Research Article

Characterization of Banana Fiber-Reinforced Bioplastics for Environmentally Friendly Packaging Applications

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Abstract
This study explores the biocomposites composed of poly(butylene succinate) (PBS) reinforced with alkali-treated banana sheath and banana leaf fibers. The fibers were treated with 5% sodium hydroxide (NaOH) and incorporated into the PBS matrix at varying mesh sizes (40 and 60) and fiber contents (1, 2, and 5 parts per hundred resin (phr)). The composites were evaluated for melt flow rate (MFR), melt volume rate (MVR), tensile properties, impact strength, hardness, and microstructural characteristics using X-ray tomographic microscopy (XTM). The addition of both banana sheath and banana leaf fibers resulted in decreased MFR and MVR, while significantly improving the Young's modulus, which reached up to 280 MPa in the composite containing 5 phr of fine banana leaf fibers. Impact strength was found to depend on both fiber size and loading, with the highest value of 10.8 kJ/m² observed in the composite reinforced with 2 phr of coarser banana sheath fibers. Microstructural analysis revealed that fiber dispersion, agglomeration, and void formation were key factors influencing mechanical performance. Furthermore, a prototype plant pot was successfully fabricated using the composite with the highest fine fiber and content, demonstrating the composite's potential for sustainable product applications.

Keywords: Banana fiber, Chemical modification, Mechanical properties, Morphology, Poly(butylene succinate), X-ray tomographic microscopy

1 Introduction

Currently, the growing awareness of environmental impacts is attracting continuous attention across various sectors, including science, industry, and society, particularly regarding plastic waste [1]. As mentioned above, the increasing interest in biocomposite materials, which combine biopolymers and natural fibers, stems from their potential to reduce environmental harm. These materials are considered sustainable due to their use of renewable resources and natural biodegradability, helping to minimize ecological risks. However, it is important to note that not all biocomposites can directly replace synthetic materials. Several factors, such as expected service life, recyclability, incompatible matrix and fillers, low thermal stability, flammability, surface modification, machining, manufacturing, and so on, must be considered when evaluating their environmental benefits [2]. This is why many works focus on biocomposite materials, containing biofibers, for example, wood, hemp, rice husk, coir, flax, kenaf, jute, banana, and so on, which focus on a potential alternative to synthetic fibers [3]–[10]. The other reason for finding a new fiber is the development of an extensive range of eco–friendly products. In recent times, the biocomposites have been applied to several applications, including aerospace, automobiles, electronics, packaging, and so on [2], [11]–[13].

Banana fiber is one of the challenges as a biofiber. It is a byproduct of agricultural activity that is readily available in several countries worldwide, including India, China, Indonesia, Nigeria, and Brazil, etc. Banana fibers can be sourced from the stem (trunk) of the bunch (peduncle). It holds a wide range of benefits in many areas of application. For example, a recyclable alternative to be used in textiles, paper production, reinforcements, and composites, as well as polymer matrix composite materials. The primary rationale lies in the availability of fibers that are cost–effective, abundantly sourced, biodegradable, and characterized by low density [9]. These attributes have garnered significant interest among researchers, positioning such fibers as promising alternatives to synthetic reinforcements in polymer composite development [10], [14]–[16]. Furthermore, the development of biocomposites using banana sheath and leaf fibers plays a key role in supporting the BCG (Bio–Circular–Green Economy) model, which emphasizes the efficient and sustainable use of resources, aiming to reduce waste and promote biodegradable materials. The biocomposites developed from banana fibers have the potential to promote a circular economy and mitigate environmental impacts by maximizing the utilization of locally available resources.

Over the past few decades, there has been a significant amount of research on several bioplastics and biofibers to improve the mechanical and other properties for industrial and commercial applications. Polylactic acid (PLA), poly(hydroxy alkanoates) (PHA), poly(hydroxy butyrates) (PHB), poly(hydroxy valerate) (PHV), poly(hydroxy hexanoate) (PHH), thermoplastic starch (TPS), polybutylene succinate (PBS), and so on. PBS is an aliphatic biodegradable polyester that has attracted significant attention due to its favorable mechanical properties and heat resistance. Notably, PBS exhibits excellent biodegradability, melt processability, and chemical resistance, as demonstrated in previous studies [17]. Moreover, among aliphatic biodegradable polyesters, PBS stands out as a promising candidate due to its exceptional biodegradability, melt processability, and chemical resistance. PBS is typically synthesized through the copolymerization of succinic acid and 1,4–butanediol, which can be sourced from fossil–based or renewable resources. Various PBS-based polymeric materials can be synthesized with different types and ratios of co–monomers, which achieve a wide range of mechanical properties and biodegradation rates. This versatility makes PBS highly suitable for diverse processing techniques, including injection molding, extrusion, thermoforming, and so on [18], [19]. However, PBS has a limited Young's modulus and tends to degrade rapidly during high–temperature melting processes. Therefore, it is commonly blended with other types of polymers and reinforced with additives to enhance its processability, stiffness, and mechanical strength [17]. The incorporation of banana fibers into PBS is expected to enhance its mechanical properties. A significant challenge in the development of biodegradable polymer and natural fiber composites is ensuring uniform fiber dispersion and strong interfacial adhesion between the fibers and the polymer matrix. Furthermore, mitigating moisture sensitivity and optimizing fiber content are critical for achieving the desired mechanical properties. One effective approach to improving the performance of biofiber–reinforced polymer composites is the chemical treatment of biofibers before incorporation into the polymer matrix. Sodium hydroxide (NaOH) treatment plays a crucial role in enhancing interfacial bonding between the fibers and the polymer matrix

while also facilitating more uniform fiber dispersion. Additionally, this treatment aids in the removal of lignin and hemicellulose, which can impede adhesion, thereby improving the composite's overall strength and durability [9], [10], [14], [15].

To address the existing challenges, this study proposes a method that combines the size selection of two types of banana fibers, such as banana sheath (BS) and banana leaf (BL), with NaOH treatment. Then, all ingredients were mixed using an internal mixer to prepare the polymer compound. To examine the properties of the developed material, the study employs X–ray Tomographic Microscopy (XTM) to analyze the structure and fiber distribution at the microscale. Also, mechanical properties such as tensile properties and hardness were investigated. To support the processing of these composites, the melt flow index was explored as well.

