diameter (*d*), lumen diameter (*l*), and fiber wall thickness (*w*)—were observed and measured through optical microscopy. Fiber length was observed under 10× magnification, whereas fiber diameter and lumen diameter were measured under 20× magnification for improved accuracy. For each bamboo species, 25 intact and representative fibers were selected per replicate. Only fibers that were whole, unbroken, and free from visible damage, such as folds, splits, or tears, were considered for measurement to ensure the reliability of the data.

Table 1. Criteria of Fiber Quality as a Raw Material for Pulp and Paper Application

Criteria	Class I		Class II		Class III	
	Standard	Value	Standard	Value	Standard	Value
Fiber length	>2000	100	1.000-2000	50	>1000	25
Runkel ratio (RR)	<0,25	100	0,25-0,50	50	0,50-1,0	25
Felting power (FP)	>90	100	50-90	50	<50	25
Muhlstep ratio (MR)	<30	100	30-60	50	60-80	25
Flexibility ratio (FR)	>0,80	100	0,50-0,80	50	<0,50	25
Coefficient of rigidity (CR)	<0,10	100	0,10-0,15	50	>0,15	25
Total value	450 – 600		225 – 449		<225	

Several derivative values of fiber dimensions—including the Runkel ratio (RR), the felting power (FP), the muhlstep ratio (MR), the flexibility ratio (FR), and the coefficient of rigidity (CR)—were calculated to clarify the fiber morphology and its suitability for various applications, as follows,

$$\text{Runkel ratio} = 2w/l \tag{4}$$

$$\text{Felting ratio} = L/d \tag{5}$$

$$\text{Muhlsteph ratio} = ((\mathrm{d}^2 - \mathrm{I}^2)/\mathrm{d}^2) \times 100 \tag{6}$$

$$\text{Coeff. of rigidity} = w/d \tag{7}$$

$$\text{Flexibility Ratio} = l/d \tag{8}$$

where *L* is the fiber length (μm), *w* is the fiber wall thickness (μm), *d* is the fiber diameter (μm), and *l* is the lumen diameter (μm). The fiber quality was then analyzed and observed according to Rachman and Siagia (1976).

Chemical component analysis

The bamboo samples were processed into particles passing through a 40- to 60-mesh sieve to ensure uniformity. The holocellulose and alpha-cellulose contents were determined as previously described (Wise *et al.* 1946; Rowell 2005). The acid insoluble lignin (AIL) and acid soluble lignin (ASL) were determined following Sluiter *et al.* (2008), extractive content soluble in ethanol-benzene *via* TAPPI T-264 cm-97 (1997), and ash content *via* TAPPI T 211 om-07 (2007). Starch contents were analyzed using inhouse samogyi method.

Statistical analysis

All the data collected in this study, including the fiber dimensions (length, diameter, lumen diameter, and wall thickness), mechanical properties (tensile strength and Young's modulus), density, and chemical composition (cellulose, hemicellulose, lignin, extractives, and ash, as well as starch content), were analyzed *via* descriptive statistics to calculate the mean values and corresponding standard deviations for all parameters. To assess significant differences among the six bamboo species studied (*Gigantochloa apus*, *Gigantochloa serik*, *Schizostachyum brachycladum*, *Schizostachyum blumei*, *Bambusa vulgaris*, and *Bambusa blumeana*), one-way analysis of variance (ANOVA) was conducted using IBM SPSS 23.0 (SPSS Inc., Chicago, USA). When significant differences were detected among the factors or their interactions, Duncan's multiple range test was applied for further comparison. Pearson's correlation analysis was also carried out to examine the associations between fiber characteristics and chemical compositions.

RESULTS AND DISCUSSION

Fiber Characteristics

This research analyzed the fiber characteristics—density, mechanical properties, and dimensions—of six indigenous bamboo species from Indonesia, specifically the *Gigantochloa*, *Schizostachyum*, and *Bambusa* genera. Figure 1 shows the variation in fiber density values among the different bamboo species. The fiber density among the species varied from approximately 1.09 to 1.43 g/cm³. These values correspond with the previous results reported by Gao *et al.* (2022) and Petroudy (2017), which indicated that the bamboo fibers's density varies from 0.6 to 1.4 g/cm³. Salim *et al.* (2021) reported that the fiber density may reach 1.9 g/cm³. The average fiber density of *Bambusa* species (1.29 g/cm³) was the highest, followed by that of *Gigantochloa* species (1.19 g/cm³) and *Schizostachyum* species (1.12 g/cm³). *B. vulgaris* presented the highest density, followed by *G. apus*, whereas *S. blumei* presented the lowest density. Rusch *et al.* (2019) reported that *Bambusa* species present the highest average density, ranging from 0.61 to 0.78 g/cm³, whereas *Dendrocalamus* and *Guadua* species demonstrate lower average densities of 0.52 to 0.59 g/cm³ and 0.45 to 0.56 g/cm³, respectively. Chin *et al.* (2020) documented a comparable fiber density range for *G. scortechinii*, approximately 1.16 g/cm³. Nevertheless, data concerning fiber density ranges for *Schizostacyum* species are notably scarce due to the lack of comprehensive studies. Earlier research on this genus have examined the anatomical and fiber dimensions, along with the physical and mechanical properties of bamboo culms. The density values of the bamboo culm for *S. brachycladum* and *S. grandis* range from 0.55 to 0.80 g/cm³ and 0.53 to 0.85 g/cm³, respectively (Siam *et al.* 2019).

