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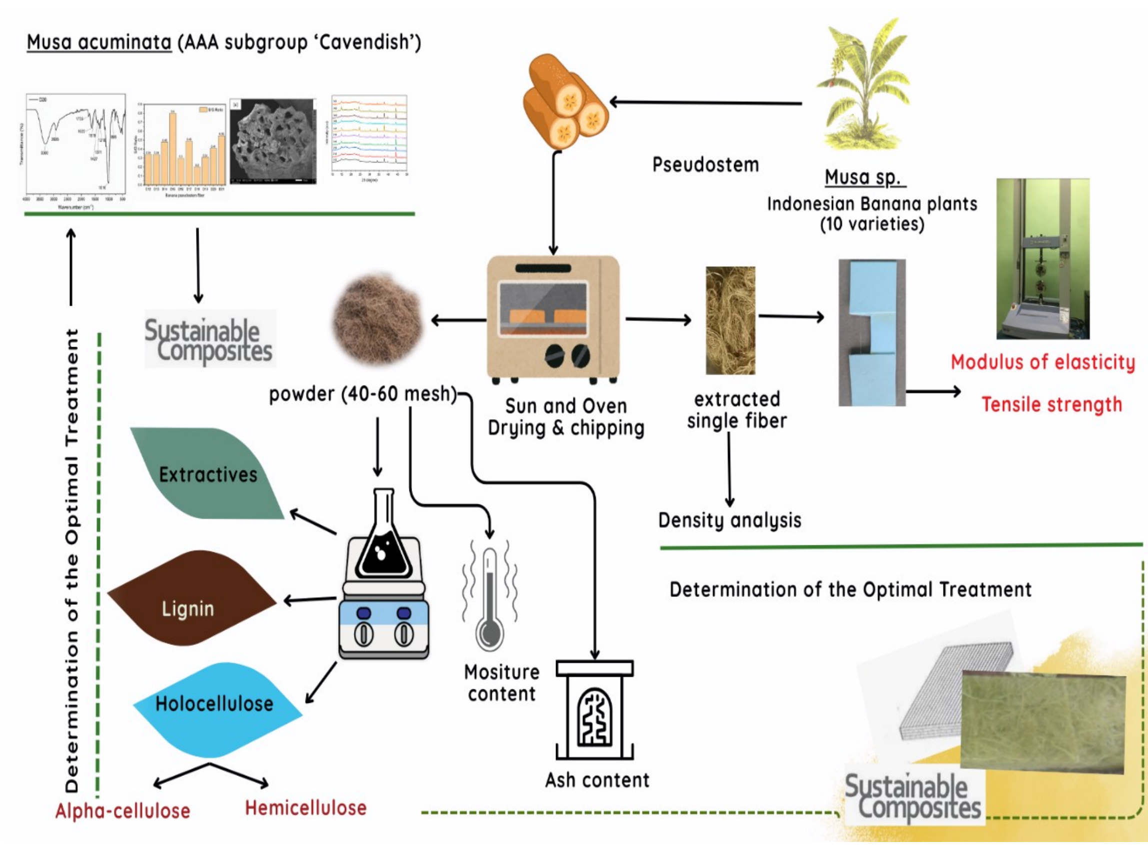
GRAPHICAL ABSTRACT



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Banana pseudostem (*Musa sp.*) fibers from 10 Indonesian cultivars were evaluated as candidate renewable sources for biomaterial development. Their physical properties (density and moisture content), mechanical strength (tensile strength and elastic modulus), and chemical composition, including lignin, holocellulose, α-cellulose, and hemicellulose content levels were analyzed. Pyrolysis–gas chromatography-mass spectrometry (Py-GC/MS) was employed to determine the syringyl-to-guaiacyl (S/G) ratio, providing insights into the lignin structure. Among the samples, D20 (Cavendish) showed consistent performance characterized by its high holocellulose content (52.2%), substantial α-cellulose fraction (33.3%), and superior mechanical strength, with a tensile strength of 166 MPa and an elastic modulus of 4480 MPa. Accordingly, this cultivar was selected for further investigation. Fourier transform infrared (FTIR) spectroscopy confirmed the presence of functional groups characteristic of lignocellulosic biomass, including hydroxyl, carbonyl, aromatic, and glycosidic linkages. X-ray diffraction (XRD) analysis revealed semicrystalline cellulose, while scanning electron microscopy (SEM) indicated a compact fiber structure with a defined lumen and minimal surface degradation. These findings suggest that fibers from D20 exhibit a promising balance of chemical, structural, and morphological characteristics, supporting their suitability for bio-based composite applications. Overall, this research emphasizes the underutilized potency of local banana waste as a foundation for sustainable material innovation.

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Keywords: Pseudostem fibers; Structural characterization; Indonesian banana varieties; Lignocellulosic biomass

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INTRODUCTION

In recent years, the exploration of natural fibers has gained growing attention as part of the global pursuit of sustainable and environmentally friendly materials. Natural fibers, which can be derived from plants, animals, or microorganisms, have been widely investigated due to their biodegradability, renewability, and favorable mechanical properties. Among plant-based fibers, cotton, hemp, jute, and sisal are commonly utilized. However, other abundant agricultural residues such as banana pseudostems remain largely underutilized, despite their significant potential as renewable fiber sources. Harnessing these residues not only supports the circular bioeconomy but also reduces agricultural waste and environmental burdens associated with synthetic materials.

The strategic value of utilizing banana pseudo stems as a natural fiber source lies in their potential as substitutes for nonrenewable material sources. In Indonesia, banana stems constitute the largest agricultural byproduct of banana cultivation. According to the Indonesian Ministry of Agriculture (2019), an estimated 100.6 million banana trees are harvested annually, contributing to about 7.2 million tons of bananas and representing 34% of the nation's total fruit production (Alzate Acevedo *et al.* 2021). Given that fruit represents roughly 23% of the total banana plant biomass, the overall biomass production is estimated at approximately 31.3 million tons. Since pseudostems comprise about 63% of this biomass (Nurrani 2012), Indonesia is estimated to generate nearly 20 million tons of pseudostem material each year, most of which remains underutilized and is typically left to decompose in the field. This underuse highlights a missed opportunity, as banana pseudostems have strong potential to serve as a sustainable natural fiber source that could be transformed into a various of value-added products.

Banana pseudostem is structurally distinct from wood and originates from the evolutionary development of tightly packed leaf sheaths rather than true secondary xylem (Li *et al.* 2010). As a result, its anatomy is characterized by a layered arrangement of vascular bundles embedded within parenchymatous tissues, leading to markedly different physical and chemical attributes compared to lignified woody materials (Motaleb *et al.* 2021). Unlike wood, banana pseudostem generally contains lower lignin content, higher moisture levels, and a more heterogeneous mixture of long vascular fibers, soft parenchyma, and sheath tissues (Jayaprabha *et al.* 2011). These characteristics render the pseudostem less rigid but often more lightweight and easier to process.

The increasing adoption of natural fiber has contributed to their broader application as reinforcement components in composite materials across multiple industries. These fibers are considered promising alternatives to conventional synthetic materials due to their favorable characteristics, including non-abrasiveness, low density, ease of thermal disposal, non-toxicity, affordability, and biodegradability. As awareness of sustainability grows, their role in the advancement of eco-friendly materials continues to gain attention. Owing to these beneficial properties, natural fiber-reinforced composites have promising applications in areas such as aerospace, defense, marine, sports equipment, and infrastructure (Karimah *et al*. 2021). Moreover, natural fibers can serve as valuable raw materials in textile manufacturing. The intrinsic characteristics of banana pseudostem fibers are fundamental in determining their potential for material applications, particularly in the creation of bio-based composites. These characteristics influence key functional aspects, for instance, fiber-matrix adhesion, load-bearing capacity, moisture resistance, and biodegradability of the final product. A robust interfacial bond between the polymer matrix and fiber surface is significant for facilitating efficient stress distribution throughout the composite material. At the same time, the inherent mechanical strength of the fiber determines its capacity to support mechanical loads and uphold the structural stability of the final product. Moreover, the natural hydrophilicity of lignocellulosic fibers can lead to excessive moisture uptake, which may compromise dimensional stability and mechanical properties over time. Their inherent biodegradability, while advantageous for environmental sustainability, must be carefully considered in relation to the material's functional lifespan. Considering these factors, it is essential to develop a detailed understanding of the physical, mechanical, chemical, and degradation characteristics of banana pseudostem fibers. This foundational knowledge allows for more targeted modification and selection of fiber properties to suit particular application needs, thereby enhancing material performance while promoting environmentally sustainable innovation.

Previous studies have reported several applications of banana pseudostem fibers. Kalangi *et al.* (2022) demonstrated their reinforcing capability in polyester composites, while Bedru and Meshesha (2022) highlighted their potential in pulp and paper production due to high cellulose content (Nurwahdah *et al.* 2018). Nonetheless, the characteristics of banana pseudostem fibers vary depending on factors such as cultivar type, growth conditions, harvesting time, and extraction method (Pickering *et al.* 2016). Considering Indonesia's extensive diversity of banana cultivars, variations in fiber characteristics are to be expected; however, systematic comparative studies on these differences remain limited.

This study aimed to characterize and compare the chemical composition, physical structure, and mechanical performance of fibers obtained from ten major Indonesian banana cultivars. By identifying the most suitable pseudostem fibers for material applications, the research provides valuable insights into the structure and property relationships of banana fibers and advances the utilization of agricultural residues for sustainable, value-added materials. The findings provide a foundation for future development of high-performance, bio-based composites derived from banana pseudostem fibers.

Although previous studies have explored banana pseudostem fibers, the literature still lacks a unified comparative framework that connects their chemical composition, structural features, and mechanical behavior across different cultivars. This gap is particularly evident in Indonesia, where the remarkable diversity of banana varieties has not yet been systematically examined for material applications. To fill this void, the present study conducts the first integrated assessment of fibers from ten major Indonesian cultivars, generating comprehensive structure property profiles. The outcomes provide a robust scientific basis for selecting high-performance fibers and unlocking the potential of pseudostem biomass as a sustainable resource for advanced biobased materials. It is hypothesized that cultivars of *Musa* sp. pseudostem differ markedly in their chemical composition, fiber morphology, and mechanical behavior, and that these inherent variations will shape their performance potential and suitability for diverse biobased material applications.

EXPERIMENTAL

Materials

This study employed banana pseudostems obtained from ten distinct cultivars, the details of which are presented in Table 1. The banana pseudostems were sourced from the Research Center for Biology, LIPI, Indonesia, which has since been integrated into the

National Research and Innovation Agency (BRIN). Several analytical-grade chemicals were employed throughout the experimental procedures. Ethanol (Merck, ≥99.9% ACS reagent grade) and benzene (Merck, ≥99.9% ACS reagent grade) were mixed in a 1:2 ratio and used as a solvent for extractive content analysis. Sulfuric acid (95 to 97% ISO grade, Merck) was diluted to a concentration of 72% (v/v) for lignin content determination. For holocellulose analysis, 25% sodium chlorite ($NaClO_2$, Merck), technical-grade glacial acetic acid, and technical-grade acetone (Bratachem, Indonesia) were utilized. Sodium hydroxide (NaOH) solutions at concentrations of 17% (w/v) and 8.3% were prepared using NaOH pellets (Merck). Additionally, a 10% (v/v) acetic acid solution was used in the determination of α-cellulose content.

Moisture and ash content determinations were carried out using an oven (Memmert, Schwabach, Germany) for drying and an electric muffle furnace (Nabertherm, Lilienthal, Germany) for the ashing process. Following heating, the samples were weighed using an analytical balance (Ohaus, Parsippany, NJ, USA) to determine their final mass. Extractive content analysis was performed using a Soxhlet extractor, operated for approximately 24 cycles or until the solvent became colorless. Acid-soluble lignin (ASL) content was quantified using a UV–visible spectrophotometer (Shimadzu 1800, Shimadzu produced in Kyoto, Japan) by measuring the solution absorbance. X-ray diffraction (XRD) analysis was conducted using a MaximaX-XRD 700 (Shimadzu, produced in Kyoto, Japan) to assess the crystallinity degree of the banana stem fibers post-treatment. Mechanical performance, including tensile strength and elastic modulus, was evaluated using a UTM or universal testing machine (Shimadzu, produced in Kyoto, Japan) in agreement with the ASTM D3800-1976 standard.

Methods

Preparation of banana pseudostem fiber samples

The preparation of banana pseudostem fiber samples involved cutting the middle part of the banana stem and subsequently drying them in a convection oven at 60 °C for a period of 24 hours. After drying, the banana stem fibers were cut into pieces, and the fibers were extracted manually by separating them from the stem. The extracted fibers were subsequently blended to reduce their length and then sieved sequentially using 40- and 60-mesh sieves. The fiber fractions of 40 to 60 mesh sizes were selected for analyses of their chemical composition and crystallinity. For tensile strength testing, fiber samples measuring approximately 8 to 10 cm in length were prepared (TAPPI 1997a).

Moisture content determination

The moisture content analysis followed the method outlined in TAPPI-1997 (TAPPI 1997b). To initiate the analysis, an empty dish was preheated in an oven at 105 °C for at least 4 h, ensuring a moisture-free baseline. The dish was placed in a desiccator for 30 min to cool and then weighed on an analytical balance to measure its empty weight. Following this, about 2 g of the sample was carefully weighed and dried at 105 °C for 24 hours. The moisture content is calculated based on the equation in the above standard.

Ash content analysis

The ash content was assessed *via* a high-temperature resistant porcelain crucible following the steps summarized in the TAPPI-2002 standard method. The equation in the TAPPI-2002 standard is used to calculate the ash level in samples.

Ethanol-benzene extractive analysis

The ethanol-benzene extractive content was determined based on the Renewable Energy Laboratory (NREL) Laboratory Analytical Procedure (LAP), 2012 version. The ethanol-benzene extractive level was calculated using the Equation as mentioned in that standard.