The novelty of this study lies in its direct comparison of BS and BL fibers, highlighting their distinct structural roles and mechanical contributions. This approach differs from previous research, which primarily focused on pseudostems and peduncles and employed a single fiber size for each type [20]. Various polymer matrices, such as epoxy, vinyl ester, phenolic resin, and polyester resin, have been investigated in combination with different anatomical sections of the banana plant, including the outer bark, middle bark, inner bark, and leaf midrib [9], [10], [16], [21]. Thermoplastic matrices have also been explored, including low-density polyethylene [14], polypropylene [15], and high–density polyethylene [22]. Additionally, polylactic acid (PLA), a widely used bioplastic, has been compounded with banana fiber to form composite materials [23], [24]. In contrast, poly(butylene succinate) (PBS) has received limited attention; only a few studies have incorporated banana fiber into PBS composites using hexamethylene diisocyanate as a compatibilizer [25]. This gap underscores the need for further investigation into PBS–banana fiber composites. Furthermore, the application of X–ray tomographic microscopy (XTM) offers valuable three-dimensional insights into fiber distribution, void formation, and internal architecture, thereby providing a mechanistic understanding of banana fiber composite behavior. Furthermore, the research aims to develop a prototype flowerpot made from PBS/banana fiber composites to evaluate the formability and industrial applicability of the material. This prototyping process serves as a basis for assessing both the performance and potential for real applications.

2 Materials and Methods

2.1 *Materials*

Poly(butylene succinate) (PBS) was procured from PPT MCC Biochem Co., Ltd., Thailand. It is synthesized through the polymerization of bio-based succinic acid and 1,4–butanediol. The specific grade, BioPBSTM FZ71PM, is designed for injection molding applications and is suitable for general–purpose use. For the chemical treatment, sodium hydroxide (NaOH) (ANaPURE, micro pearls, AR grade) was utilized. The molecular weight of NaOH is 40 g/mol. Banana fibers, comprising banana sheath (BS) and banana leaf (BL), were sourced from Nakhon Ratchasima Province, Thailand. The characteristics of dried BS and BL are presented in Figures 1(a) and (b).

(a) (b)

Figure 1: Characteristics of dried (a) BS and (b) BL.

2.2 *Banana fibers preparation*

In this study, PBS served as the polymer matrix, while BS and BL were utilized as reinforcement fibers. Before use, the BS and BL were thoroughly cleaned and pre–treated. Initially, they were dried at 40 °C for 24 h to remove moisture.

Next, the fibers were treated with a 5% NaOH solution for 1 hour to enhance their properties. Non–fibrous components were then meticulously removed using mechanical brushing. The extracted banana fibers (from both the sheath and leaf) were thoroughly washed with deionized water to eliminate residual NaOH. A calibrated pH meter was used to confirm complete neutralization of the washed fibers. Finally, the fibers were dried at 60 °C for 12 h and ground for 3–5 min to achieve uniformity, as shown in Figure 2.

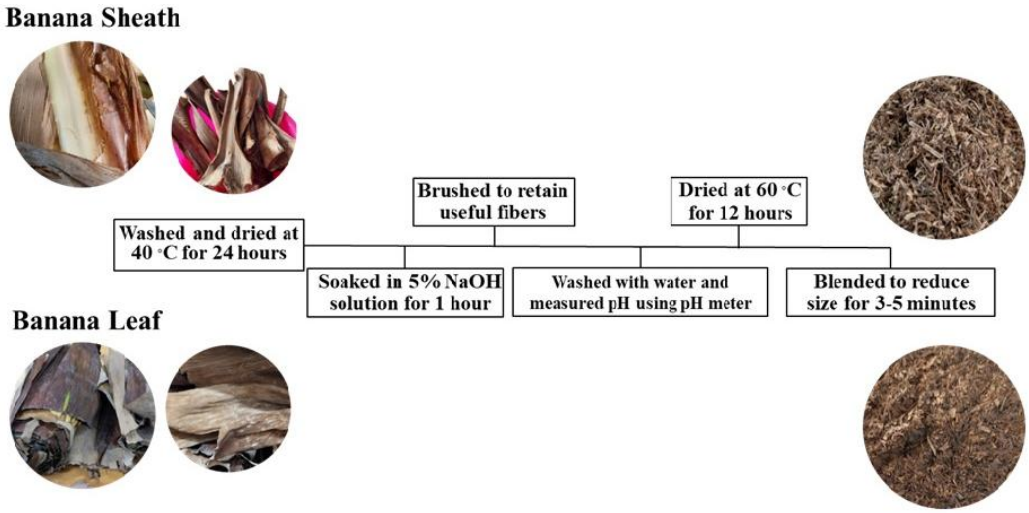


Figure 2: Preparation and treatment of banana fibers.

Then, the treated BS and BL fibers were size separated using a set of sieves with mesh sizes of 10, 40, and 60, respectively. As a result of the sieving process, the fibers were categorized into two distinct size fractions as presented in Figure 3.

Size 1 (BS1 and BL1): Fibers that passed through the 10-mesh sieve but were retained by the 40-mesh sieve, with an approximate size range of 2,000–400 microns.

Size 2 (BS2 and BL2): Fibers that passed through the 40-mesh sieve but were retained by the 60-mesh sieve, with an approximate size range of 400–250 microns.

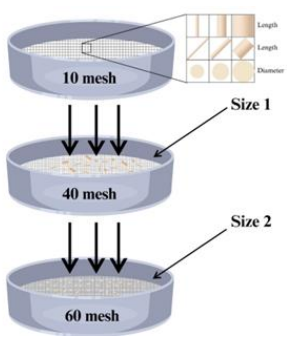


Figure 3: Fiber size classification.

2.3 *Polymer compounding and sample preparation*

Poly(butylene succinate) and treated BS and BL fibers were dried separately to remove moisture, with PBS dried at 50 °C and the fibers at 40 °C for 24 h. Following the drying process, the components were precisely weighed according to the mixing ratios outlined in Table 1. The mixtures were then compounded using an internal mixer (model MX500, Chareon Tut, Thailand) at 150 °C for 15 min, with a rotor speed of 50 rounds per minute.