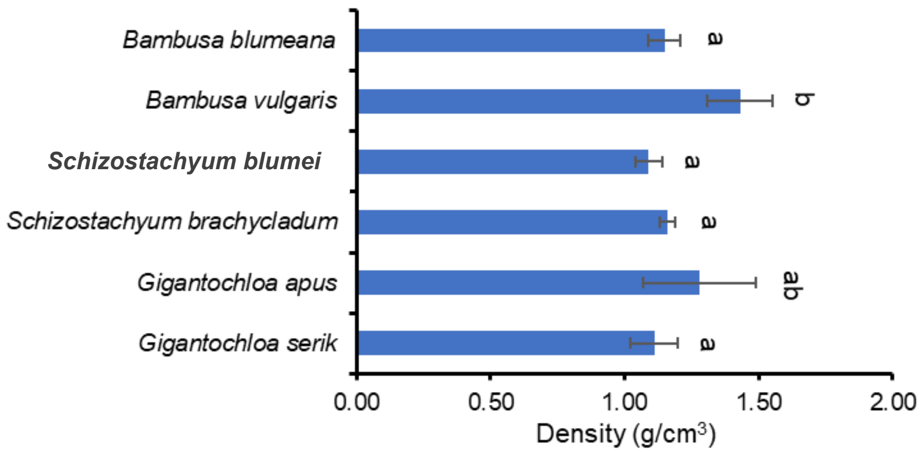
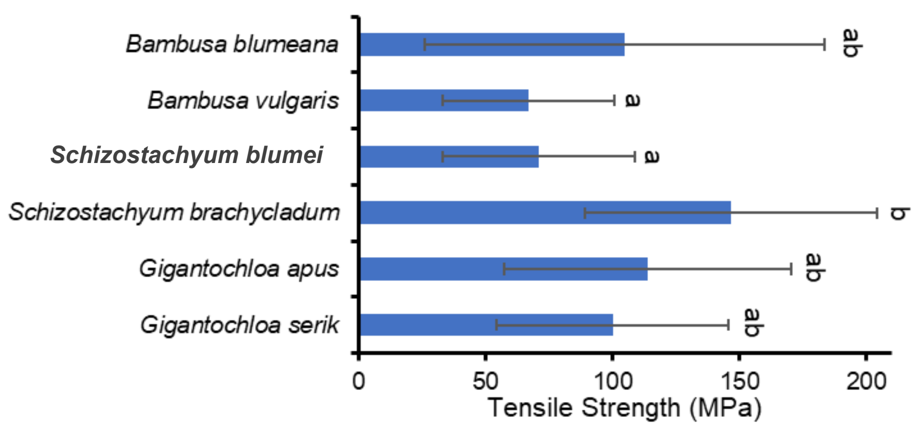
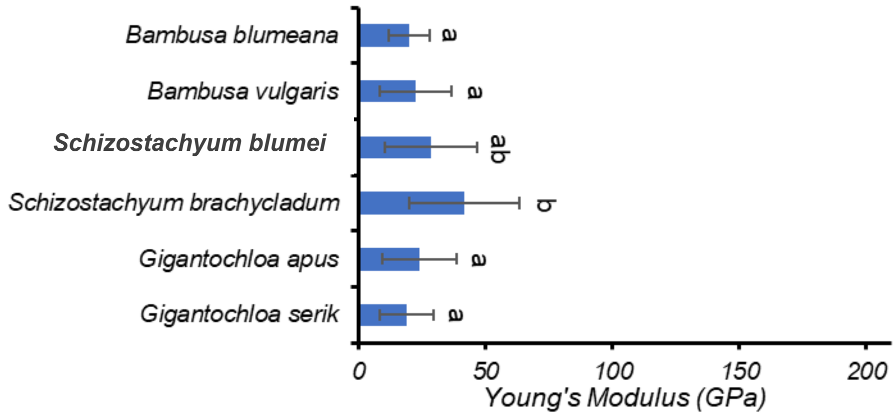


Fig. 1. Variation in the density values of six indigenous bamboo species from Indonesia. The letters displayed above the graph indicate statistically significant differences based on Duncan's test at a 5% significance level.

Conversely, the fluctuations in the mechanical properties, including the tensile strength and Young's modulus, are illustrated in Fig. 2. The tensile strength and Young's modulus values across the species ranged from 66.9 to 146.8 MPa and 18.9 to 41.7 GPa, respectively. These values are inferior to those reported by other researchers. Shekar and Ramachandra (2018) reported tensile strengths and Young's modulus ranging from approximately 193 to 600 MPa and 20.6 to 46 GPa, respectively, whereas Salim *et al.* (2021) and Ratna and Mohana (2011) stated tensile strengths and Young's modulus ranging from approximately 150 to 810 MPa and 35 to 46 GPa, respectively, for bamboo fibers. The average tensile strength and Young's modulus of *Schizostacyum* species (108.8 MPa and 35.1 GPa) were the highest, followed by those of *Gigantochloa* species (107.0 MPa and 21.4 GPa) and *Bambusa* species (85.9 MPa and 21.2 GPa) (Fig. 2). Among the examined species, *S. brachycladum* presented the highest values for both parameters, followed by *G. apus*, whereas *B. blumeana* presented the lowest density.



(a)



(b)

Fig. 2. Variation in the mechanical properties of six indigenous bamboo species from Indonesia: (a) tensile strength, and (b) Young's modulus. The letters displayed above the graph indicate statistically significant differences based on Duncan's test at a 5% significance level.

A contrasting trend was noted in the mechanical properties of these fibers relative to fiber density, especially in *Schizostachyum* and *Bambusa* species. This occurrence was substantiated by a negative correlation between fiber density and tensile strength for *Schizostachyum* species ($-1E\text{-}07x^2 + 0.0003x + 0.9746$; $R^2 = 0.80$) and *Bambusa* species ($-6E\text{-}08x^2 + 4E\text{-}05x + 1.2989$; $R^2 = 0.01$), whereas a positive correlation was observed for *Gigantochloa* species ($y = 5E\text{-}07x^2 - 0.0012x + 1.8206$; $R^2 = 0.88$). A notable negative correlation was observed between fiber density and the Young's modulus in *Gigantochloa* species ($y = -1E\text{-}11x^2 - 7E\text{-}06x + 1.3325$; $R^2 = 0.22$), *Schizostachyum* species ($y = -6E\text{-}11x^2 + 6E\text{-}06x + 1.0034$; $R^2 = 0.79$), and *Bambusa* species ($y = -1E\text{-}10x^2 + 8E\text{-}06x + 1.2199$; $R^2 = 0.06$), as illustrated in Fig. 3.

Figure 3 shows the relationships between fiber density and the mechanical properties of six indigenous bamboo species from Indonesia. The configuration of bamboo fibers directly affects their mechanical properties. A higher density is generally linked to improve mechanical performance, including increased tensile strength and Young's modulus (Shang *et al.* 2021). These findings significantly differed from the results obtained, which indicated the contrary phenomenon. Although the *Bambusa* species presented the highest average fiber density among the examined species, its tensile strength and Young's modulus values surpassed those of the *Gigantochloa* and *Schizostachyum* species. This phenomenon corresponds with previous findings (Gao *et al.* 2022) that mechanical properties are significantly contingent upon their origin and condition and are influenced primarily by bamboo species, moisture content, and matrix type. Moreover, this contrasting phenomenon may also result from the variation in the microfibril angle among the species.

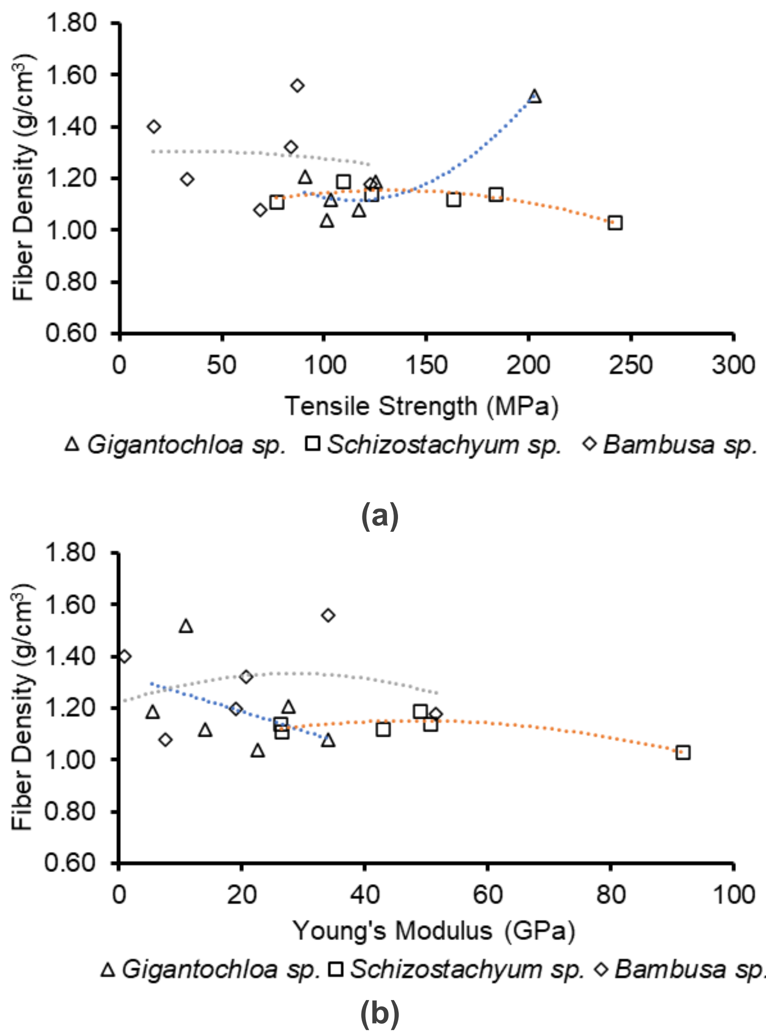


Fig. 3. Relationships between fiber density and the mechanical properties of six indigenous bamboo species from Indonesia: (a) tensile strength, and (b) Young's modulus