Acid-insoluble lignin and acid-soluble lignin analysis

The Klason lignin method, which quantifies acid-insoluble lignin (AIL), was employed to determine the lignin content in banana pseudostem fibers. This analysis followed the NREL LAP, 2012 version, with slight modifications. The Klason lignin content (AIL), and ASL were calculated using Eq. NREL LAP 2012 which refers also to the equation in that method.

Holocellulose, alpha-cellulose, and hemicellulose contents

Consistent with established procedures, the study evaluated content of the fiber's holocellulose by Wise *et al.* (1946), α-cellulose by Rowell (2005), and hemicellulose by Punyamurthy *et al.* (2012).

PyGCMS, FTIR, and SEM analyses of the optimum banana varieties

The pyrolysis products of the optimum banana pseudostem such as syringyl (S) and guiacyl (G) ratio were accessed by PyGCMS analysis (Py-GCMS, Shimadzu GC–MS system QP–2020 NX, Shimadzu, Kyoto, Japan). The condition of analysis is based on Solihat *et al*. (2022). The abundance of pyrolysis products resulted in mass spectra and retention time relative to the NIST LIBRARY 2017 database. The identification of functional groups in the optimum banana varieties was carried out using the UATR-FTIR universal attenuated total reflectance (Spectrum two Perkin Elmer Inc., USA) device connected with the Spectrum software (Ver. 10.5.3, Perkin Elmer Inc., USA). A small number of samples (~0.1 g) were mounted into diamond plate crystals and then pressed (around 80%), followed by recording the spectra. The spectra were acquired in absorbance mode with a resolution of 4.0 cm^{-1} over the wavelength range of 4000 to 400 cm^{-1}. Morphological analysis of the lignin samples was carried out using a scanning electron microscope (JEOL JSM-IT200, Japan). The banana pseudostem fibers were examined at a magnification of 1000×, with observations conducted on both cross-sectional and longitudinal sections of the samples.

XRD analysis

X-ray diffraction (XRD) was conducted *via* an instrument (MaximaX-XRD 700, Shimadzu produced in Kyoto, Japan) on 40 to 60 mesh powder. The XRD instrument was operated at 30 mA, 40 kV with Cu Kα radiation of λ = 0.15406 nm at room temperature. The results were subsequently recorded with 2θ angle scanning at a scanning rate of 2° per minute and a scanning angle range of 10 to 40°. The calculation of the crystallinity degree (Xc) of the material refers to the previous method (Wibowo *et al.* 2021).

Density analysis

The density of the banana pseudostem fibers was determined using samples with an approximate mass of ±0.1 g, which were oven-dried at 105 °C for 24 hours. The resulting dry weight was documented as the fiber mass (m). Fiber density was measured using a displacement method involving a setup with a wire attached to a Styrofoam cork on one side and a thread on the other. A beaker filled with kerosene was placed beneath the thread. The Styrofoam cork was positioned on an analytical balance, and its weight was documented. The fiber sample was then tied to the thread and fully immersed in the kerosene. The apparent weight of the fiber in kerosene was measured *via* the Styrofoam cork after stabilization. The fiber volume (v) was assessed as the difference between the dry fiber mass and the apparent mass in kerosene. The fiber density was then determined using Eq. 1,

$$\rho = m/v \tag{1}$$

Determination of modulus of elasticity and tensile strength

Tensile testing of banana pseudostem fibers was conducted using a universal testing machine equipped with a 5 KN load cell (UTM, Shimadzu produced in Kyoto, Japan) following the ASTM D3379 standard (ASTM 1989). Before testing, banana pseudostem fibers approximately 10 cm long were adhered to cardboard paper measuring 12 cm, with the right and left sides measuring 5 cm each. A 2 cm gap was provided in the middle to facilitate tensile strength testing. The sample configuration is illustrated in Fig. 1. The diameter of the banana pseudostem fibers was determined *via* a microscope connected to a computer to facilitate measurement. The diameter was measured at the tip, middle, and base. Before testing, the samples were accustomed to ambient temperature and standard relative humidity (23 ± 2°C) for 24 hours. The cardboard paper with the fiber sample was clamped *via* the UTM machine clamps. The UTM machine was subsequently connected to a computer and calibrated. After calibration, the machine was activated to apply tensile force until fiber failure occurred. During testing, data on Young's modulus, elongation at break, and tensile strength were collected.

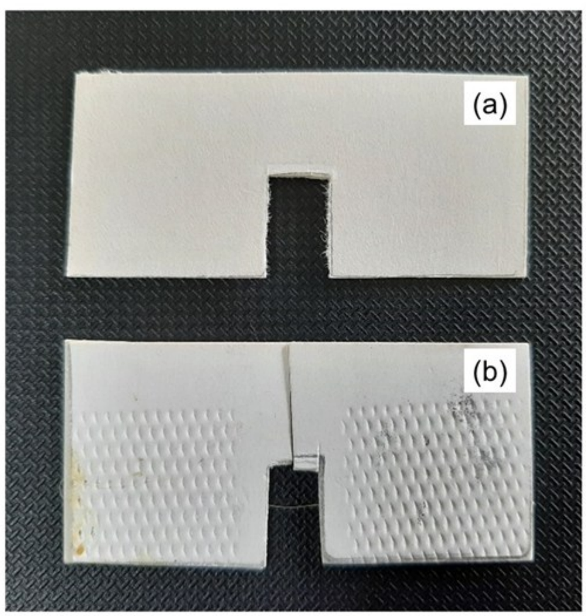

Fig. 1. (a) Cardboard paper before the fibers is adhered, (b) Cardboard paper after the banana pseudostem fibers is adhered

Banana stem fibers from different varieties were used as experimental treatments. Each treatment was replicated three times. A one-way analysis of variance (ANOVA) was performed to assess the effect of treatments, and the mean value of each treatment was separated by employing Duncan's Multiple Range Test (DMRT) at a 5% significance level. Welch's ANOVA and Games–Howell post-hoc test were applied when the assumption of homogeneity of variances was violated. Table 1 summarizes the banana varieties analyzed in this study.

Table 1. Scientific Classification and Local Nomenclature of Indigenous Banana Varieties in Indonesia

Code	Scientific Name	Local Name	LIPI Access Information
D12	*Musa acuminata* (AAA group)	Barangan	LIPI-561
D13	*Musa Spp*. (ABB group)	Siem	LIPI-315
D14	*Musa acuminata* × *Musa balbisiana* (AAB group)	Raja Sereh	LIPI-559
D15	*Musa acuminata* × *Musa balbisiana* (AAB group)	Raja	LIPI-360
D16	*Musa acuminata* (AA subgroup 'sucrier')	Mas Kirana	LIPI-550
D17	*Musa acuminata* × *Musa balbisiana* (AAB group)	Tanduk Galek	LIPI-588
D18	*Musa acuminata* (AAA)	Udang	LIPI-261
D19	*Musa acuminata* (AAA)	Tarali	LIPI-093
D20	*Musa acuminata* (AAA subgroup 'Cavendish')	Cavendish	LIPI-217
D21	*Musa acuminata* (AAA subgroup 'Cavendish')	Ambon	LIPI-250

RESULTS AND DISCUSSION

Physical Property Analysis: Moisture content, Fiber Density Evaluation

Banana pseudostem fibers in this study had a moisture content of 7.5% to 11.7% with Udang banana pseudostem showing the lowest and Tarali banana stem showing the highest values. Based on the ANOVA results, the moisture content was judged to be significantly different across varieties, possibly due to genetic factors, environmental influences, and specific characteristics of the cultivation sites (Mayerni 2018). Compared with those in drier regions, plants growing in humid or wet areas tend to have higher moisture content (Sutiya *et al.* 2012). In this study, the banana plants were grown in Bogor, Indonesia, a region characterized by high rainfall, which may have contributed to the significant effect of banana pseudostem type on the fiber moisture content. Additionally, sun drying may have contributed to variations in moisture content.

Natural fibers can absorb and release moisture depending on environmental conditions, though not all moisture evaporates, particularly the bound water within the fiber cell walls. In this study, Udang banana fibers exhibited the lowest moisture content (7.5%), a characteristic that enhances fiber durability and microbial resistance. Wang *et al.* (2006) observed that higher fiber moisture content can increase the moisture absorption in composite materials, potentially affecting their properties. Excessive moisture also weakens cellulose–lignin bonding, the main structural component of fibers (Bachchan *et al*. 2022; Chaudhary *et al*. 2018).

Among the banana pseudostem fibers studied, Udang banana fibers exhibited the best characteristics in terms of moisture content. Their lower moisture level (7.5%) helps extend storage life, limit microbial growth, and maintain fiber strength. In contrast, excessive moisture content accelerates fiber decomposition (Mayerni 2018), weakens tensile strength (Ojahan and Pratiwi 2013), and disrupts cellulose–lignin bonding, thereby negatively affecting the structural integrity of banana pseudostem fibers.

In light of the significant ANOVA results, further analysis was conducted using Duncan's DMRT at the 5% significance level (corresponding to the 95% confidence interval). The DMRT results for fiber moisture content across different banana varieties are presented in Table 2. The analysis revealed seven distinct subsets among the ten types of banana pseudostem fibers, indicating varying levels of statistically significant differences. Different letters indicate significant treatment differences; fibers with the same letter do not show significant variation.

Table 2. DMRT Test on the Moisture Content of Banana Pseudostem Fibers

Categories of Banana Pseudostem Fibers	Subset							Notation
	1	2	3	4	5	6	7	
Udang Banana	7.55							A
Raja Sereh Banana		8.35						B
Siem Banana		8.74	8.74					BC
Tanduk Galek Banana		8.92	8.92	8.92				BCD
Ambon Banana			9.33	9.33	9.33			CDE
Mas Kirana Banana				9.55	9.55	9.55		DEF
Barangan Banana					9.78	9.78		EF
Raja Banana					9.86	9.86		EF
Cavendish Banana						10.12		F
Tarali Banana							11.74	G
Sig.	1.00	.11	.11	.08	.15	.12	1.00	

The measured densities of the banana pseudostem fibers ranged from 1.1 to 1.5 g/cm³, with the Udang variety presenting the lowest value and the Raja Sereh variety the highest. While several of the measured values fell within the typical 1.3 to 1.4 g/cm³ range reported by Subagyo and Chafidz (2018) and Arul Marcel Moshi *et al.* (2019), others lay outside this interval. Such variation is expected to be reasonable and reflects the genetic and structural diversity among the banana cultivars analyzed.

This variation is attributed to the influence of the constituent elements, as the density of a material is largely determined by its composition. Since plant species differ in their structural components, their densities also vary accordingly (Arul Marcel Moshi *et al*. 2024). The density values for each banana pseudostem fiber type were statistically analyzed *via* ANOVA at the 5% significance level. ANOVA confirmed that banana variety significantly influenced fiber density (sig. 0.028 < 0.05). The significant effect of banana pseudostem type on density can be attributed to variations in growth conditions, such as environmental humidity, which affects moisture absorption and, consequently, fiber density. This finding is in agreement with the findings of Musthaq *et al.* (Musthaq *et al.*

2023), who stated that fiber structure and properties are highly variable and influenced by growth conditions, climate, and plant age (Musthaq *et al.* 2023).

In this study, the Udang banana pseudostem fiber showed the lowest density at 1.1 g/cm³, which is considered more favorable compared with the higher density of approximately 1.3 g/cm³ reported by Paul *et al.* (2008). A lower fiber density generally results in a lower overall composite density, as the density of reinforcement materials directly contributes to the final mass and volume characteristics of the composite matrix (Datta *et al.* 2016). Compared with high-density composites, low-density composites tend to absorb more moisture and preserve more water (Azman Mohammad Taib and Julkapli 2019). The integration of natural fibers in composite fabrication reduces the composite density because of the lower density of the fibers themselves. Lower-density composites are lighter, making them preferable in manufacturing industries that require lightweight yet durable materials. In this study, Udang banana pseudostem fiber exhibited the lowest density (1.1 g/cm³) among the ten banana varieties analyzed, such that it was judged to have the best density characteristics. The DMRT test results for fiber density based on banana variety are presented in Table 3.

Table 3. The DMRT Test on the Density of Banana Pseudostem Fibers

Categories of Banana Pseudostem Fibers	Subset					Notation
	1	2	3	4	5	
Udang Banana	1.11					A
Tarali Banana	1.15	1.15				AB
Ambon Banana	1.18	1.18				AB
Raja Banana	1.20	1.20				AB
Cavendish Banana		1.24	1.24			BC
Mas Kirana Banana			1.33	1.33		CD
Siem Banana				1.37		D
Tanduk Galek Banana				1.38		D
Barangan Banana				1.40		D
Raja Sereh Banana					1.52	E
Sig.	.11	.15	.09	.18	1.00	

Chemical Composition of Banana Pseudostem Fibers

The ash content serves as a parameter to indicate the concentration of inorganic materials (minerals) within a substance or product. Overall, the ash level of the banana pseudostem fibers ranged from 4.9% to 15.7%. The Cavendish banana pseudostem fiber had the lowest ash content, whereas the highest ash content was found in the Tanduk Galek variety at 15.7%. These differences in ash content may result from variations in chemical composition, which are influenced by the environmental conditions where the banana plants are cultivated (Karimah *et al.* 2021).

The type of banana pseudostem significantly influences the ash level due to the inherent compositional differences of the material. This finding agrees with the results informed by Kusić *et al*. (2020), who reported that ash composition and levels are determined by material characteristics. Furthermore, previous studies by Kumari *et al.* (2023) indicated that ash content is influenced by agronomic factors, such as fertilizer composition, application intensity, soil type, and climate variations. Since the ten banana pseudostem varieties in this study exhibit different cultivation characteristics, their chemical properties, including ash content, also vary accordingly (Kumari *et al*. 2023).