The prepared composite material was used to fabricate the test specimens for mechanical property evaluation using a vertical ram extruder (in–house fabricated and calibrated device, capable of operating up to 300 °C). The barrel temperature was maintained at 150 °C for all specimens. During extrusion, the blend remained in the barrel for 5–7 minutes until reaching the target temperature. The molten plastic was then extruded via the ram to obtain the desired specimen shape. After extrusion, the specimens were cooled to room temperature before being removed from the mold. Specimen preparation followed ASTM D638–14 (2014), ASTM D256–10, and ASTM D2240-03 standards for tensile, impact, and Shore hardness testing, respectively.

2.4 *Characterization and testing*

Advanced imaging techniques, such as synchrotron–based XTM (Synchrotron Light Research Institute, (Public Organization), Thailand) technique at beamline 1.2W, will be employed to generate a three-dimensional image of the composites' structure. Specimens with dimensions of approximately 2 × 2 × 3 mm were used for the XTM test. This imaging will provide detailed insights into fiber-polymer bonding and the presence of voids within the composite. The resulting data will support the analysis of the mechanical properties. Fourier Transform Infrared

(FTIR) spectroscopy (PerkinElmer Spectrum 100, Germany) was employed to identify the chemical functional groups present in both untreated and alkali-treated banana fibers. Spectral analysis was conducted over the wavenumber range of 4000–650 cm^{-1}.

Additionally, scanning electron microscopy (SEM, QUANTA FEG 250, Japan) was employed to analyze the interfacial adhesion between the banana fiber and the PBS matrix, using fracture surfaces obtained after tensile tests. The surface characteristics of both untreated and treated banana fibers were examined using an optical microscope (Leica MD4 M, Germany).

Table 1: Sample identification and composition.

Sample	Composition	
	BS1 (phr) Banana Sheath (40 Mesh)	**BS2 (phr) Banana Sheath (60 Mesh)**
PBS	-	-
1BS2	-	1
2BS2	-	2
5BS2	-	5
2BS1	2	-
	BL1 (phr) Banana Leaf (40 Mesh)	**BL2 (phr) Banana Leaf (60 Mesh)**
1BL2	-	1
2BL2	-	2
5BL2	-	5
2BL1	2	-

The Melt flow rate (MFR) and melt volume rate (MVR) of both pure PBS and the produced composite specimens were determined using a melt flow indexer (GÖTTFERT model mi2.1) according to ASTM D1238–13 standards, under conditions of 150 °C and a load of 2.16 kg. Tensile properties were evaluated according to ASTM D638–14 (2014), Type IV, using a universal testing machine (Lloyd Instruments model LP10K). The tests were conducted at a crosshead speed of 5 mm/min under a maximum load capacity of 10 kN. Five specimens of each composition were tested, and tensile strength, modulus, and elongation at fracture were measured and averaged. Type IV tensile specimens were selected because the PBS–banana fiber composites are semi-flexible with limited thickness. The smaller Type IV geometry helps minimize premature failure at the narrow section and allows more reliable measurement of tensile properties. It is also more suitable for the testing equipment used, requiring lower load and elongation than Type I specimens.

Furthermore, impact strength was evaluated following ASTM D256–10 standards using an impact tester (INSTRON CEAST model 9050). The specimens were notched at the center with a depth of 2 mm and a notch angle of 45°. Five specimens of each composition were tested using an impact hammer with an energy of 2.75 J. Hardness was measured using a durometer Shore D according to ASTM D2240–03 standards. Specimens with a minimum thickness of 6 mm were prepared, and five indentations were made on each specimen. The average values for impact strength and hardness were calculated. Finally, a prototype plot planter was fabricated from the composite material to evaluate flow behavior and assess the efficiency of the forming process.

3 Result and Discussion

3.1 *Morphology*

The color appearance of the composites was examined in relation to the type and fraction of banana fiber, as illustrated in Figure 4. The color changes observed in the dried BS and BL in this study indicated that dried BL were darker than the BS after undergoing a drying process at 60 °C for 12 h. This can be attributed to various factors, including the chemical composition of the BS and BL, the drying process, and the surface treatment with NaOH prior to drying, all of which enhanced the visibility of the color change. One major contributing factor is the higher lignin content in the BL compared to the BS. Quim Tarrés *et al*., reported that banana leaf contains approximately 25% lignin [26], a finding corroborated by Taslima Ferdous *et al*., who observed a similar lignin content of around 23% [27]. While André Luís S. Pereira *et al*., found that banana sheaths contain significantly lower lignin levels, approximately 13% or less [28], [29]. When the BL was dried at 60 °C, the lignin underwent structural alterations or oxidation, which increased the absorption of light, resulting in a darker color for the BL. In contrast, the BS, having lower lignin content, did not experience the same level of change, thus retaining a lighter color. Another important factor is the degradation of chlorophyll in the BL. As chlorophyll is degraded under high heat, the green color in the leaf diminishes, resulting in a darker hue. Since BS contains less chlorophyll, the color change in the sheaths is less significant, keeping their color lighter than that of the BL [30]. The surface modification using NaOH also contributes to color changes. Treating BS and BL with NaOH enhances their light absorption capacity. This effect is particularly pronounced in BL, which has a higher

lignin content, resulting in a more pronounced darkening of the dried leaf compared to BS, which contains lower levels of lignin. This can be explained considering previous studies on chlorophyll degradation, which show that high temperatures accelerate chlorophyll breakdown, resulting in color shifts due to chemical changes during drying [31]–[33]. As a result, when BS and BL are incorporated into composite materials, the color of the final product varies, with composites reinforced with BL fibers exhibiting a darker color. As shown in Figure 4, increasing the proportion of BS and BL in the composite leads to a more intense darkening of the material.