Maulana *et al.* (2022) reported that the genus *Bambusa* presents greater relative crystallinity in both its outer and inner regions than does the genus *Dendrocalamus*. Relative crystallinity denotes the ratio and dimensions of the crystalline domains within the cellulose framework. Yu *et al.* (2014) asserted that the mechanical properties along the axial direction are adversely influenced by the microfibril angle (MFA), indicating that an increased MFA can markedly diminish the mechanical strength, especially the tensile strength and Young's modulus. Moreover, Shang *et al.* (2021) found that the correlation between density and mechanical properties at the macroscopic level diverges significantly from that observed at the fiber and vascular bundle levels because of the influence of parenchymatous ground tissue.

Fiber dimensions

The fiber dimensions, including the fiber length, diameter, lumen diameter, and wall thickness, are listed in Table 2. These parameters are critical determinants affecting the physical, mechanical, and structural characteristics of the entire bamboo culm. Table 2 indicates that the fiber dimensions across the species varied from approximately 1795 to 3535 µm for fiber length; 15 to 38 µm for fiber diameter; 8 to 22 µm for lumen diameter; and 4 to 8 µm for wall thickness. The average fiber dimension of *Gigantochloa* species was the greatest, followed by that of *Schizostachyum* species, whereas *Bambusa* species presented the lowest values, with the exception of wall thickness (Table 2).

Table 2. Fiber Dimensions of Six Indigenous Bamboo Species from Indonesia

Bamboo Species	Fiber Dimensions			
	Fiber Length (µm)	Fiber Diameter (µm)	Lumen Diameter (µm)	Wall Thickness (µm)
Gigantochloa serik	3511 ± 940^{d}	38 ± 6^{e}	22 ± 8^{d}	8 ± 2^{c}
Gigantochloa apus	3177 ± 932^{cd}	33 ± 6^{d}	20 ± 5^{cd}	6 ± 2^{b}
Schizostachyum brachycladum	3535 ± 518^{d}	28 ± 5^{c}	18 ± 4^{c}	5 ± 2^{a}
Schizostacyum blumei	1795 ± 503^{a}	15 ± 4^{a}	6 ± 2^{a}	4 ± 1^{a}
Bambusa vulgaris	2307 ± 688^{b}	19 ± 6^{b}	8 ± 4^{ab}	5 ± 2^{a}
Bambusa blumeana	2839 ± 1164^{c}	20 ± 8^{b}	10 ± 6^{b}	5 ± 2^{a}

Note: The letters displayed beside the numbers indicate statistically significant differences based on Duncan's test at a 5% significance level.

S. *brachycladum* presented the longest fiber length, followed by *G. serik*, whereas *S. blumei* presented the shortest fiber length. The fiber length values were classified as moderately long (1.61 to 2.20 mm) for *S. blumei* and very long (2.21 to 3.00 mm) for the other bamboo species (IAWA 1989). Moreover, *G. serik* presented the greatest fiber diameter, lumen diameter, and wall thickness, followed by *G. apus*, whereas *S. blumei* presented the smallest values for all the parameters. Huang *et al.* (2015) documented the fiber dimensions of *B. rigida*, noting fiber lengths ranging from 1557 to 1777 µm, lumen diameters ranging from 1.90 to 4.28 µm, and wall thicknesses ranging from 9 to 11 µm.

Table 3. Variation in the Derivative Dimension Fibers of six Indigenous Bamboo Species from Indonesia

Bamboo Species	Derived Fiber Dimensions							
	Fiber Length (µm)	Runkel Ratio	Felting Power	Coefficient of Rigidity	Flexibility Ratio	Mulsteph Ratio	Total Value	Quality Class
Gigantochloa serik	3510 ± 940^{d}	0.79 ± 0.38^{a}	95 ± 27^{a}	0.21 ± 0.06^{a}	0.58 ± 0.13^{c}	64 ± 16^{a}	325	II
Gigantochloa apus	3176 ± 932^{cd}	0.67 ± 0.29^{a}	97 ± 32^{ab}	0.19 ± 0.50^{a}	0.61 ± 0.09^{c}	61 ± 11^{a}	325	II
Schizostachyum brachycladum	3535 ± 518^{d}	0.58 ± 0.24^{a}	131 ± 32^{c}	0.18 ± 0.05^{a}	0.65 ± 0.10^{c}	57 ± 12^{a}	350	II
Schizostacyum blumei	1794 ± 503^{a}	1.77 ± 0.91^{c}	126 ± 38^{bc}	0.30 ± 0.06^{b}	0.39 ± 0.11^{a}	83 ± 9^{b}	325	II
Bambusa vulgaris	2307 ± 687^{b}	1.66 ± 1.09^{bc}	138 ± 75^{c}	0.28 ± 0.09^{b}	0.44 ± 0.17^{ab}	77 ± 16^{b}	300	II
Bambusa blumeana	2838 ± 1163^{c}	1.33 ± 0.79^{b}	156 ± 80^{c}	0.26 ± 0.07^{b}	0.47 ± 0.14^{b}	75 ± 13^{b}	300	II

* Note: The letters displayed beside the numbers indicate statistically significant differences based on Duncan's test at a 5% significance level.

With the exception of wall thickness, these values were inferior to those recorded in the current study, notwithstanding the utilization of bamboo of identical age. Conversely, Maulana *et al.* (2022) reported comparable fiber lengths for *B. vulgaris*, ranging from 1982 to 2385 µm. Nordahlia *et al.* (2011) asserted analogous findings, examining the fiber morphology of *S. brachycladum* at various culm heights. They reported fiber lengths between 1907 and 3195 µm, fiber diameters ranging from 21 to 25 µm, lumen diameters ranging from 4.50 to 8 µm, and wall thicknesses ranging from 8 to 10 µm. Mustafa *et al.* (2011) documented fiber dimensions for various *Gigantochloa* species, which—in addition to wall thickness—were inferior to those presented in the present study.

Derivative dimension fibers

Table 3 indicates that the average derivative values for *Bambusa* species are the highest, followed by those for *Schizostachyum* species, whereas those for *Gigantochloa* species are the lowest, with the exception of the FR ratios. *S. blumei* presented the highest values—especially in RR, CR, and MR—followed by *B. vulgaris*, whereas *S. brachycladum* presented the lowest values, with the exceptions of FP and FR.