In natural fiber applications, a lower ash content indicates higher fiber quality, as it reflects a lower mineral content (Jayaprabha *et al*. 2011). This study revealed that Cavendish banana pseudostem fibers had the lowest ash content, at 4.9%. A lower ash content enhances fiber quality by minimizing the presence of mineral components. This aligns with the findings of Mayerni (2018), who reported that higher ash content increases mineral levels in the fiber, subsequently reducing its quality. Among the ten banana pseudostem varieties tested, Cavendish fiber presented the best characteristics in terms of ash content. The ash content reflects the mineral composition of natural fibers, which can impact their physical properties. Different mineral compositions result in distinct physical characteristics, ultimately affecting fiber-based products (Pereira *et al*. 2014). Owing to the significant ANOVA results, a DMRT test was performed at the 5% significance level, and the ash content results by banana variety are shown in Table 4. The DMRT test identified six subsets, indicating six distinct levels of significant differences. The variations in notation among the ten banana pseudostem fibers confirmed the differences between the treatments. However, fibers within the same subset, or those sharing the same letter notation, showed no statistically significant differences.

Table 4. The DMRT Test on the Ash Level of Banana Pseudostem Fibers

Categories of Banana Pseudostem Fibers	Subset						Notation
	1	2	3	4	5	6	
Cavendish Banana	4.96						A
Siem Banana		5.38					B
Raja Sereh Banana		5.41					B
Barangan Banana			6.06				C
Tarali Banana			6.06				C
Ambon Banana				6.77			D
Mas Kirana Banana				6.84			D
Udang Banana					7.31		E
Raja Banana					7.45		E
Tanduk Galek Banana						15.68	F
Sig.	1.00	.81	.98	.56	.27	1.00	

Chemical Composition Analysis: Extractive, Acid Insoluble Lignin, and Acid Soluble Lignin Contents

The extractive content of banana pseudostem fibers exhibited considerable variation, ranging from 11.3% to 25.2%. The lowest value was observed in the Tanduk Galek variety, whereas the highest value was recorded in the Tarali variety. Statistical analysis *via* ANOVA at the 5% significance level revealed that banana variety had a significant effect on the extracted content ($P = 0.007 < 0.05$). The significant variation in extractive content among banana pseudostem types is in agreement with the findings of Nurnasari and Nurindah (2017), who reported that extractive content is strongly affected by plant species, growth environment, and climatic conditions (Nurnasari and Nurindah 2017). These factors collectively shape the biochemical profile of the plant material. Additionally, these findings align with prior research (Wistara *et al.* 2016), which indicated that various types of wood fibers, including softwood and hardwoods (*e.g.*, red meranti), possess unique extractive contents.

In this study, the Tanduk Galek banana pseudostem fiber exhibited the lowest alcohol-benzene-soluble extract content, at 11.3%. This value is higher than the extractive content found in other natural fibers, such as mechanically decomposed oil palm empty fruit bunch (OPEFB) fibers, which range from 4.6% to 6.5% (Kwei-Nam *et al*. 2007). Among the ten banana pseudostem varieties tested, Tanduk Galek fiber presented the best characteristics based on its extractive content. However, the extractive content observed in this study is considered high, as Sutiya *et al.* (2012) categorized extractive levels exceeding 5% as high. High extractive contents—particularly oils and fats—can weaken fiber bonding and affect properties such as color, odor, and durability (Nurnasari and Supoyo 2018). In natural fiber applications, a low extractive content is preferred, as high levels hinder chemical penetration, slow delignification, and reduce pulp yield (Rodrigues *et al*. 2018; Aminah *et al.* 2020). Table 5 shows that the ten banana pseudostem fiber types exhibit different subsets on the basis of their average extractive content. The DMRT test identified four subsets, indicating four distinct levels of significant differences. The variations in notation among the ten banana pseudostem fibers confirmed the differences between the treatments. However, fibers within the same subset, or those sharing the same letter notation, show no statistically significant differences.

Table 5. The DMRT Test on the Extractive Content of Banana Pseudostem Fibers

Categories of Banana Pseudostem Fibers	Subset				Notation
	1	2	3	4	
Tanduk Galek Banana	11.27				A
Raja Sereh Banana	12.29	12.29			AB
Raja Banana	14.52	14.52			AB
Barangan Banana	14.59	14.59			AB
Cavendish Banana	16.83	16.83	16.83		ABC
Ambon Banana	17.90	17.90	17.90	17.90	ABCD
Udang Banana		19.85	19.85	19.85	BCD
Siem Banana		20.46	20.46	20.46	BCD
Mas Kirana Banana			24.47	24.47	CD
Tarali Banana				25.16	D
Sig.	.11	.05	.06	.08	

The overall Klason lignin content of banana pseudostem fibers across different banana varieties ranged from 6.0% to 10.2%. The lowest lignin content was provided in Raja Sereh banana pseudostem fibers, whereas the highest was recorded in Cavendish banana pseudostem fibers. These findings are consistent with the values reported by Jawaid and Abdul Khalil (2011), who reported lignin contents in banana pseudostem fibers ranging from 5% to 10%. Statistical analysis *via* one-way ANOVA at the 5% significance level revealed that the type of banana pseudostem significantly affected the Klason lignin content ($P = 0.000 < 0.05$). This result highlights the influence of many factors on the chemical composition of fibers, particularly in relation to lignin accumulation. The significant effect of banana pseudostem type on lignin content is due to differences in fiber samples, despite being from the same species. Lignin levels in plant stems are influenced by the species and maturity of the plant (Tian *et al.* 2024). Differences in lignin content among treatments result from variations in fiber structure complexity. Lignin is a key indicator of fiber strength (Nurnasari and Supoyo 2018). In natural fiber applications, a low lignin content is preferred because high lignin levels impede enzymatic fiber digestion. Lignin serves as a binding agent in cell walls, providing rigidity, but excessive amounts can weaken fiber bonding, thereby reducing the overall strength of the end product (Yulfa *et al.* 2019; Małachowska *et al.* 2020).

In this study, Raja Sereh banana pseudostem fibers exhibited the lowest lignin content, at 6.0%. Among the ten banana pseudostem types tested, Raja Sereh banana pseudostem fibers presented the best characteristics in terms of lignin content. The lignin content of banana pseudostem fibers in this research was lower than that of sisal fibers (7.1%) and significantly lower than that of kenaf fibers (Nurnasari and Supoyo 2018), which contain 15% to 21% lignin (Mohanty *et al.* 2001). A high lignin content negatively affects pulp and paper production by increasing chemical consumption and reducing process efficiency. Additionally, it increases pulp rigidity, reducing overall quality (Małachowska *et al.* 2020). The DMRT results for the lignin content in different varieties of banana pseudostem fibers are exhibited in Table 6.

Table 6. Results of the DMRT Test on the Lignin Contents of Banana Pseudostem Fibers

Categories of Banana Pseudostem Fibers	Subset						Notation
	1	2	3	4	5	6	
Raja Sereh Banana	6.04						A
Siem Banana	6.17	6.17					AB
Ambon Banana	6.65	6.65	6.65				ABC
Udang Banana	7.25	7.25	7.25	7.25			ABCD
Tanduk Galek Banana		7.38	7.38	7.38	7.38		BCDE
Barangan Banana			7.50	7.50	7.50		CDE
Tarali Banana				8.32	8.32		DE
Mas Kirana Banana				8.48	8.48		DE
Raja Banana					8.64		E
Cavendish Banana						10.21	F
Sig.	.06	.06	.17	.06	.05	1.00	

The acid-soluble lignin content of banana pseudostem fibers ranged between 3.6% and 4.7% across the different banana varieties. The Ambon variety presented the lowest level, whereas the highest value was observed for the Tarali variety. As expected, the ASL levels were lower than the AIL levels, in accordance with prior reports indicating that the lignin fraction solubilized in acidic filtrates is generally less abundant than the insoluble lignin residue. Compared with the study by Febriani (2021), which reported the highest acid-soluble lignin content in coconut shell (2.8%) and coconut fiber (2.0%), the values in this study were greater (Febriani 2021). The variations in lignin content among banana pseudostem types may result from differences in polymer composition and structural complexity. This finding corresponds with the work of Nawawi *et al*. (2019), who stated that variations in lignin content in bamboo are influenced by both species and the stem position (node *vs*. internode).

The lignin content of each banana pseudostem fiber type was statistically analyzed *via* ANOVA at the 5% significance level. The analysis confirmed that banana variety significantly affects the acid-soluble lignin content (sig. $0.000 < 0.05$). This variation is attributed to differences in the fiber samples, despite being from the same species (Lourenço and Pereira 2018). The lignin amount in plant stems differs with species and developmental stage, where acid-soluble lignin, known as an important parameter, linked to monomeric reactivity, might differ among bamboo species due to compositional variations in their lignin structure (Nawawi *et al.* 2019; Furusawa and Ashitani 2021).

The ASL content of banana pseudostem fibers in this study was higher than that of Sembilang bamboo fibers, which ranged from 1.9% to 2.4% (Murda *et al.* 2018). In pulp and paper applications, a high lignin content reduces pulp quality by increasing chemical consumption, lowering process efficiency, and causing rigidity in pulp products (Sutiya *et al.* 2012). The DMRT results for lignin content in banana pseudostem fibers are given in Table 7.

Table 7. The DMRT Test on the Dissolved Lignin Content of Banana Pseudostem Fibers

Categories of Banana Pseudostem Fibers	Subset							Notation
	1	2	3	4	5	6	7	
Ambon Banana	3.63							A
Raja Sereh Banana	3.71	3.71						AB
Tanduk Galek Banana	3.73	3.73	3.73					ABC
Udang Banana		3.87	3.87	3.87				BCD
Mas Kirana Banana			3.95	3.95	3.95			CDE
Cavendish Banana				4.05	4.05			DE
Siem Banana					4.14	4.14		EF
Raja Banana						4.31		F
Barangan Banana							4.55	G
Tarali Banana							4.69	G
Sig.	.37	16	.05	.12	.10	.11	.19	

Chemical Composition Analysis: Holocellulose, Alpha-Cellulose, and Hemicellulose Contents

Analysis of banana pseudostem fibers revealed that their holocellulose fractions spanned a concentration range between 39.6% and 52.2%. Among the evaluated varieties, the Barangan fiber presented the minimum holocellulose yield, whereas the Cavendish fiber presented the maximum yield. These values are lower than the holocellulose content reported by (Jawaid and Abdul Khalil 2011), who noted proportions ranging from 60% to 65% in similar biomass sources. Variations in lignin content occur because of differences in lignin composition across plant species. Polymer complexity and variability lead to differences in lignin content among species, even within the same genus (Rencoret *et al.* 2018). The holocellulose content of each banana pseudostem fiber type was statistically analyzed *via* ANOVA at the 5% significance level. The analysis confirmed that banana variety significantly affects the holocellulose content (sig. 0.000 < 0.05).

Holocellulose content greatly affects the characteristics and performance of natural fiber composites (Yang *et al.* 2019; Zha *et al.* 2024). High holocellulose content enhances fiberboard strength, as the presence of higher hemicellulose levels promotes stronger hydrogen bonding and better interfibrillar adhesion among holocellulose nanofibrils, thereby improving the Young's modulus and tensile strength of the resulting fiber-based materials (Park *et al.* 2017). In this study, Cavendish banana pseudostem fibers presented the highest holocellulose content at 52.2%, which is consistent with the findings of (Ihwah *et al.* 2019), who informed a holocellulose content of 53.8%. Holocellulose levels above 45% are generally considered high, particularly in the context of lignocellulosic materials used for fiber-based composites. This is supported by a previous study (Wahab *et al.* 2013), which described that the holocellulose level in 3-year-old bamboo culms from various *Gigantochloa* species ranged from 74.0% to 85.1%, indicating that values exceeding 45% reflect a substantial presence of hemicellulose and cellulose as the key components contributing to fiber strength, flexibility, and bonding potential in composite applications (Wahab *et al.* 2013). An increase in holocellulose content is typically associated with a decrease in lignin content and *vice versa* (Xie *et al.* 2016). High holocellulose content plays a critical role in improving the tensile strength of fibers as it strengthens the bonding between individual fibers, thereby enhancing the material structural integrity. This increased bonding reduces the likelihood of fiber detachment under stress, resulting in a more robust and durable material (Zhao *et al.* 2016). Among the ten banana pseudostem varieties tested, Cavendish fiber demonstrated the best characteristics for composite applications on the sources of the holocellulose content. The DMRT results for the holocellulose content in banana pseudostem fibers by variety are described in Table 8.

Table 8. The DMRT Test on the Holocellulose Content of Banana Pseudostem Fibers

Categories of Banana Pseudostem Fibers	Subset					Notation
	1	2	3	4	5	
Barangan Banana	39.56					A
Raja Sereh Banana	40.04					A
Siem Banana		42.94				B
Udang Banana		43.08				B
Raja Banana			45.45			C
Tarali Banana			45.46			C
Tanduk Galek Banana			45.97			C
Ambon Banana			46.27	46.27		CD
Mas Kirana Banana				48.29		D
Cavendish Banana					52.15	E
Sig.	.66	.89	.49	.07	1.00	

The α-cellulose content of the banana pseudostem fibers ranged from 23.9% to 33.3%. The lowest content was recorded in Barangan banana pseudostem fibers, whereas the highest content was found in Cavendish banana pseudostem fibers. The alpha-cellulose content in this observation was greater than that of the Klutuk banana pseudostem fiber, which ranged from 22.3% to 28.8% (Zulaekha *et al.* 2018). The determination of the α-cellulose content in banana pseudostem fibers revealed significant variation with respect to banana variety. Statistical analysis via ANOVA confirmed that the type of pseudostem fiber significantly affects the α-cellulose content (sig. $0.000 < 0.05$). This variation aligns with previous findings indicating that chemical composition, particularly α-cellulose levels, is influenced by multiple factors, including plant variety, growth environment, maturity, and the analytical methods employed (Nurnasari and Supoyo 2018). Differences in testing methods can lead to discrepancies in α-cellulose measurements, as analytical techniques may vary in chemical principles and sensitivity (Salem *et al.* 2023). The α-cellulose content serves as an important indicator of fiber quality, with higher values being positively correlated with greater tensile strength and improved overall mechanical performance of natural fibers (Sathishkumar *et al.* 2024).