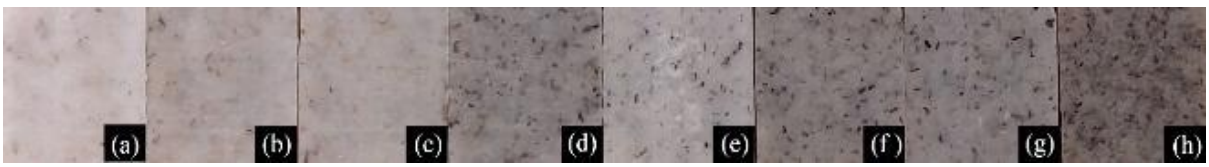


Figure 4: Appearance of polymer composite samples (a) 1BS2, (b) 2BS2 (c) 2BS1, (d) 5BS2, (e) 1BL2, (f) 2BL2, (g) 2BL1 and (h) 5BL2.

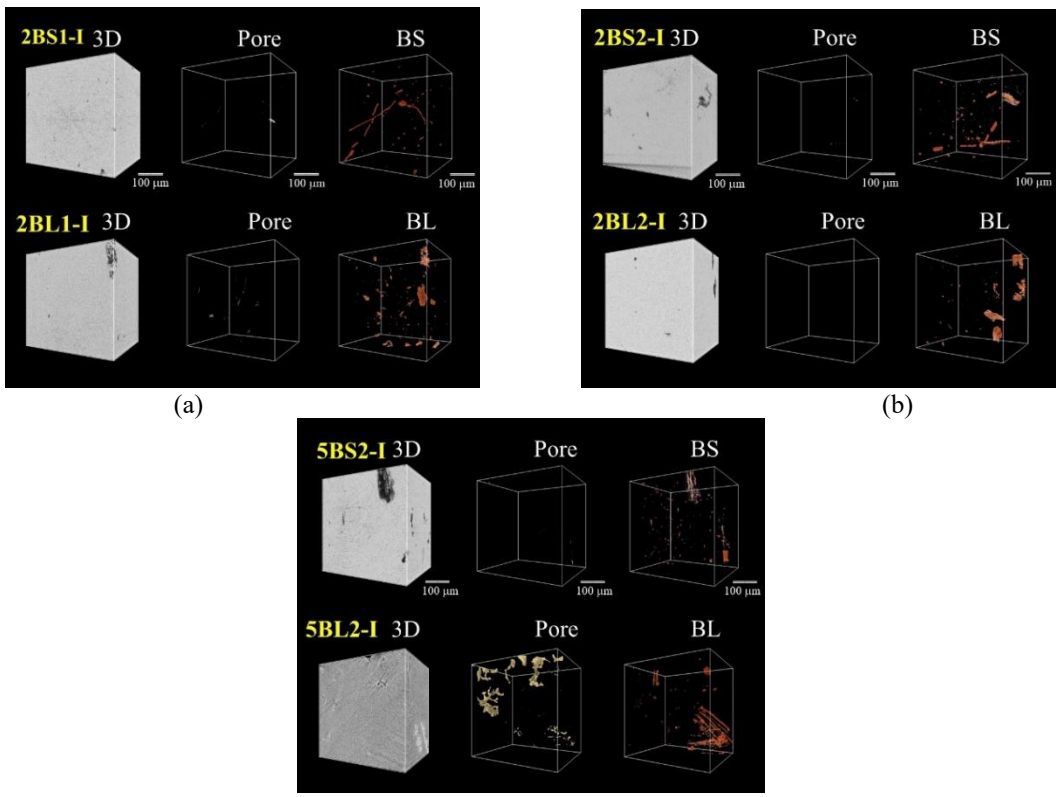


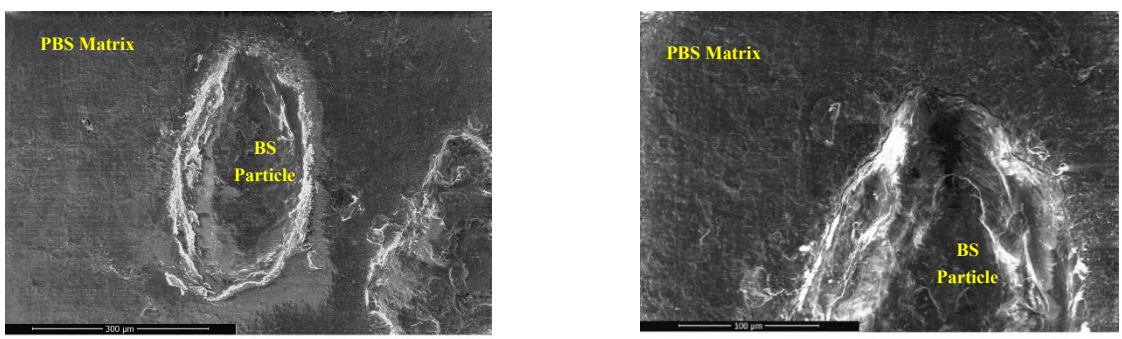
Figure 5: XTM images revealing the internal structure of composites (a) with 2 phr of BS and BL (40 Mesh), (b) with 2 phr of BS and BL (60 Mesh) and (c) with 5 phr of BS and BL (60 Mesh).

X–ray tomographic microscopy (XTM) analysis is another technique used to investigate the morphology of polymer composites. X–ray Tomography enables precise, non-destructive three–dimensional (3D) inspections of fiber architectures, manufacturing defects, and in-service damage accumulation. It allows users to analyze cross–sections that would have previously required labor–intensive and highly skilled mechanical sectioning, which carries the risk of material damage or loss [34]. Previous studies have utilized XTM analysis to examine the internal structure, focusing on the

dispersion phases and pores within the composite, as these characteristics significantly influence its properties [34]–[36]. Based on XTM analysis (Figure 5), the 3D images reveal a clear distinction between the internal structures of the two fiber types. BS fibers are evenly dispersed and well–embedded within the PBS matrix. This uniform distribution, along with the relatively low presence of voids around the BS fibers, suggests strong interfacial adhesion between the fibers and the matrix. In contrast, BL fibers appeared predominantly as large sheet–like structures, rather than as discrete fibers. These sheet formations tended to cluster in certain regions of the matrix, contributing to structural inhomogeneity and a higher tendency for pore formation or delamination at the fiber–matrix interface.