The Runkel ratio (RR) values for the examined species varied between 0.58 and 1.77. Comparable findings by Mohmod and Liese (2001) indicated that RR values for *G. scortechinii* range from 0.50 to 0.70, whereas *B. vulgaris* species demonstrate lower RR values of 0.20 to 0.26. The values exceed the RR values documented for *Acacia* hybrid, *Acacia mangium*, and *Eucalyptus* spp. (0.36 to 0.48), which are frequently utilized as raw materials in the pulp and paper sector (Ona *et al.* 2001; Yahya *et al.* 2010). Mohmod and Liese (2001) asserted that RR values less than one are typically regarded as favorable and appropriate for utilization as raw materials in the pulp and paper industry. Consequently, *G. serik*, *G. apus*, and *S. brachycladum* exhibit significant potential for this purpose. A lower RR typically signifies superior pulp and paper quality, as fibers with a reduced RR are more amenable to flattening and shaping, thereby increasing the surface area (Fatriasari and Hermiati 2008). Istikowati *et al.* (2016) and Ashori and Nourbakhsh (2009) reported that an increased fiber surface area augments interfiber bonding, consequently enhancing the strength of the resultant pulp and paper products.

Among the examined bamboo species, the FP values ranged from 156 to 95, with the highest values observed in *B. blumeana* and the lowest in *G. serik*. A comparable report was reported by Fatriasari and Hermiati (2008), who noted that the FR values for *Gigantochloa*, *Bambusa*, and *Dendrocalamus* species are significantly greater, ranging from 89 to 190. These values significantly exceeded the FP value of *A. mangium* (51.3%) documented by Yahya *et al.* (2010). A higher FP value signifies enhanced fiber flexibility, facilitating easier conformation and effective bonding with neighboring fibers during sheet formation (Fatriasari and Hermiati 2008). This improved bonding enhances interfiber adhesion, resulting in pulp and paper sheets with superior mechanical strength and durability (Augustina *et al.* 2020). Additionally, the CR values derived from this study varied between 0.30 and 0.18, surpassing those documented for *Acacia* spp. (0.13 to 0.17) (Yahya *et al.* 2010). *S. brachycladum* presented a CR value within this range, indicating that its fiber properties are analogous to those of widely utilized pulpwood species. Fatriasari and Hermiati (2008) reported that the CR values for *Gigantochloa*, *Bambusa*, and *Dendrocalamus* species are relatively high, ranging from 0.31 to 0.43. A reduced CR value is generally associated with increased tensile strength and burst factor, increased fiber flexibility, and superior interfiber bonding, all of which increase the mechanical performance of pulp and paper sheets.

The FR and MR values for the bamboo species varied from 0.39 to 0.65 and 83 to 57, respectively (Table 3). Fatriasari and Hermiati (2008) reported reduced FR values between 0.14 and 0.38, alongside elevated MR values ranging from 86.0 to 97.9 for the species *Gigantochloa*, *Bambusa*, and *Dendrocalamus.* The observed FR values were predominantly lower than those of *Eucalyptus* spp. (Ona *et al.* 2001), although *G. apus* and *S. brachycladum* presented FR values akin to those of *Acacia* spp. (Yahya *et al.* 2010). Ona *et al.* (2001) and Ashori and Nourbakhsh (2009) asserted that an elevated MR value enhances the sheet density, burst factor, breaking length, and folding endurance of pulp and paper products. Concurrently, the MR values were markedly elevated compared with those of *Acacia* spp., ranging between 45% and 55% (Yahya *et al.* 2010), especially in *S. blumei*, *B. vulgaris*, *B. blumeana*, *G. serik*, and *G. apus*. Moreover, *S. brachycladum* has a comparable MR value (57.2) to that of *Acacia* spp. (Ona *et al.* 2001) assert that reduced MR values are advantageous, as they facilitate the generation of superior pulp and paper products.

The total values of the derived fiber dimensions indicate that *S. brachycladum* (350) had the highest score, followed by *G. serik* and *G. apus* (325), whereas the lowest scores were attributed to *B. apus* and *B. blumeana* (300). Despite variations in scores among species, it was determined that all the examined bamboo species belonged to fiber quality class II. This classification indicates that the fiber characteristics remain appropriate for pulp and paper manufacturing. Class II fibers generally exhibit sufficient flexibility, slenderness, and wall thickness, which enhance fiber bonding and the mechanical strength of the final products (Rachman and Siagia 1976). The findings underscore the potential of the examined bamboo species, especially *S. brachycladum*, as a substitute sources for sustainable pulp and paper applications.

Chemical Compositions

Table 4 shows that the average chemical composition of *Bambusa* species is the highest, especially for holocellulose, α-cellulose, and hemicellulose, followed by that of *Gigantochloa* and *Schizostachyum* species. The highest ASL, extractive compound, and ash contents were identified in *Schizostacyum* species. Moreover, AIL values were elevated in *Gigantochloa* species, followed by *Bambusa* and *Schizostachyum* species.

The holocellulose and α-cellulose contents ranged from 64.3% to 69.8% and 47.0% to 51.8%, respectively, with *G. serik* exhibiting the highest values and *S. brachycladum* and *S. blumei* the lowest. The values are inferior to those documented by Fatriasari and Hermiati (2008) for *Gigantochloa*, *Bambusa*, and *Dendrocalamus* species, which ranged from 73.3% to 83.8%. The holocellulose and α-cellulose contents were also inferior to those of the prevalent wood species utilized in the pulp and paper industry, such as *Acacia* spp., which range from 71.3% to 82.9% and 40.6% to 45.7%, respectively (Yahya *et al.* 2010). Holocellulose and α-cellulose contents are positively correlated with pulp yield in the kraft pulping process (Yahya *et al.* 2010).

The lignin content, which encompasses AIL and ASL, ranged from 25.4% to 29.0%. The values were inferior to those of *Acacia* spp., which ranged from 30.9% to 34.1% (Yahya *et al.* 2010), as were those of *Gigantochloa*, *Bambusa*, and *Dendrocalamus* species obtained from another study, which ranged from 30.0% to 36.9% (Fatriasari and Hermiati 2008). A lignin content of 25 to 30% is typically advantageous, as it yields superior pulp quality—encompassing enhanced appearance, color, and physical characteristics—while necessitating reduced chemical usage in the kraft pulping process (Fatriasari and Hermiati 2008).