In this study, Cavendish banana pseudostem fibers presented the highest α-cellulose content, at 33.3%. Among the ten banana pseudostem varieties tested, Cavendish fiber demonstrated the best characteristics on the basis of its alpha-cellulose content. Given the significant ANOVA results, further analysis was conducted via the DMRT method at the 5% significance level (95% confidence interval). The DMRT results for α-cellulose content in banana pseudostem fibers by variety are described in Table 9.

Table 9. The DMRT Test on the α-Cellulose Content of Banana Pseudostem Fibers

Categories of Banana Pseudostem Fibers	Subset					Notation
	1	2	3	4	5	
Barangan Banana	23.89					A
Raja Sereh Banana	24.25					A
Raja Banana	25.88	25.88				AB
Siem Banana		27.24	27.24			BC
Udang Banana		27.25	27.25			BC
Tarali Banana			29.29	29.29		CD
Tanduk Galek Banana			29.99	29.99		CD
Ambon Banana				31.43	31.43	DE
Mas Kirana Banana				31.96	31.96	DE
Cavendish Banana					33.28	E
Sig.	.15	.32	.06	.07	.18	

Quantitative analysis showed that hemicellulose content in the banana pseudostem fibers ranged from 14.8% to 19.6%, with Ambon presenting the lowest value and Tarali the highest. These results are consistent with the observations of Jawaid and Abdul Khalil (2011), who reported a hemicellulose content of around 19% in banana pseudostem fibers. According to the ANOVA results, hemicellulose content differed significantly across banana varieties ($p = 0.028$), indicating a clear cultivar-dependent effect.

The observed significant variation among banana cultivars suggests that genetic factors substantially influence the chemical composition of the fibers (Xu *et al.* 2020). The post hoc subset analysis further grouped the cultivars based on similarities in their mean hemicellulose content. The first subset, including Ambon, Barangan, Siem, Raja Sereh, and Udang showed relatively low hemicellulose levels (14.8 to 15.8%). Lower hemicellulose content is generally associated with a reduced amorphous fraction and a more consolidated cell-wall structure, which may contribute to higher crystallinity and enhanced thermal stability of the fibers (Rowell *et al.* 2016). Such characteristics are often linked to more consistent mechanical properties and chemical resistance. The second subset included Tanduk Galek, Tarali, and Mas Kirana (15.9 to 16.3%), which displayed slightly higher hemicellulose levels while remaining statistically comparable to the first group. Fibers with moderate hemicellulose content typically exhibit greater flexibility due to the increased amorphous fraction, influencing their swelling behavior and reactivity toward chemical modification (Bledzki and Gassan 1999). Cavendish contained 18.9% of hemicellulose content and formed a distinct group (Group BC) that differed significantly from most other cultivars. Higher hemicellulose levels are commonly associated with a looser matrix structure, greater moisture sorption capacity, and reduced dimensional stability (Wang *et al.* 2019).

Tarali exhibited the highest hemicellulose content (19.6%; Group D) and was statistically different from all other cultivars. Higher hemicellulose levels make the fibers more prone to hydrolysis and thermal degradation, which reduces their mechanical performance and stability in fiber-based composites (Tarasov *et al.* 2018). Furthermore, its gelatinous nature facilitates fiber bonding, enhancing interfiber interactions. Hemicellulose molecules attached to cellulose act as microfibril binders, forming a cellulose–hemicellulose network that constitutes a primary structural component of fiber cells (Lu *et al.* 2021). Consequently, Tarali may be less suitable for applications requiring high dimensional stability and tensile performance.

In this study, Tarali banana pseudostem fibers presented the highest hemicellulose content, at 19.6%. Among the ten banana pseudostem varieties analyzed, Cavendish fiber demonstrated the best characteristics based on hemicellulose content. The DMRT test results for hemicellulose content in banana pseudostem fibers by variety are performed in Table 10.

Table 10. The DMRT Test on the Hemicellulose Content of Banana Pseudostem Fibers

Categories of Banana Pseudostem Fibers	Subset			Notation
	1	2	3	
Ambon Banana	14.84			A
Barangan Banana	15.67			A
Siem Banana	15.70			A
Raja Sereh Banana	15.79			A
Udang Banana	15.83			A
Tanduk Galek Banana	15.98	15.98		AB
Tarali Banana	16.17	16.17		AB
Mas Kirana Banana	16.33	16.33		AB
Cavendish Banana		18.88	18.88	BC
Tarali Banana			19.58	D
Sig.	.37	16	.05	

Mechanical Property Analysis: Elastic Modulus, Tensile Strength, and Crystallinity

The tensile strength of banana pseudostem fibers in this study ranged from 117 to 432 MPa. The lowest tensile strength was observed in the Raja banana pseudostem fibers, whereas the highest tensile strength was recorded for Tarali banana pseudostem fibers. These results are consistent with the findings of Asroni and Handono (2018), who reported tensile strength of 260 MPa for Kepok banana pseudostem fibers, 202 MPa for Raja banana pseudostem fibers, and 153 MPa for Raja Sereh banana pseudostem fibers (Asroni and Handono 2018).

The variation in tensile strength among different banana pseudostem fibers may be attributed to differences in chemical composition. Each fiber type exhibits variations in moisture content, ash content, holocellulose, hemicellulose, α-cellulose, and lignin levels, which influence tensile strength. High moisture content, for example, has been shown to reduce fiber tensile strength due to improper fiber arrangement within the matrix and weak interfiber bonding caused by excessive water content (Ojahan and Pratiwi 2013). Additionally, lignin content significantly affects fiber tensile strength; fibers with higher lignin levels tend to be weaker because of reduced interfiber bonding (Zhang *et al.* 2013; Yulfa *et al.* 2019).

Variations in tensile strength among the fibers are strongly influenced by differences in diameter and aspect ratio. Fibers with small diameters often show higher tensile strength because they contain fewer structural defects and have higher aspect ratios that support efficient stress transfer. In contrast, large-diameter fibers usually contain more internal flaws and have lower aspect ratios that limit their ability to carry load (Alcock *et al.* 2018). Therefore, the strong tensile performance of the Tarali variety may result from its finer fiber morphology, which allows stress to be distributed more effectively.

The differences in tensile strength across the various banana pseudostem fibers can also be attributed to variations in anatomical structure and chemical composition. Lignin and cellulose contents play crucial roles in determining fiber strength. A high cellulose content generally enhances tensile strength due to its crystalline structure, which provides rigidity and load-bearing capacity (Nasri *et al.* 2023). In contrast, lignin primarily contributes to fiber stiffness but may reduce interfiber bonding. The distribution of lignin within the fiber and its interaction with other cell wall components influence this effect (Le *et al.* 2020). The present findings align with these results, where Tarali banana pseudostem fibers, which contained the highest lignin level, exhibited the maximum tensile strength at 432 MPa. The results obtained in this study for Raja Sereh banana pseudostem fiber (286 MPa) and Raja banana pseudostem fiber (117 MPa) are in line with the tensile strength values reported by previous research (Asroni and Handono 2018). Given the critical role of tensile strength in determining the mechanical properties of composites, the Tarali banana pseudostem fibers exhibited the most favorable characteristics among the ten varieties assessed.

The tensile strength data were normally distributed according to the Shapiro–Wilk test; however, the assumption of homogeneity of variances was not met based on Levene's test. Consequently, the results from the conventional ANOVA were deemed invalid. Therefore, a statistical approach using Welch's ANOVA was employed, followed by a post hoc Games–Howell test to identify significant differences among the groups. The statistic test results for tensile strength based on banana variety are depicted in Table 11.

Table 11. Mean Tensile Strength (MPa) of Samples and Statistical Grouping Based on the Games–Howell Post Hoc Test

Categories of Banana Pseudostem Fibers	Mean ± SD (MPa)	Notation
Tarali Banana	495.41 ± 209.49	a
Raja Sereh Banana	286.53 ± 52.01	ab
Barangan Banana	257.79 ± 8.52	b
Udang Banana	241.57 ± 32.07	b
Siem Banana	162.96 ± 8.53	b
Cavendish Banana	165.50 ± 52.60	c
Ambon Banana	140.43 ± 58.28	c
Mas Kirana Banana	125.98 ± 5.35	cd
Tanduk Galek Banana	123.63 ± 38.29	cd
Raja Banana	116.63 ± 3.55	d

Elastic modulus testing was conducted to assess the ability of banana pseudostem fibers to resist deformation under applied loads. The overall elastic modulus values ranged from 2620 to 7850 MPa. The lowest elastic modulus was observed for the Tanduk Galek banana pseudostem fiber, whereas the highest elastic modulus was recorded for the Tarali banana pseudostem fiber. The variation in elastic modulus among the banana pseudostem fibers was likely associated with differences in fiber stiffness, which are influenced by factors such as cellulose crystallinity, microfibril orientation, and cell-wall structure. Although tensile strength and elastic modulus describe different aspects of mechanical behavior, both properties can vary across cultivars due to differences in fiber morphology and cellulose structure that arise from genetic and environmental influences. A significant difference in the elastic modulus was observed among the banana pseudostem fibers (ANOVA, p = 0.001). In this study, the Tarali banana pseudostem fiber presented the highest elastic modulus at 7850 MPa. This result aligns with the research conducted by Subagyo and Chafidz (2018), which indicated that the elastic modulus of banana pseudostem fibers is approximately 7.7 GPa (7700 MPa). The elastic modulus reflects the intrinsic stiffness of a material and its resistance to elastic deformation, but it is independent of material strength, which refers to the maximum stress a material can sustain before failure. Higher cellulose content generally increases fiber stiffness because the crystalline domains of cellulose enhance resistance to deformation and contribute to a greater elastic modulus (Richely *et al.* 2023). This relationship is closely associated with the orientation of microfibrils, where fibers with a spiral arrangement along the fiber axis tend to exhibit greater elasticity (Richely *et al.* 2023). In composite materials such as fiberboard, a higher elastic modulus indicates greater resistance to deformation. The flexural strength of fiberboard is significantly influenced by the fiber dimensions, with larger and stiffer fibers contributing to stronger and more resilient boards. Therefore, fibers with higher cellulose content and more lengthwise oriented microfibril alignment offer superior mechanical properties, making them more suitable for applications where durability and resistance to deformation are critical (Akhyar *et al.* 2024). Among the ten banana pseudostem fiber types tested, the Tarali banana pseudostem fiber demonstrated the best characteristics on the basis of its elastic modulus value of 7850 MPa. Banana pseudostem fibers are characterized by their long fiber length, thin cell walls, and low specific gravity. The fiber length of banana pseudostem fibers typically ranges from 4.2 to 5.5 mm, resulting in strong fiber sheets with compact fiber bonding (Montoya Berrio *et al.* 2024). This finding is in agreement with that of Haygreen and Bowyer (Bowyer *et al.* 2007), who reported that fiber length enhances interfiber bonding, leading to increased fiber compactness (Bowyer *et al.* 2007). Additionally, thin cell walls facilitate flattening, which improves fiber bonding and density, particularly during fiberboard formation (Akhyar *et al.* 2024). Given the significant ANOVA results, further analysis was conducted via the DMRT method at the 5% significance level (95% confidence interval). The DMRT test results for the elastic modulus of banana pseudostem fibers by variety are presented in Table 12.

Table 12. The DMRT Test on the Modulus of Elasticity of Banana Pseudostem Fibers

Categories of Banana Pseudostem Fibers	Subset			Notation
	1	2	3	
Tanduk Galek Banana	2622.62			A
Raja Banana	2647.41			A
Mas Kirana Banana	3308.59			A
Siem Banana	3722.74	3722.74		AB
Ambon Banana	3821.50	3821.50		AB
Udang Banana	4123.31	4123.31		AB
Cavendish Banana	4479.63	4479.63		AB
Barangan Banana	4808.58	4808.58		AB
Raja Sereh Banana		6142.21	6142.21	BC
Tarali Banana			7846.20	C
Sig.	.09	.06	.13	

The XRD diffractograms of various banana pseudostem fibers analyzed in this study are presented in Fig. 2. All the samples were examined within a 2θ range of 10 to

50°. The analysis revealed both crystalline and amorphous phases. The crystalline phase is indicated by diffraction peaks with high intensity at specific 2θ values, relating to diffraction from crystal planes, forming what are referred to as crystalline phase peaks (Segal *et al.* 1959). In contrast, the amorphous phase is characterized by low-intensity, broad diffraction patterns, which are often referred to as background signals (French 2014). The diffractograms of samples D12–D21 exhibit several similarities. The diffractograms of the Barangan banana pseudostem fiber (D12), Siem banana pseudostem fiber (D13), and Raja Sereh banana pseudostem fiber (D14) samples were closely aligned, with minimal differences in the positions of their crystalline peaks. The crystalline phase positions for sample D12 were 14.89°, 21.85°, 24.36°, 30.10°, 34.07°, 37.94°, 39.69°, and 44.25° 2θ. Similarly, sample D13 exhibited crystalline peaks at 2θ values of 14.96°, 21.94°, 24.56°, 30.28°, 34.02°, 37.94°, 39.59°, and 44.15°, whereas sample D14 presented peaks at 2θ values of 14.86°, 21.94°, 24.36°, 30.09°, 34.07°, 38.33°, 39.59°, and 44.15°.