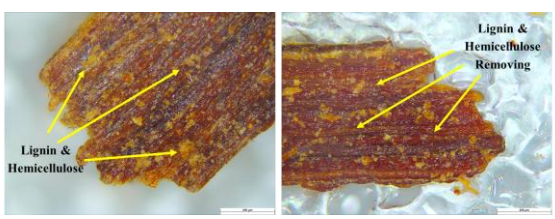
However, smaller particle sizes of both BS and BL tend to exhibit greater agglomeration than larger particle sizes. This phenomenon can be attributed to the increased surface area of smaller particles, which enhances their tendency to attract and interact with one another [37], [38]. Moreover, as the banana fiber content increases, both pore formation and particle agglomeration become more pronounced, as illustrated in Figures 5(b) and (c). These factors may influence the mechanical properties of PLB/banana fiber composites, which will be examined in detail in the following section.

Furthermore, the impact of alkali treatment (NaOH) on the surface of banana fibers within the PBS matrix was observed, as shown in Figure 6. In the case of BS fibers, the treated fibers embed effectively within the PBS matrix, demonstrating strong matrix-fiber interaction bonding and minimal cavity formation. The fiber surface facilitates improved interlocking, enhancing adhesion between the matrix and the fibers. This interlocking contributes to the mechanical bonding between the matrix and the fiber [21], [32].



(a) (b)

Figure 6: SEM images of 2BS2 at magnifications of (a) 500X and (b) 1200X.



(a) (b)

Figure 7: OM images of (a) untreated BL and (b) treated BL at magnifications of 10X.

The surface morphology of banana fiber, both untreated and treated with NaOH, reflects the presence and removal of impurities such as lignin, as illustrated in Figure 7. The untreated fiber surface displays visible lignin and hemicellulose (Figure 7(a)), whereas the treated fiber exhibits a cleaner appearance after removing these components (Figure 7(b)). Additionally, the treated fiber shows a smoother surface compared to the untreated one, which can be attributed to the densification of the cell walls and the encapsulation of pores by infused molecules. This enhanced surface structure, as observed in the SEM images, suggests improved interfacial bonding between the banana fiber and the PBS matrix, consistent with findings reported in previous studies [39].

Fourier Transform Infrared (FTIR) spectroscopy was employed to analyze BL fibers, both untreated and alkali-treated with NaOH, as well as pure PBS and PBS composites reinforced with treated banana stem (BS) and banana leaf (BL) fibers. Spectrum data were collected in the range of 4000 to 400 cm^{-1}, as shown in Figure 8. The FTIR spectrum of untreated BL fibers

(60 mesh) revealed distinct vibrational bands associated with cellulose, hemicellulose, and lignin. A broad band at 3277 cm^{-1} was attributed to the O–H stretching vibrations of hydroxyl groups present in cellulose, hemicellulose, and lignin. The peak at 1746 cm^{-1} corresponded to the stretching vibrations of acetyl groups in hemicellulose, while the band at 1381 cm^{-1} was assigned to C–H bending and phenolic O–H stretching, characteristic of lignin structures. Following alkali treatment, the FTIR spectrum of BL fibers exhibited a marked disappearance and reduction of the peaks at 3277 cm^{-1}, 1746 cm^{-1}, and 1381 cm^{-1}. These changes suggest the effective removal of lignin, pectin, and hemicellulose components [9], [32], [33], [40], [41]. Additionally, the treatment altered the fiber's surface chemistry, reducing its hydrophilicity and enhancing hydrophobicity [39]. The FTIR spectrum of pure PBS showed a prominent band near 1700 cm^{-1}, corresponding to the stretching vibration of ester carbonyl groups (C=O), and a band around 1300 cm^{-1}, attributed to symmetric C–H stretching vibrations [42]. In the PBS composites containing treated BS and BL fibers, bands were observed near 1740 cm^{-1} and 1250 cm^{-1}. Notably, the intensity of these peaks increased with higher fiber loading, indicating enhanced interaction between the PBS matrix and the banana fibers. These findings are consistent with the SEM micrograph of PBS composites with BS fiber, as presented in Figure 6. The morphological characteristics observed, in conjunction with the FTIR spectral data, provide evidence for the enhancement of Young's modulus. This improvement is attributed to the effective incorporation and progressive increase in the content of both BS and BL fibers within the PBS matrix, which contributes to better interfacial adhesion and structural reinforcement.

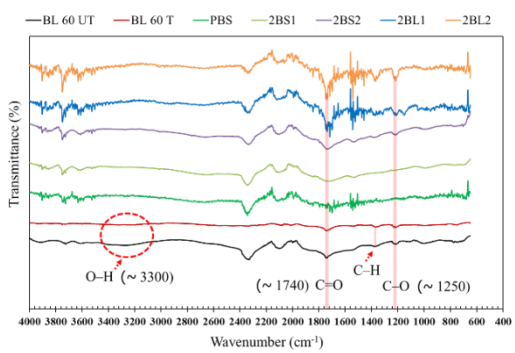


Figure 8: FTIR of untreated and treated BL and PBS/banana fiber composites with different types and content of banana fibers.

3.2 *Melt Flow Behavior*

In this study, the internal mixing technique was chosen for its ability to achieve high melt flow rate (MFR) and melt volume rate (MVR) values, indicating superior flow properties that facilitate rapid and efficient material shaping. Additionally, this technique effectively balances tensile strength, flexibility, impact resistance, and appropriate hardness—key properties for producing products requiring both durability and moldability, such as packaging, household items, and electronic components. Furthermore, efficient heat dissipation in the internal mixer reduces thermal degradation caused by exposure to high temperatures in the twin-screw extrusion process, preserving material stability and enhancing overall performance.