Table 4. Variation in the Chemical Compositions of Six Indigenous Bamboo Species from Indonesia

Bamboo Species	Chemical Compositions						
	Holocellulose (%)	α-cellulose (%)	Hemicellulose (%)	AIL (%)	ASL (%)	Extractives (%)	Ashes (%)
Gigantochloa serik	69.81 ± 1.23^{a}	51.79 ± 1.33^{a}	16.99 ± 1.06^{a}	23.01 ± 1.66^{a}	2.41 ± 0.04^{ab}	5.47 ± 0.86^{b}	1.48 ± 0.07^{a}
Gigantochloa apus	65.13 ± 1.30^{a}	48.91 ± 1.48^{b}	16.39 ± 0.28^{a}	26.82 ± 2.74^{c}	2.18 ± 0.13^{a}	5.81 ± 1.09^{b}	2.78 ± 0.27c
Schizostachyum brachycladum	64.34 ± 1.1^{a}	47.64 ± 0.62^{b}	14.85 ± 0.52^{a}	23.40 ± 0.25^{ab}	2.79 ± 0.12^{cd}	9.94 ± 0.88^{d}	2.22 ± 0.12^{b}
Schizostacyum blumei	66.23 ± 1.84^{a}	46.99 ± 2.02^{b}	12.63 ± 0.84^{a}	22.74 ± 0.31^{ab}	3.21 ± 0.34^{d}	1.85 ± 0.11^{a}	5.67 ± 0.14^{e}
Bambusa vulgaris	69.51 ± 3.16^{a}	51.54 ± 2.49^{b}	19.39 ± 3.98^{a}	22.98 ± 0.62^{ab}	2.60 ± 0.34^{bc}	3.28 ± 0.68^{a}	1.63 ± 0.03^{a}
Bambusa blumeana	66.84 ± 4.12^{a}	51.10 ± 1.64^{b}	15.83 ± 3.48^{a}	24.39 ± 0.98^{bc}	2.29 ± 0.08^{ab}	3.01 ± 1.12^{a}	3.46 ± 0.14^{d}

* Note: The letters displayed beside the numbers indicate statistically significant differences based on Duncan's test at a 5% significance level.

The values for extractives and ash content varied among species, ranging from 1.85% to 9.94% and from 1.48% to 5.67%, respectively. The values were higher than those reported for the *Gigantochloa*, *Bambusa*, and *Dendrocalamus* species by Fatriasari and Hermiati (2008), which ranged from 0.91 to 1.52% and from 1.89 to 4.63%, respectively. Yahya *et al.* (2010) reported that the extractively soluble in ethanol-benzene for *Acacia* spp. ranges from 2.90% to 5.96%. The extractive constituents soluble in ethanol-benzene solvents generally include resins, fatty acids, waxes, and tannins (Fatriasari and Hermiati 2008). These nonstructural compounds are deemed undesirable in pulp and paper production because they can disrupt chemical reactions during pulping and diminish pulp yield. A reduced concentration of ethanol–benzene extracts promote superior infiltration of pulping chemicals into the fiber matrix, thereby increasing lignin extraction efficiency and enhancing the overall efficacy of the pulping process. This also enhances paper quality and diminishes chemical usage during processing.

The starch content among the bamboo species ranged from 3.65% to 10.69% (Fig. 4). *Schizostachyum* presented the highest average starch content at 7.95%, followed by *Gigantochloa* at 7.56% and *Bambusa* at 5.87%. Rusch *et al.* (2023) reported that bamboo contains approximately 2.0 to 5.0% starch, 1.5 to 6.0% protein, 2.0% glucose, and 2.0 to 3.5% fat and wax. These values were comparable to those of *B. blumeana* and *S. blumei* but exceeded those of the other bamboo species examined in this research. Felisberto *et al.* (2019, 2020a; b) reported that the starch content of *B. vulgaris* reached 15%, surpassing that of *B. tuldoides* (3.12%) and *D. asper* (10%). The disparity in values among species may be ascribed to variations in starch accumulation patterns (Felisberto *et al.* 2020b). The starch yield in bamboo is chiefly determined by the age of the culm and the precise arrangement of starch granules within the tissue (Felisberto *et al.* 2020b). In addition to the obtained results, layer-specific chemical heterogeneity, such as localized concentrations of lignin, silica, or waxy substances in the outer layers, can significantly affect the behavior and performance of individual fibers and the bamboo culm as a whole.

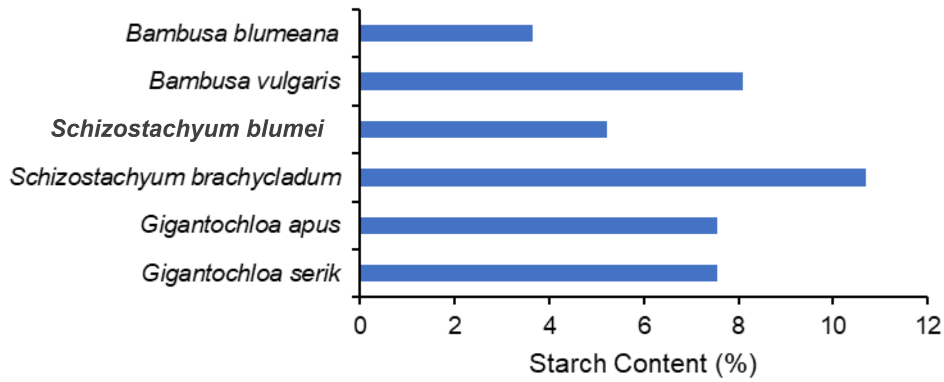


Fig. 4. Variation in starch content within six indigenous bamboo species from Indonesia

Correlation between the Mechanical Properties of Fibers and the Chemical Composition of Fibers

The characteristics of fibers and their chemical compositions are related to the mechanical properties of individual fibers or fiber bundles, which also represent the overall properties of the bamboo culm. Table 5 shows the Pearson correlations between the fiber dimensions and mechanical properties of six indigenous bamboo species from the genera *Gigantochloa*, *Schizostachyum*, and *Bambusa*. Overall, fiber length and diameter, along with lumen diameter, were negatively correlated with mechanical properties, whereas fiber wall thickness was positively correlated with mechanical properties.

Table 5. Pearson's Correlation between Fiber Dimensions and Fiber Mechanical Properties

Fiber Dimension	Pearson's Correlation		
	Fiber Density	Tensile Strength	Young Modulus
Fiber Length	-0.547	-0.034	-0.051
Fiber Diameter	-0.268	-0.070	-0.160
Lumen Diameter	-0.243	-0.195	-0.223
Wall Thickness	0.051	0.168	0.079

Table 5 indicates a moderate negative correlation between fiber length and fiber density, implying that longer fibers are generally less dense. A negligible negative correlation was observed between the fiber length and both the tensile strength and the Young's modulus. This may result from longer fibers being linked to a more open void and a less compact structure, potentially detrimental to their mechanical properties. Habibi *et al.* (2017) reported that fiber length substantially affects pore size and porosity, as longer fibers tend to be less densely arranged due to an enlarged maximum pore size

(MaxPS). Tomczak *et al.* (2007) reported a similar phenomenon, identifying a negative correlation between the curaua fiber length and its tensile strength and strain to failure values. Petroudy (2017) reported that comprehending the minimum fiber length/critical fiber length (lcrit) and its distribution is crucial for maintaining fiber strength and assessing the efficacy of the reinforcement material.

The fiber diameter and lumen diameter exhibited moderate to weak negative correlations with the fiber density, tensile strength, and Young's modulus. Cell wall thickness demonstrated a marginal positive correlation with these parameters. Fibers with larger diameters and lumen cells may result in reduced packing density and increased interfiber voids. Karimah *et al.* (2021) reported that an increase in porosity is directly correlated with a larger fiber diameter and lumen size, resulting in a decrease in density. This finding aligns with Jones and Duncan (1971) and (Baley (2002), who reported that fibers with a greater diameter and higher lumen proportion demonstrate lower tensile strength and Young's modulus than thinner fibers do. This may be due to a diminished surface area-to-volume ratio, potentially influencing the load-bearing capacity of the fibers during mechanical testing. Baley (2002) asserted that an increase in the lumen size may substantially reduce the actual cross-sectional area of the fibers.