Similarly, the diffractograms of Raja banana pseudostem fiber (D15), Mas Kirana banana pseudostem fiber (D16), and Tanduk Galek banana pseudostem fiber (D17) showed crystalline peaks at slightly different positions. The 2θ crystalline peaks for sample D15 were located at 14.96°, 18.16°, 21.19°, 24.27°, 30.19°, 34.07°, 37.94°, 39.59°, and 44.15°. Sample D16 exhibited peaks at 14.86°, 21.94°, 24.27°, 30.09°, 34.07°, 36.00°, 37.94°, 39.59°, and 44.15°, whereas sample D17 had peaks at 13.61°, 14.96°, 22.23°, 24.56°, 30.47°, 33.96°, 37.94°, 39.69°, and 44.15°. The diffractograms of Udang banana fiber (D18), Tarali banana fiber (D19), Cavendish banana pseudostem fiber (D20), and Ambon banana pseudostem fiber (D21) also show characteristic crystalline peaks at specific 2θ values. The crystalline peaks for sample D18 appear at 2θ values of 13.60°, 14.86°, 22.13°, 24.47°, 30.28°, 38.43°, 39.69°, and 44.05°. For sample D19, the crystalline peaks were located at 14.86°, 22.04°, 24.56°, 30.28°, 34.06°, 37.94°, 39.69°, and 44.15°. Sample D20 had crystalline peaks at 13.41°, 14.57°, 22.04°, 24.41°, 30.19°, 38.24°, 39.79°, and 44.15°, whereas sample D21 had peaks at 14.96°, 21.94°, 24.47°, 30.19°, 34.06°, 37.94°, 39.59°, and 44.16°. Any positions beyond these values were considered amorphous phases in the samples.

The peak of crystallinity at around 2θ ~22.00° is associated with the (200) crystal plane, indicating the presence of the crystalline cellulose phase (Terinte *et al.* 2011). The peak at approximately 2θ ~17.00 to 18.00° corresponds to amorphous or noncrystalline cellulose (Wulandari *et al.* 2016). Notably, samples D17 and D19 lack peaks in the 2θ ~17.00° to 18.00° range, which may be attributed to lignin and hemicellulose removal during acid treatment and crystallite storage. The peaks at 2θ values near 15.00° and 16.00° correlate with the (110) crystal plane, which is predominantly associated with cellulose I crystal structures. The cellulose I structure comprises two distinct crystalline phases: Iα and Iβ (Nishiyama *et al.* 2003; Matthews *et al.* 2012). Among these phases, the Iβ phase is the predominant form of cellulose found in plant fibers (Gopinathan *et al.* 2017). Additionally, the diffraction peaks at ~30.00°, ~38.00°–39.00°, and ~44.00° correspond to inorganic components such as chlorine, potassium, phosphorus, and calcium, respectively, as identified *via* X-ray fluorescence (XRF) characterization (Pereira *et al.* 2014).

Cellulose crystallinity analysis was performed to find out the ratio of crystalline regions to amorphous regions within the banana pseudostem fibers. This analysis highlights the fiber's structure and its impact on mechanical properties and chemical resistance. The crystallinity index (CrI) of each sample was considered on the basis of the relative intensity of the crystalline peak (typically near 2$\theta \approx$ 22.5°) and the amorphous background (near 2$\theta \approx$ 18°) (Madhushani *et al*. 2021), as shown in Fig. 2. The crystallinity degree plays a significant function in affecting key fiber properties, including compatibility in composite materials and water absorption behavior (French 2014). The crystallinity values obtained from these calculations are presented in Table 13. These results are in line with previous findings (Pereira *et al.* 2014). The overall crystallinity index ranged from 23.6% to 37.4%. In this study, Udang banana pseudostem fibers presented the lowest crystallinity, whereas Tanduk Galek banana pseudostem fibers presented the highest crystallinity. A high crystallinity index indicates a well-ordered polymer chain arrangement or a more perfect crystalline lattice (Lu and Hsieh 2010).

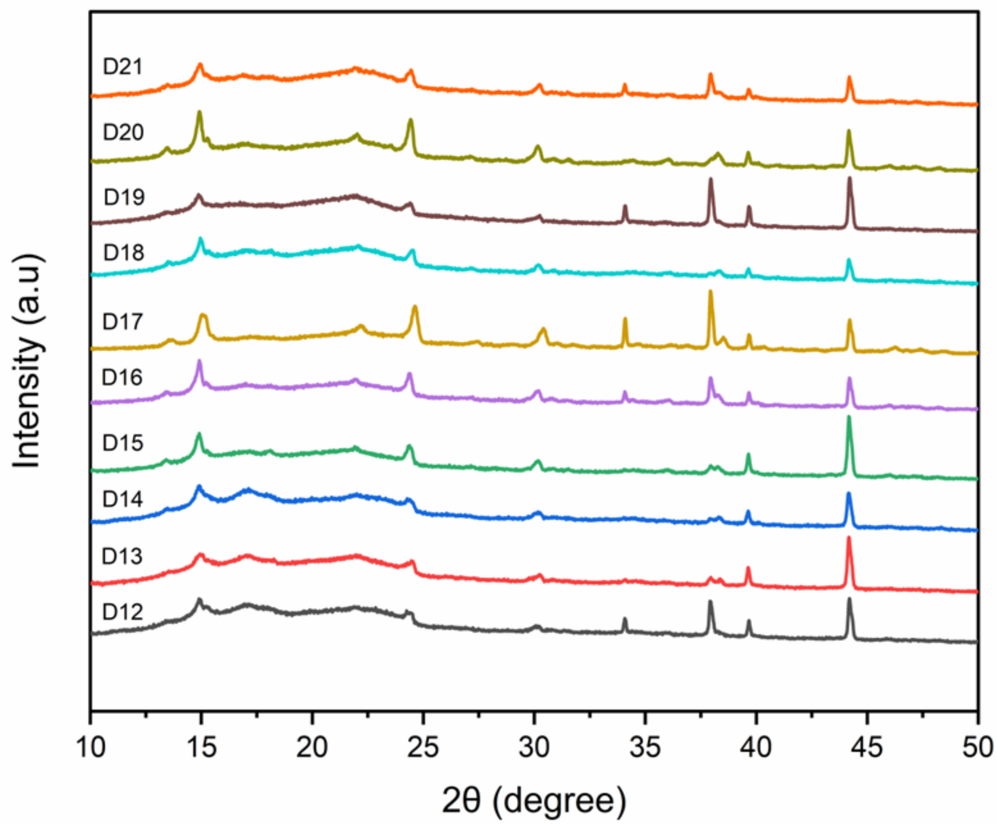

Fig. 2. Diffractogram of banana pseudostem fibers (D12 = Barangan banana; D13 = Siem banana; D14 = Raja Sereh banana; D15 = Raja banana; D16 = Mas Kirana banana; D17 = Tanduk Galek banana; D18 = Udang banana; D19 = Tarali banana; D20 = Cavendish banana; D21 = Ambon banana).

The crystallinity degree is influenced by the proportion of the amorphous phase. A dominant amorphous phase results in lower crystallinity, which is why removing the amorphous phase during cellulose processing aims to increase crystallinity. The crystallinity degree of cellulose differs depending on the biomass sources and the treatments applied to it (Dien *et al.* 2015). Fatriasari *et al.* described that the crystallinity degree of various biomass sources ranges from 20% to 60% (Fatriasari *et al.* 2020). Additionally, Lu and Hsieh (2010) reported that fibers with higher cellulose purity exhibit a higher crystallinity index.

Table 13. Selected Optimal Treatments for Various Types of Banana Pseudostems

Code	Moisture content (%)	Ash content (%)	Extractive content (%)	Lignin content (%)	Acid soluble lignin (%)	Holocellulose content (%)	Alpha cellulose content (%)	Hemicellulose content (%)	Density (g/cm^3)	Tensile Strength (MPa)	Modulus of Elasticity (GPa)
D12	9.78±1.10 (4)	6.06±0.13 (7)	14.59±4.24 (7)	7.57±0.70 (5)	4.55±0.08 (2)	39.57±2.70 (1)	23.89±1.74 (2)	15.67±1.33 (1)	1.40±0.07 (2)	257.80±8.52 (8)	4.81±1.15 (8)
D13	8.74± 0.28 (8)	5.38±0.18 (9)	20.46±7.38 (3)	6.17±0.64 (9)	4.14±0.12 (4)	42.94±0.99 (4)	27.24±0.39 (3)	15.70±1.21 (3)	1.36±0.02 (4)	162.96±8.53 (6)	3.72±0.60 (4)
D14	8.35± 0.12 (9)	5.41±0.10 (8)	12.29±1.48 (9)	6.04±0.12 (10)	3.71±0.05 (9)	40.04±1.50 (2)	24.26±0.30 (4)	15.79±1.71 (2)	1.51±0.05 (1)	286.53±52.01 (9)	6.14±2.29 (9)
D15	9.86± 0.25 (3)	7.45±0.06 (3)	14.52±4.97 (8)	8.64±0.22 (2)	4.31±0.29 (3)	45.45±1.19 (3)	25.88±1.61 (10)	19.58±0.44 (5)	1.20±0.02 (7)	116.63±3.55 (1)	2.65±0.57 (2)
D16	9.55± 0.06 (5)	6.84±0.11 (5)	24.47±0.56 (2)	8.48±1.01 (3)	3.95±0.13 (5)	48.29±1.46 (9)	31.96±1.29 (8)	16.33±0.27 (9)	1.33±0.04 (5)	125.98±5.36 (3)	3.31±0.78 (3)
D17	8.92± 0.37 (7)	15.68±0.03 (2)	11.27±3.76 (10)	7.38±0.74 (6)	3.73±0.17 (8)	45.97±0.66 (7)	29.99±1.43 (6)	15.98±0.80 (7)	1.38±0.11 (3)	123.63±38.29 (2)	2.62±1.23 (1)
D18	7.55± 0.08 (10)	7.31±0.03 (4)	19.85±3.08 (1)	7.24±0.30 (7)	3.87±0.00 (7)	43.08±1.22 (5)	27.26±0.82 (5)	15.82±0.68 (4)	1.11±0.04 (10)	241.57±32.07 (7)	4.12±1.98 (6)
D19	11.74± 0.12 (1)	6.06±0.12 (7)	25.16±5.74 (4)	8.32±1.10 (4)	4.69±0.07 (1)	45.48±0.24 (6)	29.29±0.77 (7)	16.17±0.53 (6)	1.15±0.08 (9)	495.41±209.49 (10)	7.06±4.08 (10)
D20	10.13± 0.21 (2)	4.96±0.37 (10)	16.83±4.62 (6)	10.21±0.55 (1)	4.05±0.01 (5)	52.16±0.54 (10)	33.28±0.54 (9)	18.88±0.72 (10)	1.24±0.08 (6)	165.50±52.60 (4)	4.48±2.53 (7)
D21	9.33± 0.21 (6)	6.77±0.06 (6)	17.90±1.66 (5)	6.65±0.61 (8)	3.63±0.03 (10)	46.27±0.47 (8)	31.43±3.58 (1)	14.85±4.05 (8)	1.18±0.05 (8)	140.43±58.28 (5)	3.82±1.82 (5)

The lignocellulosic composition of banana pseudostem fibers varies among different varieties, leading to differences in cellulose purity (Pinheiro *et al.* 2022). The cellulose content in Raja, Tanduk Galek, Cavendish, and Ambon banana pseudostem fibers were relatively greater than that in other varieties. This is reflected in their crystallinity index, which was also among the highest. Since these four banana pseudostem fibers had similar cellulose contents, their crystallinity index values also showed minimal variation. Higher crystallinity increases the efficiency of these fibers as reinforcement materials for composite applications (Pinheiro *et al.* 2022).

Determination of the Most Suitable Banana Cultivar

After the complete chemical, physical, and mechanical characteristics of the banana pseudostem fibers from the different *Musa* sp. cultivars (treated as separate evaluation groups) were obtained, the next step was to determine the banana variety that produced fibers with the best characteristics on the basis of the evaluated parameters. This was conducted *via* the scoring method (Balakrishnan *et al.* 2020) and De Garmo's effectiveness method. The scoring assignment was based on a literature-supported discussion of the results. Each parameter was scored on a scale of 1 to 10, where the most suitable parameter received the highest score (10), and the least suitable parameter received the lowest score (1). The final score was determined by accumulating the scores based on their alignment with the literature findings, with the highest cumulative score indicating the optimal treatment.

Table 13 presents a summary of the fiber characterization results for different banana pseudostem varieties. The ranking from best- to lowest-performing fiber was as follows: Cavendish banana, Ambon banana, Tarali banana, Raja banana, Tanduk Galek banana, Mas Kirana banana, Udang banana, Raja Sereh banana, Siem banana, and Barangan banana.

The results denote that the Cavendish banana pseudostem fiber presented the best overall characteristics based on the evaluated parameters in this study. The corresponding values for Cavendish banana pseudostem fiber were as follows: Moisture content, 10.1%; ash content, 4.9%; extractive content, 16.8%; Klason lignin content, 10.2%; acid-soluble lignin content, 4.1%; holocellulose content, 52.2%; alpha-cellulose content, 33.3%; hemicellulose content, 18.9%; density, 1.2 g/cm^3; tensile strength, 165.5 MPa; elastic modulus, 4479.6 MPa; and crystallinity, 35.1%.

Table 14 presents a consolidated summary of chemical, physical, and mechanical properties of banana pseudostem fibers reported in selected reference studies. The parameters compiled included holocellulose, cellulose and hemicellulose fractions, lignin content, extractives, moisture content, fiber density, crystallinity, and tensile-related properties. Considerable variability was evident across studies, reflecting differences in cultivar, anatomical region, growth conditions, and extraction or analytical methodologies. The table is intended to provide a broader context for interpreting the present findings and to highlight the heterogeneous nature of banana pseudostem fibers documented in the literature. Values marked with an asterisk (*) represent calculated holocellulose contents obtained as the sum of cellulose and hemicellulose fractions reported in the respective studies.