Analysis of the influence of banana fiber type on the melt flow behavior of the composite material (Figure 9) revealed that the composite material reinforced with BS fiber exhibited significantly higher MFR and MVR values compared to that reinforced with BL fiber. This observation suggests that the differing physical structures of BS and BL fibers affect the melt flow behavior. The structural characteristics of BS fiber contribute to a reduced level of fiber–matrix interaction compared to banana leaf fiber, thereby enhancing the flow behavior of the polymer. This outcome aligns with the morphological features observed in PBS and BS, as illustrated in Figure 6. Notably, BS particles were found to be embedded in the PBS matrix, accompanied by only minimal cavity formation observed around the fiber–matrix interface. Consequently, the PBS composite containing BS fiber demonstrates higher MFR and MVR values than the BL fiber composite.

Additionally, BS fibers tend to absorb less moisture, which helps minimize the impact of moisture on the melt flow behavior of the material. However, both MFR and MVR decrease with increasing BS content. This can relate to improving the interfacial adhesion between the PBS matrix and fibers, as shown in Figures 6 and 7. The treated fiber had a good interaction between fiber and matrix because lignin and hemicellulose were removed. Therefore, increasing the fiber content disrupts the flow behavior of the PBS matrix, significantly altering the viscoelastic dynamics of the melt. This disruption hinders the mobility of molecular chains, which in turn affects both MFR and MVR [43].

In Figures 9(b) and (c), the effect of fiber size used to reinforce PBS revealed that PBS reinforced

with large banana sheath fiber (2BS1) exhibited lower MFR and MVR values compared to the material reinforced with smaller fibers (2BS2). This outcome can be explained by two main factors: the specific surface area of the fibers and the interaction between the fibers and the polymer matrix. Larger fibers have a lower specific surface area than smaller ones, resulting in less interaction with the polymer. However, this also leads to slower flow due to the arrangement of the larger fibers, which increases the viscosity of the material. On the other hand, smaller fibers, with their higher specific surface area, promote more interaction with the polymer, leading to better flow behavior. Another contributing factor is that smaller fibers have a greater tendency to agglomerate, leading to increased discontinuities within the polymer matrix. This structural disruption subsequently results in a reduction of both MFR and MVR, as illustrated in Figure 9(b).

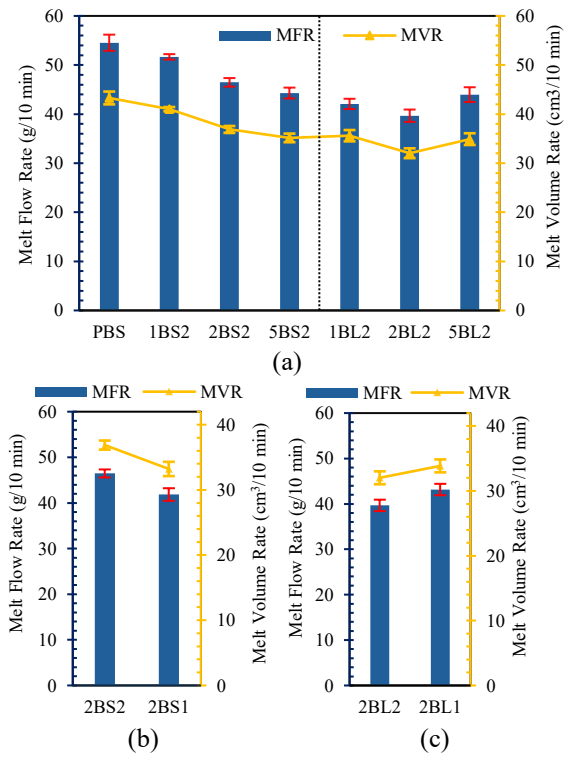


Figure 9: MFR and MVR results of PBS/banana fiber composites (a) with different types and varying content of banana fibers (b) with 2 phr of BS at different particle sizes and (c) with 2 phr of BL at different particle sizes.

While larger fibers typically reduce flow due to increased viscosity from their different arrangements, the composite material reinforced with BL fibers showed the opposite trend, as shown in Figure 9(c). Specifically, the polymer mixed with 2BL1 exhibited higher MFR and MVR values than the polymer mixed with 2BL2. This may be attributed to the differing physical characteristics of the BL fibers, which could enhance the melt flow behavior in the composite reinforced with larger fibers. Compared to the flow behavior of neat PBS, the fiber-reinforced composites exhibit lower MFR and MVR. This indicates that the added banana fibers influence the flow characteristics during the melting and forming processes by increasing the material's viscosity.

3.3 *Mechanical properties*

The incorporation of banana fibers significantly enhances the Young's modulus of the biocomposites derived from both BS and BL, as illustrated in Figure 10(a). Young's modulus increased from 221 MPa for pure PBS to 271 MPa for the 5BS2 formulation. Similarly, the addition of BL fibers raised the Young's modulus to 280 MPa at a loading of 5 phr. This enhancement is attributed to the role of banana fibers as reinforcing fibers within the PBS matrix. Furthermore, chemical treatment of the fibers improves interfacial compatibility between the banana fibers and the PBS matrix, thereby strengthening the fiber-matrix interface. This improved adhesion enhances the composite's resistance to deformation, contributing to the observed increase in modulus. Additionally, the uniform distribution of the reinforcing fibers effectively restricts polymer chain mobility during deformation, leading to increased stiffness of the composites [9], [14], [15]. However, the BL composite at 5 phr exhibited the highest Young's modulus (280 MPa), which may be attributed to the intrinsic structural characteristics of the BL fibers. The influence of fiber size in both BS and BL composites reveals a consistent pattern across Young's modulus, MFR, and MVR results, as depicted in Figure 10(b) and (c). The PBS composite containing BL fibers showed that 2BL1 exhibited a higher Young's modulus than 2BL2 at the same content. This demonstrates that the higher specific surface area of smaller BL fibers leads to better interfacial adhesion between the fibers and the polymer matrix, and consequently, an increase in Young's modulus [25], as present in Table 2. In contrast, the 2BS1in the BS composite resulted in a slightly lower Young's

modulus, which may be attributed to similar factors influencing the MFR and MVR outcomes.