Conversely, the cell wall thickness exhibited an inverse relationship with the other parameters. Increased cell wall thickness can enhance the mechanical properties of fibers. This enhancement can be ascribed to the optimal alignment of the crystalline structures along the fiber axis, which promotes more effective stress transfer and improve the tensile strength and stiffness of the fibers (Chesney *et al.* 2016). Jones and Duncan (1971) asserted that the crystallite structure near the fiber surface (sheaths) tends to be larger, better aligned, and oriented parallel to the fiber axis. Consequently, an increase in the sheath yields a higher modulus value in the fully graphitized fiber (Jones and Duncan 1971). Chesney *et al.* (2016) noted that the 'core-sheath' effect relates to the fiber's layered structure and the differences in mechanical properties across its cell walls. Beyond the observed phenomena, microstructural characterization represents a critical avenue for future research, offering deeper insights into the relationship between fiber morphology, internal structure, *e.g.*, alignment and porosity, and mechanical performance.

Table 6 shows the Pearson correlation between the chemical composition and the mechanical properties of the fibers. It is apparent that holocellulose and α-cellulose were moderately positively correlated with the fiber density, tensile strength, and Young's modulus. Komuraiah *et al.* (2014) reported analogous findings, indicating the cellulose content is the primary factor affecting the mechanical properties of natural fibers, which is positively correlated with both the tensile strength and Young's modulus. The positive correlations may be attributed to the highly ordered parallel polymer chains and the rigid structure of cellulose, which enhance intermolecular bonding and increase the load-bearing capacity (Huang *et al.* 2015). Petroudy (2017) reported that several factors influence the mechanical properties of fibers, including cellulose content, polymerization degree, crystallinity, and microfibrils alignment within the cellulose structure.

Table 6. Pearson's Correlation between Chemical Composition and Fiber Mechanical Properties

Chemical Compositions	Pearson's Correlation		
	Fiber Density	Tensile Strength	Young Modulus
Holocellulose	0.301	0.112	0.214
α-cellulose	0.282	0.344	0.251
Hemicellulose	-0.432	-0.004	0.155
Total lignin	0.321	0.332	-0.275
Extractives	-0.017	-0.020	0.027
Ashes	0.075	-0.175	-0.405

Hemicellulose was significantly negatively correlated with fiber density, indicating that increased hemicellulose content undermines structural compactness. The insignificant impact on tensile strength and weak positive correlation with Young's modulus indicate its limited structural contribution. Similarly, Komuraiah *et al.* (2014) reported that the hemicellulose content is negatively correlated with the tensile strength and density but positively correlated with the specific Young's modulus. This is anticipated because hemicellulose is a heterogeneous polysaccharide characterized by irregularly arranged side chain groups, a lower degree of polymerization, an amorphous structure, and high hygroscopicity, resulting in inadequate reinforcement properties (Youssefian and Rahbar 2015). Simultaneously, total lignin—comprising AIL and ASL—exhibits a positive correlation with density and tensile strength, indicating a role in structural reinforcement. Nonetheless, its adverse effect on the Young's modulus signifies restricted flexibility and diminished resilience under stress. Komuraiah *et al.* (2014) reported divergent findings, indicating that lignin is negatively correlated with tensile strength, specific strength, specific Young's modulus, and density. This dual function illustrates the role of lignin as a matrix filler and its intrinsic brittleness (Youssefian and Rahbar 2015). Rusch *et al.* (2023) asserted that bamboo lignin is an amorphous phenolic macromolecule characterized by a molar ratio of 10:68:22 and has higher degree of polymerization values than dicotyledonous wood does (maximum 15,000).

Extractives demonstrate minimal correlations with mechanical properties, suggesting that their presence neither significantly enhances nor impairs fiber performance. Moreover, the ash content has a moderate negative correlation with the Young's modulus and a weaker negative correlation with the tensile strength, while it has a negligible positive correlation with the fiber density. Komuraiah *et al.* (2014) reported a similar correlation, indicating that wax, which is soluble in ethanol-benzene solution, is positively correlated with the Young's modulus but negatively correlated with the density and specific strength of fibers. These findings indicate that elevated levels of extractives and ash may impede fiber–matrix adhesion in composites, causing microdefects and stress concentrations, which ultimately diminish their mechanical performance (Rusch *et al.* 2023).

CONCLUSIONS

1. Significant variations in fiber characteristics, including density, mechanical properties, fiber dimensions, and fiber derived dimensions, alongside the chemical

composition were identified among the six indigenous bamboo species from Indonesia (*Gigantochloa, Schizostachyum, Bambusa*), demonstrating their distinct material potentials.

2. Additional significant variations were observed in fiber characteristics, where *Bambusa* exhibited the highest fiber density, *Gigantochloa* possessed the largest fiber dimensions, and *Schizostachyum* showed intermediate values.
3. An inverse relationship exists between fiber density and mechanical properties.
4. Based on the derived fiber values, *Bambusa* exhibited superior overall performance, followed by *Schizostachyum*, while *Gigantochloa* generally ranked lowest, except in the case of the flexibility ratio (FR), where a deviation from this pattern was observed. All species qualified for fiber quality class II.
5. In terms of chemical composition, *Bambusa* exhibited the highest levels of holocellulose, α-cellulose, and hemicellulose. Starch content varied from 3.65% to 10.69%, with *Schizostachyum* presenting the highest concentration and *Bambusa* the lowest.
6. Three species (*G. serik, S. brachycladum, B. blumeana*) show strong potential for pulp and paper applications, comparable to conventional pulpwood.
7. Pearson correlation analysis revealed:
    - Negative correlations between fiber length, diameter, lumen size, and mechanical properties.
    - Positive correlation between fiber wall thickness and mechanical strength.
    - Holocellulose, α-cellulose, and lignin contributed positively to fiber density and strength.
    - Hemicellulose and ash content negatively affected mechanical properties.
    - Extractives had minimal effect.
8. These findings demonstrate the high potential of selected indigenous bamboo species from Indonesian as sustainable raw materials for pulp, paper, and broader industrial uses.

ACKNOWLEDGMENTS

The authors express gratitude for the support from the Ministry of Finance in conjunction with the Ministry of Research and Technology/National Research and Innovation Agency (Kemenristek-BRIN), grant numbers 273/E1/PRN/2020, B-4528/IPH/KS.02.04/VII/2020 and Research Collaboration Center (PKR) of Biomass and Bioproducts Bamboo Indonesia, grant numbers B-1146/II.7/HK.01.00/5/2025. The authors are grateful to the postdoctoral program of the National Research and Innovation Agency-BRIN (grant number: 140/II/HK/2024), Dr. Pati Kemala. The authors like to express their gratitude to the Integrated Laboratory of Bioproducts, National Research and Innovation Agency (BRIN), for providing the facilities for experimentation and testing services. This research received assistance and funding from the project titled "Development, Exploitation Properties and Application of Eco-Friendly Wood-Based Composites from Alternative Lignocellulosic Raw Materials," project No. НИС-Б-1290/19.10.2023, conducted at the University of Forestry in Sofia, Bulgaria.