Table 14. Summary of Chemical, Physical, and Mechanical Properties of Banana Pseudostem Fibers Reported in the Literature

Parameter	Present Study (D20)	Cordeiro *et al.* 2004	Li *et al.* 2010	Silva *et al.* 2020	Melesse *et al.* 2022	Karuppuchamy *et al.* 2024
Holocellulose (%)	52.16	60.10 - 65.20	72.71*	77.31*	n.d	77.47*
α-cellulose (%)	33.28	n.d	n.d	49.51	n.d	n.d
Hemicellulose (%)	18.88	25 - 25.60	7.71	27.80	23.37	15.23
Cellulose	n.d	34.5 - 40.2	39.12	n.d	41.45	62.24
Klason lignin (%)	10.21	12 - 12.70	8.88	27.77	10.46	18.51
Acid soluble lignin (%)	4.05	n.d	1.9	n.d	n.d	n.d
Extractives (%)	16.83	8 - 14.10	3.05	14.29	12.72	0.29 (wax)
Moisture content (%)	10.13	n.d	n.d	n.d	n.d	11.53
Fiber density (g/cm³)	1.24	n.d	n.d	0.22	n.d	0.984
Crystallinity (%)	35.10	n.d	n.d	n.d	n.d	61.12
Tensile strength (MPa)	165.50	n.d	n.d	583.46	n.d	n.d
Elastic modulus (MPa)	4479.60	n.d	n.d	21.05	n.d	n.d

The FTIR spectra obtained from all the banana pseudostem fiber samples exhibited similar patterns across the different varieties. Each spectrum revealed the presence of major functional groups correlated with hemicellulose, cellulose, and lignin. This spectral resemblance indicates that the fundamental lignocellulosic composition was preserved among the various banana pseudostem fibers analyzed in this study. Owing to this uniformity, sample D20 was selected for more detailed discussion, as it consistently demonstrated favorable performance across several key parameters, as presented in Table 13. This focused approach aims to correlate the occurrence of specific chemical functional groups with the structural and functional attributes of the fiber.

Figure 3 shows that the FTIR spectrum of sample D20 had a broad absorbance band at around 3300 cm^{-1}, indicating O–H stretching vibrations, and the presence of hydroxyl groups in hemicellulose and cellulose. The prominent peak observed at 2920 cm^{-1} is assigned to the C–H stretching of aliphatic chains. Within the fingerprint region, moderate absorbance at 1730 cm^{-1} is credited to C=O stretching vibrations in ester and acetyl groups, which are commonly found in hemicellulose (Yuan *et al.* 2022). The peak at 1622 cm^{-1} is correlated with absorbed O–H groups (Mamudu *et al*. 2025), whereas the signal at 1515 cm^{-1} corresponds to aromatic skeletal vibrations of guaiacyl and syringyl units, confirming the presence of lignin (Zhou *et al*. 2015). The band at 1427 cm^{-1} is attributed to C–H deformation in cellulose and hemicellulose, and the peak at 1316 cm^{-1} is concerned with C–H vibrations in cellulose. The strong peak at 1016 cm^{-1} indicates C–O–C stretching vibrations typical of glycosidic linkages in hemicellulose and cellulose (Liang and Wang 2016). Additionally, the peak at 895 cm^{-1} corresponds to C–H deformation vibrations associated with β-glycosidic linkages in cellulose (He *et al*. 2022). These spectral features collectively reaffirm the lignocellulosic nature of sample D20 and are consistent with the structural characteristics identified through complementary analyses, including XRD, pyrolysis–gas chromatography-mass spectrometry (Py-GC/MS), and SEM.

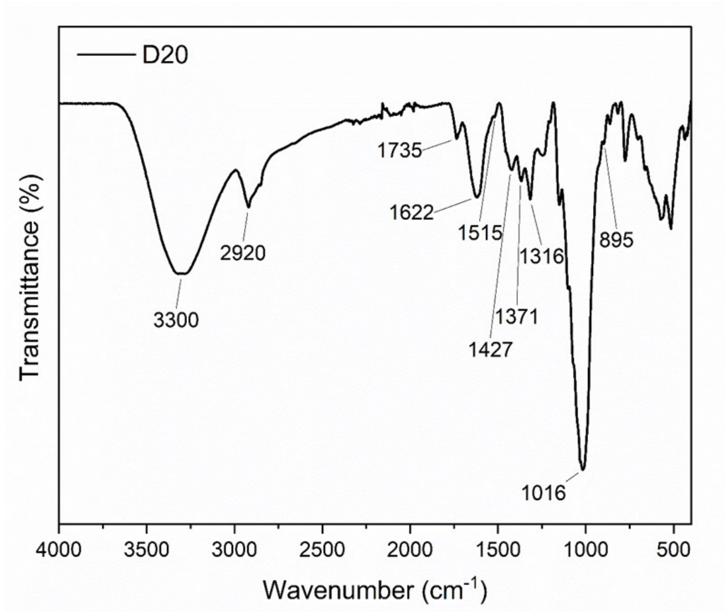

Fig. 3. FTIR spectrum of banana pseudostem fiber sample D20

To further elucidate the lignin composition of banana pseudostem fibers, Py-GC/MS analysis was performed. The results confirmed the presence of syringyl and guaiacyl compounds, which are well established as the principal monomeric units of lignin. These findings provide molecular insight into the lignocellulosic structure of the fibers. On the basis of the relative intensities of these compounds, the syringyl-to-guaiacyl (S/G) ratio was calculated to measure the lignin structural characteristics. The calculations of the S/G ratio are presented in Fig. 4**.**

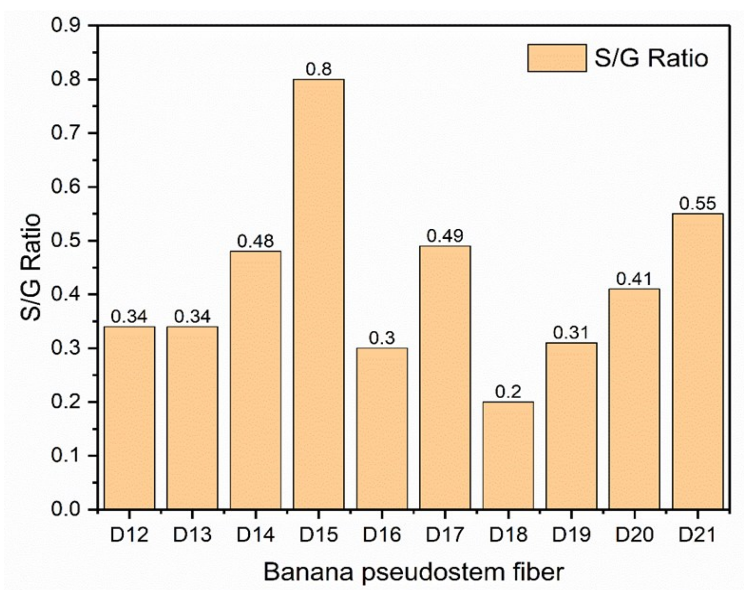

Fig. 4. Syringyl-to-guaiacyl (S/G) ratios of lignin in various banana pseudostem fiber samples

Figure 4 illustrates the notable variance in the syringyl-to-guaiacyl (S/G) ratio among the banana pseudostem fiber samples. The highest S/G ratio was observed in sample D15 (0.8), indicating that the lignin structure in this sample was predominantly composed of syringyl units. Syringyl-rich lignin is typically associated with greater chemical reactivity and increased susceptibility to polymer degradation (Ohra-aho *et al*. 2013). In contrast, sample D18 displayed the lowest S/G ratio (0.2), reflecting a lignin composition that is more enriched in G-units, which are known to form more condensed carbon-carbon structures and contribute to a more rigid molecular structure (Ralph *et al.* 2004). Banana pseudostem fibers with intermediate S/G ratios, such as those in sample D21, can be considered to possess a balanced lignin composition. Similarly, samples with S/G ratios in the range of 0.30 to 0.49 are likely to exhibit a desirable equilibrium between structural stability and the potential for chemical modification (Fatriasari *et al.* 2022). These results suggest that understanding and adjusting lignin traits, such as the S/G ratio, should correspond with intended functional use in biomaterial applications.

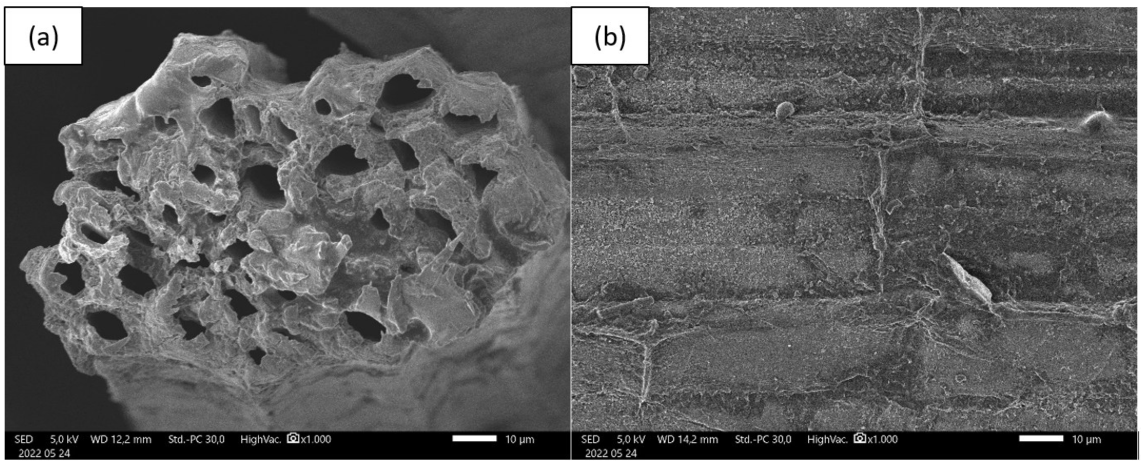

Fig. 5. SEM morphology of banana pseudostem fiber sample D20 that is taken in cross-section (a) and longitudinal section (b)

Morphologically, Fig. 5a displays a well-organized, hollow tubular structure with numerous lumens arranged in a pattern characteristic of the native vascular tissue of banana pseudostems, which function as conduits for water and nutrient transport (Xu *et al.* 2015). The presence of naturally large and open lumens indicates a high degree of internal porosity, suggesting the potential of banana pseudostem fibers as lightweight structural materials (Ennos *et al.* 2000). In the longitudinal section, the fiber structure appears highly compact, with no visible large cracks, indicating that the cellulose and lignin framework remained intact and undisturbed (Fig. 5b). The fine surface fragments observed were likely residues of the cuticle, silica, or other mineral deposits. These superficial particles may be removed through cleaning or appropriate pretreatment, which could also expose the underlying microfibrillar structure. The absence of matrix fractures in the cross-section further supports the conclusion that fiber had a dense morphology, making it well-suited for application as a filler or reinforcement material in composite applications.

CONCLUSIONS

1. Banana pseudostem fibers (*Musa* sp.) exhibit considerable variation in their physical, chemical, and mechanical properties, including crystallinity, depending on varietal and structural differences.

2. The Cavendish variety demonstrated the most favorable characteristics, suggesting its high potential for sustainable material applications.
3. The results showed significant variability in moisture content, ash, lignin, extractives, α-cellulose, hemicellulose, holocellulose, density, tensile strength, elastic modulus, and crystallinity degree among different banana pseudostem fiber varieties, which can be influenced by environmental conditions, fiber composition, and structural differences.

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REFERENCES CITED

ASTM D3379-75 (1989). "Standard test method for tensile strength and Young's modulus for high-modulus single-filament materials," ASTM International, West Conshohocken, Pennsylvania.

Akhyar, Gani, A., Ibrahim, M., Ulmi, F., and Farhan, A. (2024). "The influence of different fiber sizes on the flexural strength of natural fiber-reinforced polymer composites," *Results in Materials* 21, article 100534. https://doi.org/10.1016/j.rinma.2024.100534

Alcock, M., Ahmed, S., DuCharme, S., and Ulven, C. A. (2018). "Influence of stem diameter on fiber diameter and the mechanical properties of technical flax fibers from linseed flax," *Fibers* 6(1), article 10. https://doi.org/10.3390/fib6010010

Alzate Acevedo, S., Díaz Carrillo, Á. J., Flórez-López, E., and Grande-Tovar, C. D. (2021). "Recovery of banana waste-loss from production and processing: A contribution to a circular economy," *Molecules* 26(17), article 5282. https://doi.org/10.3390/molecules26175282

Aminah, D., Fatriani, F., and Arryati, H. (2020). "Sifat Fisik dan Kimia Pelepah Aren (*Arenga pinnata* Merr) Untuk Bahan Baku Alternatif Pulp dan Kertas (Physical and chemical properties of aren palm stems (*Arenga pinnata* Merr) as alternative raw materials for pulp and paper)," *Jurnal Sylva Scienteae* 3, article 460. https://doi.org/10.20527/jss.v3i3.2179

Arul Marcel Moshi, A., Ravindran, D., and Venkatkumar, D. (2024). "Mechanical characterization of natural fiber composites prepared with untreated and treated ficus religiosa root fibers," *Proceedings of the Institution of Mechanical Engineers, Part C*, 239(5), 1694-1701. https://doi.org/10.1177/09544062241293300

Asroni, A., and Handono, S. (2018). "Kaji Eksperimen Variasi Jenis Serat Batang Pisang

Untuk Bahan Komposit Terhadap Kekuatan Mekanik (Experimental study of variation of banana stem fiber types for composite materials on mechanical strength)," *Turbo : Jurnal Program Studi Teknik Mesin*, 7. https://doi.org/10.24127/trb.v7i2.764

Azman Mohammad Taib, M. N., and Julkapli, N. M. (2019). "4 - Dimensional stability of natural fiber-based and hybrid composites," in: *Mechanical and Physical Testing of Biocomposites, Fibre-Reinforced Composites and Hybrid Composites*, series: *Woodhead Publishing Series in Composites Science and Engineering*, M. Jawaid, M. Thariq, and N. Saba (eds.), Woodhead Publishing, pp. 61-79. https://doi.org/10.1016/B978-0-08-102292-4.00004-7

Bachchan, A. A., Das, P. P., and Chaudhary, V. (2022). "Effect of moisture absorption on the properties of natural fiber reinforced polymer composites: A review," *Materials Today: Proceedings*, 49, 3403-3408. https://doi.org/10.1016/j.matpr.2021.02.812

Balakrishnan, S., Wickramasinghe, G. L. D., and Wijayapala, S. (2020). "A novel approach for banana (*Musa*) pseudo-stem fibre grading method: Extracted fibres from Sri Lankan banana cultivars," *Journal of Engineered Fibers and Fabrics* 15, article 155892502097176. https://doi.org/10.1177/1558925020971766

Bedru, T. K., and Meshesha, B. T. (2022). "Synthesis, optimization and characterization of pulp from banana pseudo stem for paper making *via* soda anthraquinone pulping process," in: *BT - Advances of Science and Technology*, M. L. Berihun (ed.), Springer International Publishing, Cham, 3–16.