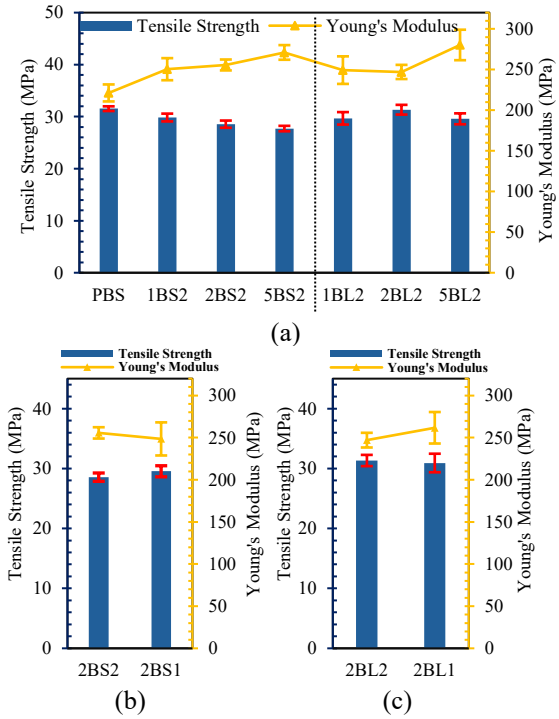


Figure 10: Tensile strength and Young's modulus results of PBS/banana fiber composites (a) with different types and varying content of banana fibers (b) with 2 phr of BS at different particle sizes and (c) with 2 phr of BL at different particle sizes.

Table 2: Tensile properties of PBS/banana fiber composites.

Sample	Tensile Strength (MPa)	S.D.	Young's Modulus (MPa)	S.D.	Elongation at Fracture (mm)	S.D.
PBS	31.54	0.45	221	10.45	8.67	0.57
1BS2	29.84	0.75	250	13.59	6.55	0.26
2BS2	28.56	0.69	256	6.71	5.62	0.57
5BS2	27.72	0.52	271	9.00	5.22	0.17
1BL2	29.68	1.20	249	16.97	5.76	0.62
2BL2	31.34	0.94	247	8.71	6.23	0.36
5BL2	29.59	1.05	280	18.74	5.51	0.33
2BS1	29.54	0.92	248	19.63	6.48	0.04
2BL1	30.92	1.55	262	18.68	5.97	0.50

An increase in BS fiber content significantly reduced the tensile strength (from 30 MPa to 28 MPa) and elongation at fracture (from 7 mm to 5 mm) of the polymer composite (Figures 10(a) and 11(a)). This phenomenon is attributed to the matrix dilution effect, caused by increasing fiber content, which reduces the volume fraction of the PBS matrix, which is inherently more ductile and cohesive [44].

Conversely, an increase in BL fiber content resulted in a slight increase in tensile strength and elongation at fracture when added up to 2 phr, 31 MPa, and 6 mm, respectively. After that, both of them decreased. This indicates that the alignment of BL fibers within the PBS matrix effectively reinforces the composite at optimal content, while excessive fiber content can lead to some fiber agglomeration, resulting in a decrease in tensile strength and elongation at fracture [45]. Despite these evident structural differences, mechanical testing at a fiber content of 5 phr revealed no significant differences between the composites reinforced with BS and BL fibers. This result may be attributed to the fact that most of the pores observed were not interconnected and thus did not critically compromise the material's overall mechanical integrity. Moreover, the sheet–like morphology of the BL fibers may have aided in distributing stress across the plane of the composite, allowing the material to maintain its mechanical properties even in the presence of internal flaws [46].

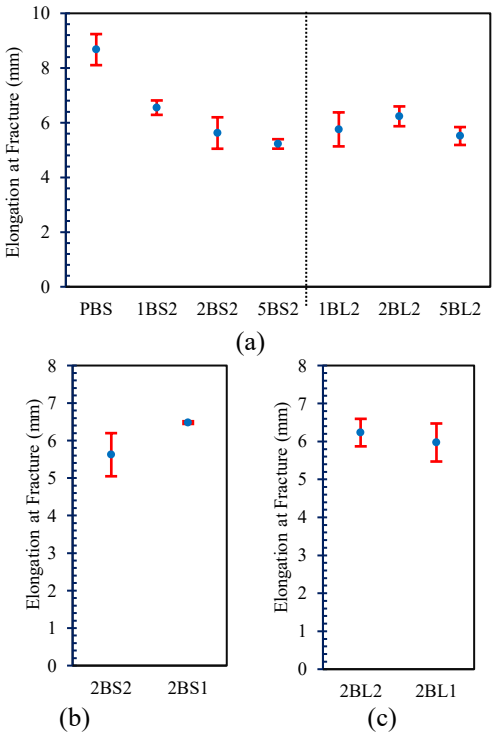


Figure 11: Elongation of fracture of PBS/banana fiber composites (a) with different types and varying content of banana fibers (b) with 2 phr of BS at different particle sizes and (c) with 2 phr of BL at different particle sizes.

Regarding the elongation at fracture, which indicates the ductility and ability to withstand tensile stress before fracture, it was observed that an increase in BS fiber content significantly reduced the elongation at fracture. This reduction in elongation may be attributed to enhanced interfacial adhesion between the fiber and polymer matrix, which increases the material's rigidity and hardness, thereby diminishing its ductility [18], [21]. Additionally, fiber agglomeration, coupled with inconsistent dispersion within the polymer matrix, arising from the biological variability of the fibers and the differing viscosities of the polymer components, may further compromise structural uniformity [41]. Another contributing factor may be the ability of BL fibers to serve as nucleating agents, promoting localized polymer crystallization in the vicinity of the fibers [47]. However, excessive BL fiber content may lead to crystal aggregation, resulting in a decrease in elongation at fracture. Notably, fiber size had a measurable impact on the elongation at fracture of the BS fiber composite, where an increase was observed; however, no significant change was detected in the BL fiber composite, as shown in Figure 11. This may be attributed to morphological differences in the banana fiber and is associated with fiber size [48].

Incorporating both BS and BL fibers reduced the impact strength of PBS composites (Figure 12(a)). However, the highest impact strength with adding BS and BL fibers is 9.2 kJ/m^2 (2BS2) and 6.6 kJ/m^2 (5BL2), respectively. Increasing the fiber content in composite materials can reduce tensile strength and elongation in some cases [22]. However, when fibers are added in the optimal amount, they help enhance strength and improve impact resistance. On the other hand, exceeding the fiber content limit may reduce the adhesion between the fibers and the polymer matrix, leading to a loss of impact strength in the material [49]–[51]. Therefore, controlling the fiber content in the composite is crucial for optimizing material performance.