REFERENCES CITED

Ashori, A., and Nourbakhsh, A. (2009). "Studies on Iranian cultivated paulownia - A potential source of fibrous raw material for paper industry," *Holz als Roh- und Werkstoff* 67, 323-327. DOI: 10.1007/s00107-009-0326-0

ASTM D3822-14 (2020). "Standard test method for tensile properties of single textile fibers," ASTM International, West Conshohocken, PA, USA.

ASTM D3800 (2017). "Standard test method for density of high-modulus fibers," ASTM International, West Conshohocken, PA, USA.

Augustina, S., Wahyudi, I., Darmawan, W., and Malik, J. (2020). "Ciri Anatomi, Morfologi Serat, dan Sifat Fisis Tiga Jenis Lesser-Used Wood Species Asal Kalimantan Utara, Indonesia," *Jurnal Ilmu Pertanian Indonesia* 25, 599-609. DOI: 10.18343/jipi.25.4.599

Baley, C. (2002). "Analysis of the flax fibres tensile behaviour and analysis of the tensile stiffness increase," *Composites Part A: Applied Science and Manufacturing* 33(7), 939-948. DOI: 10.1016/S1359-835X(02)00040-4

Camargo Caicedo, Y., Arango, J. A. M., and Muriel, A. P. (2025). "Anato-morphological and chemical characterization of bamboo (*Guadua amplexifolia* J. Presl) from San Jorge River Basin, Colombia," *Cleaner Engineering and Technology* 24, 100884. DOI: 10.1016/j.clet.2025.100884

Chesney, P., Jernot, J., Bréard, J., and Gomina, M. (2016). "Young's modulus of plant fibers. In: *Natural Fibres: Advances in Science and Technology Towards Industrial Applications*, F. Rohel and R. Sohel R (eds.), Springer International Publishing, Cham, Switzerland.

Chin, S. C., Tee, K. F., Tong, F. S., Ong, H. R., and Gimbun, J. (2020). "Thermal and mechanical properties of bamboo fiber reinforced composites," *Materials Today Communications* 23, article 100876. DOI: 10.1016/j.mtcomm.2019.100876

Clark, L. G., Londoño, X., and Ruiz-Sanchez, E. (2015). "Bamboo taxonomy and habitat," in: *Bamboo: The Plant and its Uses*, W. Liese and M. Köhl (eds.), Springer International Publishing, Cham, Switzerland, pp. 1-30. DOI: 10.1007/978-3-319-14133-6_1

Fatriasari, W., and Hermiati, E. (2008). "Analisis Morfologi Serat dan Sifat Fisis-Kimia Pada Enam Jenis Bambu Sebagai Bahan Baku Pulp dan Kertas," *Jurnal Ilmu dan Teknologi Hasil Hutan* 1(2), 67-72.

Fei, B., Gao, Z., Wang, J., and Liu, Z. (2016). "Biological, anatomical, and chemical characteristics of bamboo," in: *Secondary Xylem Biology: Origins, function, and application*, Y. S. Kim, R. Funada, and A. P. Singh (eds.), Academic Press Inc.

Felisberto, M. H. F., Beraldo, A. L., Costa, M. S., Boas, F. V., Franco, C. M. L., and Clerici, M. T. P. S. (2019). "Physicochemical and structural properties of starch from young bamboo culm of *Bambusa tuldoides*," *Food Hydrocolloids* 87, 101-107. DOI: 10.1016/j.foodhyd.2018.07.032

Felisberto, M. H. F., Beraldo, A. L., Costa, M. S., Boas, F. V., Franco, C. M. L., and Clerici, M. T. P. S. (2020a). "*Bambusa vulgaris* starch: Characterization and technological properties," *Food Research International* 132, article 109102. DOI: 10.1016/j.foodres.2020.109102

Felisberto, M. H. F., Beraldo, A. L., Costa, M. S., Boas, F. V., Franco, C. M. L., and Clerici, M. T. P. S. (2020b). "Characterization of young bamboo culm starch from *Dendrocalamus asper*," *Food Research International* 124, 222-229. DOI:

10.1016/j.foodres.2018.03.074
Gao, X., Zhu, D., Fan, S., Rahman, M. Z., Guo, S., and Chen, F. (2022). "Structural and mechanical properties of bamboo fiber bundle and fiber/bundle reinforced composites: A review," *Journal of Materials Research and Technology* 19, 1162-1190. DOI: 10.1016/j.jmrt.2022.05.077
Habibi, Mohamed, Ruiz, Édu, Lebrun, Gilbert, and Laperrière, Luc. (2017). "Effect of surface density and fiber length on the porosity and permeability of nonwoven flax reinforcement," *Textile Research Journal* 88(15), 1776-1787. DOI: 10.1177/0040517517708542
Hakeem, K., Ibrahim, S., Ibrahim, F., and Tombuloglu, H. (2015). "Bamboo biomass: Various studies and potential applications for value-added products," in: *Agricultural Biomass Based Potential Materials*, K. Hakeem, M. Jawaid, and O. Y. Alothman (Eds.), Springer, Cham, Switzerland. DOI: 10.1007/978-3-319-13847-3_11
Huang, X., Jin, Q., Xie, J., Jian, F., Bai, D., and Si, M. (2015). "Variation in anatomical characteristics of bamboo, *Bambusa rigida*," *Sains Malaysiana* 44, 17-23. DOI: 10.17576/jsm-2015-4401-03
Istikowati, W. T., Haruna, A., Budi, S., Futoshi, I., Jyunichi, O., Kazuya, I., and Yokota, S. (2016). "Wood, chemical, and pulp properties of woods from less-utilized fast-growing tree species found in naturally regenerated secondary forest in South Kalimantan, Indonesia," *Journal of Wood Chemistry and Technology* 36(4), 250-258. DOI: 10.1080/02773813.2015.1124121
Jones, B. F., and Duncan, R. G. (1971). "The effect of fibre diameter on the mechanical properties of graphite fibres manufactured from polyacrylonitrile and rayon," *Journal of Materials Science* 6(4), 289-293. DOI: 10.1007/BF02403094
Karimah, A., Ridho, M. R., Munawar, S. S., Adi, D. S., Ismadi, Damayanti, R., Subiyanto, B., Fatriasari, W., and Fudholi, A. (2021). "A review on natural fibers for development of eco-friendly bio-composite: Characteristics, and utilizations," *Journal of Materials Research and Technology* 13, 2442-2458. DOI: 10.1016/j.jmrt.2021.06.014
Komuraiah, A., Kumar, N. S., and Prasad, B. D. (2014). "Chemical composition of natural fibers and its influence on their mechanical properties," *Mechanics of Composite Materials* 50(3), 359-376. DOI: 10.1007/s11029-014-9422-2
Maulana, M. I., Jeon, W. S., Purusatama, B. D., Kim, J. H., Prasetia, D., Yang, G. U., and Muhammad Savero, A. Nawawi, D., Nikmatin, S., Sari, R. K., Febrianto, F., Lee, S. H., and Kim, N. H. (2022). "Anatomical characteristics for identification and quality indices of four promising commercial bamboo species in Java, Indonesia," *BioResources* 17(1), 1442-1453. DOI: 10.15376/biores.17.1.1442-1453
Mohmod, A., and Liese, W. (2001). "Anatomical features of *Bambusa vulgaris* and *Gigantochloa scortechinii* from four harvesting sites in peninsular Malaysia," *Journal of Tropical Forest Products* 7(1), 10-28.
Moradbak, A., Tahir, P., Mohamed, A., and Halis, R. (2016). "Alkaline sulfite anthraquinone and methanol pulping of bamboo (*Gigantochloa scortechinii*)," *BioResources* 11(1), 235-248. DOI: 10.15376/biores.11.1. 235-248
Mustafa, M., Wahab, R., Sudin, M., Sulaiman, O., Ain, N., Kamal, M., and Khalid, I. (2011). "Anatomical and microstructures features of tropical bamboo *Gigantochloa brang*, *G. levis*, *G. scotechinii* and *G. wrayi*," *International Journal of Forest, Soil and Erosion* 1(1), 25-35.
Nordahlia, A., Uyup, M. K. A., Husain, H., Mohmod, A., and Sarif, M. (2011).