Bledzki, A. K., and Gassan, J. (1999). "Composites reinforced with cellulose-based fibres," *Progress in Polymer Science* 24, 221-274. https://doi.org/1016/S0079-6700(98)00018-5

Bowyer, J. L., Shmulsky, R., and Haygreen, J. G. (2007). *Forest Products and Wood Science: An Introduction*, Blackwell, New Jersey, America.

Chaudhary, V., Bajpai, P., and Maheshwari, S. (2018). "Effect of moisture absorption on the mechanical performance of natural fiber reinforced woven hybrid bio-composites," *Journal of Natural Fibers* 17, 1-17. https://doi.org/10.1080/15440478.2018.1469451

Cordeiro, N., Belgacem, M. N., Torres, I. C., and Moura, J. C. V. P. (2004). "Chemical composition and pulping of banana pseudo-stems," *Industrial Crops and Products* 19(2), 147-154. https://doi.org/10.1016/j.indcrop.2003.09.001

Datta, P., Chandan, G., and and Sarkhel, G. (2016). "Morphological, dynamic mechanical, creep and weathering behavior of carbon nanotube-reinforced 50/50 ASA/Zn-ionomer blend," *Polymer-Plastics Technology and Engineering* 55(5), 453-462. https://doi.org/10.1080/03602559.2015.1098691

Dien, L. Q., Phuong, N. T. M., Hoa, D. T., and Huy Hoang, P. (2015). "Efficient pretreatment of Vietnamese rice straw by soda and sulfate cooking methods for enzymatic saccharification," *Applied Biochemistry and Biotechnology* 175(3), 1536-1547. https://doi.org/10.1007/s12010-014-1359-3

Ennos, A. R., Spatz, H. C., and Speck, T. (2000). "The functional morphology of the petioles of the banana, *Musa textilis*," *Journal of Experimental Botany* 51(353), 2085-2093. https://doi.org/10.1093/jexbot/51.353.2085

Fatriasari, W., Muhammad Rasyidur, R., Azizatul, K., Yusup, A., Maya, I., Muhammad Adly Rahandi, L., Nissa Nurfajrin, S., Fahriya Puspita, S., Danang Sudarwoko, A., Faizatul, F. *et al*. (2022). "Characterization of Indonesian banana species as an alternative cellulose fibers," *Journal of Natural Fibers* 19(16), 14396-14413.

https://doi.org/10.1080/15440478.2022.2064394

Fatriasari, W., Nurhamzah, F., Raniya, R., Laksana, R. P. B., Anita, S. H., Iswanto, A. H., and Hermiati, E. (2020). "Enzymatic hydrolysis performance of biomass by the addition of a lignin based biosurfactant," *Journal of the Korean Wood Science and Technology* 48(5), 651-665. https://doi.org/10.5658/WOOD.2020.48.5.651

Febriani, C. (2021). "Hidrolisis lignoselulosa dan karakterisasi lignin dari material limbah kelapa dengan metode hidrolisis asam sulfat (Hydrolysis of lignocellulose and characterization of lignin from coconut waste material using sulfuric acid hydrolysis method)," *Jurnal Teknologi Kimia Unimal* 10, article 45. https://doi.org/10.29103/jtku.v10i2.5573

French, A. D. (2014). "Idealized powder diffraction patterns for cellulose polymorphs," *Cellulose* 21(2), 885-896. https://doi.org/10.1007/s10570-013-0030-4

Furusawa, Y., and Ashitani, T. (2021). "Assessing the impacts of cell wall composition on the optimum stage for 'Uradome' in moso bamboo," *Journal of Wood Science* 67. https://doi.org/10.1186/s10086-021-01971-x

Gopinathan, P., Subramanian, K., Paliyath, G., and Subramanian, J. (2017). "Genotypic variations in characteristics of nano-fibrillated cellulose derived from banana pseudostem," *BioResources* 12(4), 6984-7001. https://doi.org/10.15376/biores.12.4.6984-7001

He, Z., Liu, Y., Tewolde, H., and Zhang, H. (2022). "Fourier transform infrared spectral features of plant biomass components during cotton organ development and their biological implications," *Journal of Cotton Research* 5, article 11. https://doi.org/10.1186/s42397-022-00117-8

Ihwah, A., Setyawan, H., Kurniasari, A., and Ulfah, A. (2019). "Optimasi Proses Delignifikasi Pelepah Pisang Untuk Bahan Baku Pembuatan Kertas Seni (Optimization of banana stem delignification process for raw materials in making art paper)," *Sebatik* 23, 447-454. https://doi.org/10.46984/sebatik.v23i2.797

Jawaid, M., and Abdul Khalil, H. P. S. (2011). "Cellulosic/synthetic fibre reinforced polymer hybrid composites: A review," *Carbohydrate Polymers* 86(1), 1-18. https://doi.org/10.1016/j.carbpol.2011.04.043

Jayaprabha, J. S., M., B., and and Manilal, V. B. (2011). "Banana pseudostem characterization and its fiber property evaluation on physical and bioextraction," *Journal of Natural Fibers* 8(3), 149-160. https://doi.org/10.1080/15440478.2011.601614

Kalangi, C., Antony Prabu, D., Sujin Jose, A., and Jani, S. P. (2022). "Experimental characterization of banana fiber reinforced polyester composites," *Materials Today: Proceedings* 60, 2236-2239. https://doi.org/10.1016/j.matpr.2022.03.232

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. https://doi.org/10.1016/j.jmrt.2021.06.014

Karuppuchamy, A., Ramya, K., and Siva, R. (2024). "Novel banana core stem fiber from agricultural biomass for lightweight textile applications," *Industrial Crops and Products* 204, article 117985. https://doi.org/10.1016/j.indcrop.2023.117985

Kumari, P., Gaur, S., and Tiwari, R. (2023). "Banana and its by-products: A comprehensive review on its nutritional composition and pharmacological benefits," *eFood* 4. https://doi.org/10.1002/efd2.110

Kusić, D., Božič, U., Monzón, M., Paz, R., and Bordón, P. (2020). "Thermal and mechanical characterization of banana fiber reinforced composites for its application in injection molding," *Materials* 3(16), article 3581. https://doi.org/10.3390/ma13163581

Kwei-Nam, L., Wan Daud, W. R., and Ghazali, A. (2007). "Morphological and chemical nature of fiber strands of Oil Palm Empty-Fruit-Bunch (OPEFB)," *BioResources* 2(4), 351-362. https://doi.org/10.15376/biores.2.4.351-362

Le, N.-D., Trogen, M., Ma, Y., Varley, R. J., Hummel, M., and Byrne, N. (2020). "Cellulose-lignin composite fibers as precursors for carbon fibers: Part 2 – The impact of precursor properties on carbon fibers," *Carbohydrate Polymers* 250, article 116918. https://doi.org/10.1016/j.carbpol.2020.116918

Li, K., Fu, S., Zhan, H., Zhan, Y., and Lucia, L. (2010). "Analysis of the chemical composition and morphological structure of banana pseudo-stem," *BioRes*ources 5(2), 576-585. https://doi.org/10.15376/biores.5.2.576-585

Liang, T., and Wang, L. (2016). "Thermal treatment of poplar hemicelluloses at 180 to 220 °C under nitrogen atmosphere," *BioResources* 12(1), 1128-1135. https://doi.org/10.15376/biores.12.1.1128-1135

Lourenço, A., and Pereira, H. (2018). "Compositional variability of lignin in biomass," in: *Lignin – Trends and Applications*, M. Potetto (ed.). https://doi.org/10.5772/intechopen.71208

Lu, P., and Hsieh, Y.-L. (2010). "Preparation and properties of cellulose nanocrystals: Rods, spheres, and network," *Carbohydrate Polymers* 82(2), 329-336. https://doi.org/10.1016/j.carbpol.2010.04.073

Lu, Y., He, Q., Fan, G., Cheng, Q., and Song, G. (2021). "Extraction and modification of hemicellulose from lignocellulosic biomass: A review," *Green Processing and Synthesis* 10, 779-804. https://doi.org/10.1515/gps-2021-0065

Madhushani, W. H., Priyadarshana, I., Ranawana, C., Senarathna, C., and Kaliyadasa, E. (2021). "Determining the crystallinity index of cellulose in chemically and mechanically extracted banana fiber for the synthesis of nanocellulose," *Journal of Natural Fibers* 1-9. https://doi.org/10.1080/15440478.2021.1958428

Małachowska, E., Dubowik, M., Boruszewski, P., Łojewska, J., and Przybysz, P. (2020). "Influence of lignin content in cellulose pulp on paper durability," *Scientific Reports* 10(1), article 19998. https://doi.org/10.1038/s41598-020-77101-2

Mamudu, U., Kabyshev, A., Bekmyrza, K., Kuterbekov, K. A., Baratova, A., Omeiza, L. A., and Lim, R. C. (2025). "Extraction, preparation and characterization of nanocrystalline cellulose from lignocellulosic simpor leaf residue," *Molecules* 30(7), article 1622. https://doi.org/10.3390/molecules30071622

Matthews, J. F., Himmel, M. E., and Crowley, M. F. (2012). "Conversion of cellulose Iα to Iβ via a high temperature intermediate (I-HT) and other cellulose phase transformations," *Cellulose* 19(1), 297-306. https://doi.org/10.1007/s10570-011-9608-x

Mayerni, R. (2018). "Characterization of agronomic and quality from three clones of Ramie plant (*Boehmeria nivea* [L.] Gaud.) in Ultisol Limau Manis," *JERAMI Indonesian Journal of Crop Science* 1, 1-8. https://doi.org/10.25077/jijcs.1.1.01-08.2018

Melesse, E., Bedru, T. K., and Meshesha, B. T. (2022). "Production and characterization of pulp from banana pseudo-stem for paper making via soda-anthraquinone pulping process," *International Journal of Engineering Research in Africa*, 58, 63-76.

https://doi.org/10.4028/www.scientific.net/JERA.58.63
Mohanty, A. K., M., M., and and Drzal, L. T. (2001). "Surface modifications of natural fibers and performance of the resulting biocomposites: An overview," *Composite Interfaces* 8(5), 313-343. https://doi.org/10.1163/156855401753255422
Montoya Berrio, J., Negrete Martínez, J., Altamiranda Suárez, J., Ávila Díaz, C., Rivero-Romero, O., and Unfried-Silgado, J. (2024). "Influence of drying temperature on the properties of Colombian banana fibers for its potential use as reinforcement in composite materials," *Scientific Reports* 14(1), article 25180. https://doi.org/10.1038/s41598-024-76460-4
Moshi, A, A., Ravindran, D., Bharathi, S. R., Suganthan, V., and Singh, G. (2019). "Characterization of new natural cellulosic fibers – A comprehensive review," *IOP Conference Series: Materials Science and Engineering* 574, article 12013. https://doi.org/10.1088/1757-899X/574/1/012013
Motaleb, K. Z. M. A., Ahad, A., Laureckiene, G., and Milasius, R. (2021). "Innovative banana fiber nonwoven reinforced polymer composites: Pre- and post-treatment effects on physical and mechanical properties," *Polymers* 13(21), article 3744. https://doi.org/10.3390/polym13213744
Murda, R. A., Nawawi, D. S., Maulana, S., Maulana, M. I., Park, S.-H., and Febrianto, F. (2018). "Chemical components changed in three bamboo species treated by steaming and washing processes (Perubahan Kadar Komponen Kimia pada Tiga Jenis Bambu Akibat Proses Steam dan Pembilasan)," *Jurnal Ilmu dan Teknologi Kayu Tropis* 16(2).
Musthaq, M. A., Dhakal, H. N., Zhang, Z., Barouni, A., and Zahari, R. (2023). "The effect of various environmental conditions on the impact damage behaviour of natural-fibre-reinforced composites (NFRCs)—A critical review," *Polymers* 15(5), article 1229. https://doi.org/10.3390/polym15051229
Nasri, K., Loranger, É., and Toubal, L. (2023). "Effect of cellulose and lignin content on the mechanical properties and drop-weight impact damage of injection-molded polypropylene-flax and -pine fiber composites," *Journal of Composite Materials* 57, 3347-3364. https://doi.org/10.1177/00219983231186208
Nawawi, D. S., Sari, R. K., Wistara, N. J., Fatrawana, A., Astuti, P., and Syafii, W. (2019). "Lignin characteristic of four bamboo species (Karakteristik Lignin Empat Jenis Bambu)," *Jurnal Ilmu dan Teknologi Kayu Tropis* 17(1).
Nishiyama, Y., Sugiyama, J., Chanzy, H., and Langan, P. (2003). "Crystal structure and hydrogen bonding system in cellulose iα from synchrotron X-ray and neutron fiber diffraction," *Journal of the American Chemical Society* 125(47), 14300-14306. https://doi.org/10.1021/ja037055w
Nurnasari, E., and Nurindah, N. (2017). "Karakteristik Kimia Serat Buah, Serat Batang, dan Serat Daun," *Buletin Tanaman Tembakau, Serat & Minyak Industri* 9(22), 64-72.
Nurnasari, E., and Supoyo, N. (2018). "Karakteristik Kimia Serat Buah, Serat Batang, dan Serat Daun," *Buletin Tanaman Tembakau, Serat & Minyak Industri* 9, article 64. https://doi.org/10.21082/btsm.v9n2.2017.64-72
Nurrani, L. (2012). "Pemanfaatan Batang Pisang (Musa sp.) Sebagai Bahan Baku Papan Serat Dengan Perlakuan Termo-Mekanis," *Jurnal Penelitian Hasil Hutan* 30, 1-9. https://doi.org/10.20886/jphh.2012.30.1.1-9
Nurwahdah, N., Naini, A., Nadia, A., Lestari, R., and Sunardi, S. (2018). "Pretreatment Lignoselulosa dari Jerami Padi dengan Deep Eutectic Solvent untuk Meningkatkan Produksi Bioetanol Generasi Dua (Lignocellulose pretreatment of rice straw using

deep eutectic solvent to increase second-generation bioethanol production)," *Jurnal Riset Industri Hasil Hutan* 10, article 43. https://doi.org/10.24111/jrihh.v10i1.4079