"Anatomical, physical and strength properties of *Shizostachyum brachycladum* (Buluh lemang)," *Journal of Bamboo and Rattan* 10, 111-122.
Ona, T., Sonoda, T., Ito, K., Shibata, M., Tamai, Y., Kojima, Y., Ohshima, J., Yokota, S., and Yoshizawa, N. (2001). "Investigation of relationships between cell and pulp properties in Eucalyptus by examination of within-tree property variations," *Wood Science and Technology* 35(3), 229-243. DOI: 10.1007/s002260100090
Petroudy, D. (2017). "Physical and mechanical properties of natural fibers," in: *Advanced High Strength Natural Fibre Composites in Construction*, M. Fan and F. B. T.-A. H. S. N. F. C. in C. Fu (eds.), Woodhead Publishing, Sawston, UK, pp. 59-83. DOI: 10.1016/B978-0-08-100411-1.00003-0
Rachman, A., and Siagia, R. (1976). *Dimensi Serat Jenis Kayu Indonesia Bagian III. Laporan LPHH No. 75. Bogor*, Pusat Litbang Hasil Hutan.
Ratna, P., and Mohana, R. (2011). "Mechanical properties of natural fibre reinforced polyester composites: Jowar, sisal and bamboo," *Materials & Design* 32(8), 4658-4663. DOI: 10.1016/j.matdes.2011.03.015
Rocky, B. P., and Thompson, A. J. (2021). "Analyses of the chemical compositions and structures of four bamboo species and their natural fibers by infrared, laser, and X-ray spectroscopies," *Fibers and Polymers* 22(4), 916-927. DOI: 10.1007/s12221-021-0303-8
Rowell, R. (2005). *Handbook of Wood Chemistry and Wood Composites* (2nd Ed.), Taylor and Francis, New York. DOI: 10.1201/b12487
Rusch, F., Ceolin, G., and Hilig, É. (2019). "Morphology, density and dimensions of bamboo fibers: A bibliographical compilation," *Pesquisa Agropecuária Tropical* 49(1), article e55007.
Rusch, F., Wastowski, A. D., de Lira, T. S., Moreira, K. C. C. S. R., and de Moraes Lúcio, D. (2023). "Description of the component properties of species of bamboo: A review," *Biomass Conversion and Biorefinery* 13(3), 2487-2495. DOI: 10.1007/s13399-021-01359-3
Salim, Suryani, Rihayat, Teuku, Riskina, Shafira, and Safitri, Aida. (2021). "Physical and mechanical properties of bamboo/flax fibre reinforced epoxy composite water absorption behaviour and high-temperature conditions," *Plastics, Rubber and Composites* 50(8), 415-424. DOI: 10.1080/14658011.2021.1910776
Shang, L., Liu, X., Jiang, Z., Tian, G., and Yang, S. (2021). "Variation in tensile properties of single vascular bundles in moso bamboo," *Forest Products Journal* 71(3), 246-251.
Shekar, H. S. S., and Ramachandra, M. (2018). "Green composites: A review," *Materials Today: Proceedings* 5(1, Part 3), 2518-2526. DOI: 10.1016/j.matpr.2017.11.034
Siam, N., Uyup, M., Husain, H., Mohmod, A., and Awalludin, M. (2019). "Anatomical, physical, and mechanical properties of thirteen Malaysian bamboo species," *BioResources* 14(2), 3925-3943. DOI: 10.15376/biores.14.2.3925-3943
Sluiter, A., Hames, B., Ruiz, R., Scarlata, C., Sluiter, J., Templeton, D., and Crocker, D. (2008). *Determination of Structural Carbohydrates and Lignin in Biomass* (NREL/TP-510-42618), National Renewable Energy Laboratory, Golden, CO, USA.
TAPPI T 264 cm-97 (1997). "Preparation of wood for chemical analysis," TAPPI Press, Atlanta, USA.
TAPPI T 211 om-02 (2007). "Ash in wood, pulp, paper and paperboard: Combustion at 525°C," TAPPI Press, Atlanta, USA.
Tomczak, F., Satyanarayana, K. G., and Sydenstricker, T. H. D. (2007). "Studies on

lignocellulosic fibers of Brazil: Part III – Morphology and properties of Brazilian curauá fibers," *Composites Part A: Applied Science and Manufacturing* 38(10), 2227-2236. DOI: 10.1016/j.compositesa.2007.06.005

Widjaja, E. (2000). "Bamboo diversity and its future prospect in Indonesia," in: *Proceeding of the third International Wood Science Symposium-Wood Research Institute*, Kyoto, Japan.

Widjaja, E. (2014). "Budidaya bambu untuk menunjang pemanfaatan dan konservasinya," *Makalah dalam Lokakarya Bambu Flores di Borong tanggal 2–5 September 2014*.

Wise, L. E., Murphy, M., and Adieco, A. A. D. (1946). "A chlorite holocellulose, its fractionation and bearing on summative wood analysis and studies on the hemicelluloses," *Paper Trade Journal* 122(2), 35-43.

Yahya, R., Sugiyama, J., Silsia, D., and Gril, J. (2010). "Some anatomical features of an Acacia hybrid, A. mangium and A. auriculiformis grown in Indonesia with consideration of pulp yield and paper strength," *Journal of Tropical Forest Science* 22.

Youssefian, S., and Rahbar, N. (2015). "Molecular origin of strength and stiffness in bamboo fibrils," *Scientific Reports* 5(1), article 11116. DOI: 10.1038/srep11116

Yu, Y., Wang, H., Lu, F., Tian, G., and Lin, J. (2014). "Bamboo fibers for composite applications: A mechanical and morphological investigation," *Journal of Materials Science* 49(6), 2559-2566. DOI: 10.1007/s10853-013-7951-z

Zhao, H., Wang, J., Meng, Y., Li, Z., Fei, B., Das, M., and Jiang, Z. (2022). "Bamboo and rattan: Nature-based solutions for sustainable development," *The Innovation* 3(6), article 100337. DOI: 10.1016/j.xinn.2022.100337

Article submitted: June 16, 2025; Peer review completed: July 19, 2025; Revised version received and accepted: July 25, 2025; Published: August 5, 2025.
DOI: 10.15376/biores.20.4.8493-8514