Ohra-aho, T., Gomes, F. J. B., Colodette, J. L., and Tamminen, T. (2013). "S/G ratio and lignin structure among Eucalyptus hybrids determined by Py-GC/MS and nitrobenzene oxidation," *Journal of Analytical and Applied Pyrolysis* 101, 166-171. https://doi.org/10.1016/j.jaap.2013.01.015

Ojahan, T., and Pratiwi, D. K. (2013). *Kajian Proses Ekstraksi Serat Batang Pisang Kepok Sebagai Fiber Dengan Matriks Recycled Polypropylene (Rpp) Material Komposit*, Conference: SNTTM V, Bandar Lampung

Paul, S. A., Boudenne, A., Ibos, L., Candau, Y., Joseph, K., and Thomas, S. (2008). "Effect of fiber loading and chemical treatments on thermophysical properties of banana fiber-polypropylene commingled composite materials," *Composites Part A: Applied Science and Manufacturing* 39, 915-928. https://doi.org/10.1016/j.compositesa.2008.06.004

Park, C.-W., Han, S.-Y., Choi, S.-K., and Lee, S.-H. (2017). "Preparation and properties of holocellulose nanofibrils with different hemicellulose content," *BioResources* 12(3), 6298-6308. https://doi.org/10.15376/biores.12.3.6298-6308

Pereira, A., Magalhães do Nascimento, D., Souza, M., Cassales, A., Saraiva Morais, J. P., Paula, R., Rosa, M., and Feitosa, J. (2014). "Banana (*Musa* sp. cv. Pacovan) pseudostem fibers are composed of varying lignocellulosic composition throughout the diameter," *BioResources* 9(4), 7749-7763. https://doi.org/10.15376/biores.9.4.7749-7763

Pickering, K. L., Efendy, M. G. A., and Le, T. M. (2016). "A review of recent developments in natural fibre composites and their mechanical performance," *Composites Part A: Applied Science and Manufacturing*, 83, 98-112. https://doi.org/10.1016/j.compositesa.2015.08.038

Pinheiro, L. F., Garavello, M. E. de P. E., Baruque-Ramos, J., Kohan, L., Duarte, L. O., Fernandes, P. R. B., Siqueira, M. U., and Fangueiro, R. (2022). "Banana pseudostem fibers (Musa sp.—cultivar AAB Prata): Physicochemical characteristics," *Materials Circular Economy* 4(21), 1-14. https://doi.org/10.1007/s42824-022-00062-6

Punyamurthy, R., Dhanalakshmi, D., Bennehalli, B., and Chikkol Venkateshappa, S. (2012). "Influence of esterification on the water absorption property of single abaca fiber," *Chemical Science Transactions* 2, 413-422. https://doi.org/10.7598/cst2013.371

Ralph, J., Lundquist, K., Brunow, G., Lu, F., Kim, H., Schatz, P. F., Marita, J. M., Hatfield, R. D., Ralph, S. A., Christensen, J. H., and Boerjan, W. (2004). "Lignins: Natural polymers from oxidative coupling of 4-hydroxyphenyl- propanoids," *Phytochemistry Reviews* 3(1), 29-60. https://doi.org/10.1023/B:PHYT.0000047809.65444.a4

Rencoret, J., Kim, H., Evaristo, A. B., Gutiérrez, A., Ralph, J., and del Río, J. C. (2018). "Variability in lignin composition and structure in cell walls of different parts of Macaúba (*Acrocomia aculeata*) palm fruit," *Journal of Agricultural and Food Chemistry* 66(1), 138-153. https://doi.org/10.1021/acs.jafc.7b04638

Richely, E., Zarei, A., Melelli, A., Rajan, D. K., Govilas, J., Gabrion, X., Clévy, C., Legland, D., Perez, J., Guessasma, S. *et al*. (2023). "Measurement of microfibril angle in plant fibres: Comparison between X-ray diffraction, second harmonic generation and transmission ellipsometry microscopies," *Composites Part C: Open Access* 11, article 100355. https://doi.org/10.1016/j.jcomc.2023.100355

Rodrigues, P. F., Dmitry D., E., Dmitry V., E., and and Prates, A. (2018). “Extractive profiles in the production of sulfite dissolving pulp from *Eucalyptus globulus* wood,” *Journal of Wood Chemistry and Technology* 38(5), 397-408. https://doi.org/10.1080/02773813.2018.1513037

Rowell, R. (2005). *Handbook of Wood Chemistry and Wood Composites*, *Handbook of Wood Chemistry and Wood Composites*, Second Edition. https://doi.org/10.1201/b12487

Rowell, R. M., Pettersen, R., Han, J. S., Rowell, J., and Tshabalala, M. (2016). “Cell wall chemistry,” in: *Handbook of Wood Chemistry and Wood Composites*. https://doi.org/10.1201/b12487

Salem, K., Kasera, N., Rahman, M., Habibi, Y., Eichhorn, S., French, A., Pal, L., and Lucia, L. (2023). “Comparison and assessment of methods for cellulose crystallinity determination,” *Chemical Society Reviews* 52, 6417-6446. https://doi.org/10.1039/D2CS00569G

Sathishkumar, T. P., Shah, M., Panchal, H., Sharma, K., Gopinath, R., M R, S., Siengchin, S., Kumar L, R., and Rampradheep, G. (2024). “Characterization of new cellulose fiber extracted from second generation Bitter Albizia tree,” *Scientific Reports* 14. https://doi.org/10.1038/s41598-024-51719-y

Segal, L., Creely, J. J., MartinJr, A. E., and Conrad, C. M. (1959). “An empirical method for estimating the degree of crystallinity of native cellulose using the X-ray diffractometer,” *Textile Research Journal* 29(10), 786-794. https://doi.org/10.1177/004051755902901003

Silva, F. S., Ribeiro, C. E. G., Demartini, T. J. da C., Rodríguez, R. J. S. (2020). “Physical, chemical, mechanical, and microstructural characterization of banana pseudostem fibers from *Musa sapientum*,” *Macromol. Symp.* 394, article 2000052. https://doi.org/10.1002/masy.202000052

Solihat, N. N., Santoso, E. B., Karimah, A., Madyaratri, E. W., Sari, F. P., Falah, F., Iswanto, A. H., Ismayati, M., Lubis, M. A., Fatriasari, W. *et al*. (2022). “Physical and chemical properties of acacia mangium lignin isolated from pulp mill byproduct for potential application in wood composites,” *Polymers* 14(3), article 49. https://doi.org/10.3390/polym1403049

Subagyo, A., and Chafidz, A. (2018). “Banana pseudo-stem fiber: preparation, characteristics, and applications,” in: *Banana Nutrition – Function and Processing Kinetics*, IntechOpen. https://doi.org/10.5772/intechopen.82204

Sutiya, B., Istikowati, W., Rahmadi, A., and Sunardi, S. (2012). “Kandungan Kimia dan Sifat Serat Alang-Alang (*Imperata cylindrica*) Sebagai Gambaran Bahan Baku Pulp dan Kertas,” *Bioscientiae* 9, 8-19. https://doi.org/10.20527/b.v9i1.2583

Tappi. (1997a). “Preparation of wood for chemical analysis,” *TAPPI Test Method T 264 cm-97*, TAPPI Press, Atlanta, GA.

Tappi. (1997b). “Solvent extractives of wood and pulp,” *TAPPI Test Method T 204,* TAPPI Press, Atlanta, GA.

Tarasov, D., Leitch, M., and Fatehi, P. (2018). “Lignin-carbohydrate complexes: Properties, applications, analyses, and methods of extraction: A review,” *Biotechnology for Biofuels* 11, article 269. https://doi.org/10.1186/s13068-018-1262-1

Terinte, N., Ibbett, R., and Schuster, K. (2011). “Overview on native cellulose and microcrystalline cellulose I structure studied by X-ray diffraction (WAXD): Comparison between measurement techniques,” *Lenzinger Berichte* 89.

Tian, Y., Gao, Y., Turumtay, H., Turumtay, E. A., Chai, Y. N., Choudhary, H., Park, J.-H., Wu, C.-Y., De Ben, C. M., Dalton, J. *et al*. (2024). "Engineered reduction of S-adenosylmethionine alters lignin in sorghum," *Biotechnology for Biofuels and Bioproducts* 17(1), article 128. https://doi.org/10.1186/s13068-024-02572-8

Wahab, R., Mustafa, M., Mohamed, A., W.Samsi, H., and Mat Rasat, M. S. (2013). "Extractives, holocellulose, a-cellulose, lignin and ash contents in 3 year-old bamboo culms Gigantochloa Brang," in: *Research Journal of Pharmaceutical, Biological and Chemical Sciences*, 4, 1235-1247.

Wang, Q., Xiao, S., and Shi, S. (2019). "The effect of hemicellulose content on mechanical strength, thermal stability, and water resistance of cellulose-rich fiber material from poplar," *BioResources* 14(3), 5288-5300. https://doi.org/10.15376/biores.14.3.5288-5300

Wang, W., Sain, M., and Cooper, P. A. (2006). "Study of moisture absorption in natural fiber plastic composites," *Composites Science and Technology* 66(3), 379-386. https://doi.org/10.1016/j.compscitech.2005.07.027

Wibowo, E., Lubis, M. A., and PARK, B.-D. (2021). "Simultaneous Improvement of formaldehyde emission and adhesion of medium-density fiberboard bonded with low-molar ratio urea-formaldehyde resins modified with nanoclay," *Journal of the Korean Wood Science and Technology* 49, 453-461. https://doi.org/10.5658/WOOD.2021.49.5.453

Wise, L. E., Murphy, M., and Addieco, A. A. d'. (1946). "Chlorite holocellulose, its fractionation and bearing on summative wood analysis and studies on the hemicelluloses," *Paper Trade Journal TA - TT* -. LK - https://worldcat.org/title/708721051

Wistara, N., Sukowati, M., and Pamoengkas, P. (2016). "The properties of red meranti wood (Shorea leprosula Miq) from stand with thinning and shade free gap treatments," *Journal of the Indian Academy of Wood Science* 13. https://doi.org/10.1007/s13196-016-0161-y

Wulandari, W., Rochliadi, A., and Arcana, I. M. (2016). "Nanocellulose prepared by acid hydrolysis of isolated cellulose from sugarcane bagasse," *IOP Conference Series: Materials Science and Engineering* 107, article 12045. https://doi.org/10.1088/1757-899X/107/1/012045

Xie, J., Hse, C.-Y., Shupe, T., Pan, H., and Hu, T. (2016). "Extraction and characterization of holocellulose fibers by microwave-assisted selective liquefaction of bamboo," *Journal of Applied Polymer Science* 133, article 43394. https://doi.org/10.1002/app.43394

Xu, P., Cheng, S., Han, Y., Zhao, D., Li, H., Wang, Y., Zhang, G., and Chen, C. (2020). "Natural variation of lignocellulosic components in miscanthus biomass in China," *Frontiers in Chemistry* 8, article 595143. https://doi.org/10.3389/fchem.2020.595143

Xu, S., Xiong, C., Tan, W., and Zhang, Y. (2015). "Microstructural, thermal, and tensile characterization of banana pseudo-stem fibers obtained with mechanical, chemical, and enzyme extraction," *BioResources* 10(2), 3724-3735. https://doi.org/10.15376/biores.10.2.3724-3735

Yang, X., Berthold, F., and Berglund, L. A. (2019). "High-density molded cellulose fibers and transparent biocomposites based on oriented holocellulose," *ACS Applied Materials and Interfaces* 11(10), 10310-10319. https://doi.org/10.1021/acsami.8b22134

Yuan, T., Du, W., Bai, K., Huang, D., Nguyen, T. T., Li, J., and Ji, X. (2022).

"Preparation of an environment-friendly fiberboard with high mechanical strength using delignified wood fiber," *Vacuum* 196, article 110753. https://doi.org/10.1016/j.vacuum.2021.110753

Yulfa, D., Mayerni, R., and Yusniwati, Y. (2019). "Kualitas Kimia Serat beberapa Klon Rami Asal Sumatera Barat," *Agrotechnology Research Journal* 3, article 115. https://doi.org/10.20961/agrotechresj.v3i2.34761

Zha, L., Yan, M., Berglund, L. A., and Zhou, Q. (2024). "Tailoring the holocellulose fiber/acrylic resin composite interface with hydrophobic carboxymethyl cellulose to enhance optical and mechanical properties," *Biomacromolecules* 25(6), 3731-3740. https://doi.org/10.1021/acs.biomac.4c00295

Zhang, S.-Y., Fei, B.-H., Yu, Y., Cheng, H.-T., and Wang, C.-G. (2013). "Effect of the amount of lignin on tensile properties of single wood fibers," *Forest Science and Practice* 15(1), 56-60. https://doi.org/10.1007/s11632-013-0106-0

Zhao, C., Zhang, H., Zeng, X., Li, H., and Sun, D. (2016). "Enhancing the inter-fiber bonding properties of cellulosic fibers by increasing different fiber charges," *Cellulose* 23, 1617-1628. https://doi.org/10.1007/s10570-016-0941-y

Zhou, C., Jiang, W., Cheng, Q., and Via, B. K. (2015). "Multivariate calibration and model integrity for wood chemistry using fourier transform infrared spectroscopy," *Journal of Analytical Methods in Chemistry* 429846. https://doi.org/10.1155/2015/429846

Zulaekha, R., Nawafil, S. A., Harianti, S. F. (2018). "Isolasi alfa selulosa batang pisang klutuk (*Musa balbisiana* Colla) menggunakan pengadukan magnetik dengan ultrasonik," *Jurnal Teknologi Bahan Alam* 2, 129.

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