The study of fiber size effects found that larger fibers can enhance various properties of the material, such as impact resistance and tensile strength, but may reduce flexibility in some cases. This observation suggests that larger fibers improve stress distribution, but also reduce material viscosity, which affects its flow. On the other hand, using smaller fibers may improve material flexibility, but the increased surface area of these fibers can enhance the interaction between the fibers and the matrix, leading to higher viscosity, which is related to the melt flow results [22]. The differences observed in some cases may be due to the varying properties of natural fibers, which affect the interaction between the fibers and the polymer matrix [52]. The impact strength of PBS/BS composites is higher than that of PBS/BL composites, likely due to the superior interfacial adhesion characteristics of BS fibers compared to BL fibers, as illustrated in Figure 12.

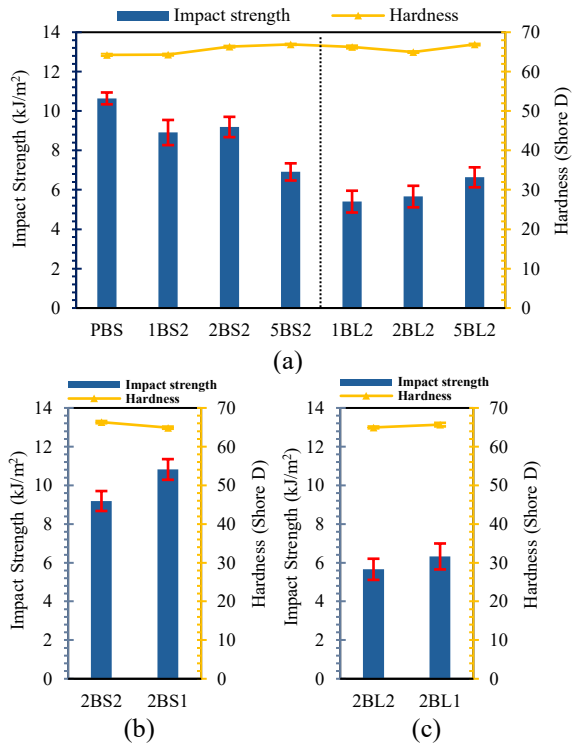


Figure 12: Impact strength and hardness of PBS/banana fiber composites (a) with different types and varying content of banana fibers (b) with 2 phr of BS at different particle sizes and (c) with 2 phr of BL at different particle sizes.

At the same time, an excessive amount of fibers may reduce the adhesion between the fibers and the matrix (shown in Figure 12(a)). Excessive fiber content or the use of oversized fibers can reduce flexibility. In terms of particle size, larger fibers reduced impact strength due to limited energy absorption and increased brittleness and reduced matrix continuity [52]. However, they also increase viscosity, reflected in a reduced MFR, which adversely affects flow characteristics. Conversely, the 2BS1 composite exhibits elevated impact strength (shown in Figure 12(b)), suggesting that a combination of factors collectively governs the mechanical performance of the composite

system [53]. Furthermore, the incorporation of both BS and BL fibers exhibited no significant impact on the Shore D hardness of PBS composites (in the range of 64–67 Shore D), suggesting that the content, type, and size of banana fibers do not substantially influence the hardness characteristics. This outcome may be attributed to the tendency of banana fibers to form clusters, leading to poor dispersion within the polymer matrix [54].

3.4 *Application of PBS/banana fiber composites*

The development of prototypes in this research is of utmost importance, as it serves as a crucial step in testing the forming processes of composite material in environments that closely replicate actual usage scenarios. This includes assessing the flow behavior and forming capability of the composites, which exhibit different viscosities and flow characteristics compared to PBS. Although the composites have lower MFR and MVR values than PBS, testing under the same conditions and forming methods used for the prototype revealed that these conditions are both suitable and effective, enabling the composites to be shaped precisely according to specifications.

As shown in Figure 13, the prototype was developed using a high content of fine banana leaf fibers (5BL2), which proved to be highly formable despite the large amount used. The material maintained good shaping capability and produced consistent results. The resulting product also exhibited uniform color and pattern, adding both character and visual appeal. The external surface of the prototype plant pot is smooth, and the final shape precisely matches the intended design, achieved through the vertical RAM extrusion process. This method not only ensured the product retained its desired form but also contributed to its overall high quality, especially in terms of clean, minimal design.

Figure 13: Prototype plant pot from 5BL2 formulation.

4 Conclusions

Biocomposites composed of poly(butylene succinate) (PBS) and banana fibers demonstrate considerable potential for packaging applications, attributed to enhancements in melt flow behavior, mechanical performance, morphological characteristics, and successful fabrication of a plant pot prototype. The incorporation of banana fibers, specifically banana sheath (BS) and banana leaf (BL), significantly affected the mechanical properties of the composites. BS and BL fibers contributed to an increase in Young's modulus (the highest of 27% compared to neat PBS at 5BL2). BL fibers enhanced both strength and ductility at a loading of 2 phr, though these properties declined at 5 phr. Moreover, biocomposites reinforced with smaller BS fibers (2BS2) exhibited a higher Young's modulus compared to those with larger BS fibers (2BS1), a trend not observed with varying BL fiber sizes.

PBS composites reinforced with finer–structured BS fibers exhibited higher melt flow rate (MFR) and melt volume rate (MVR) compared to those containing BL fibers. An increase in BS fiber content generally led to reductions in both MFR and MVR, decreasing from 52 to 44 g/10 min and from 41 to 35 cm^3/10 min, respectively. As with BL, both MFR and MVR, decrease from 42 to 40 g/10 min and from 36 to 32 cm^3/10 min, respectively. However, reinforced BL fiber composites displayed an opposite trend at 5 phr, potentially due to fiber agglomeration. Furthermore, composites incorporating fine BS at 2 phr (2BS2) demonstrated higher MFR and MVR than those with coarse (2BS1), a behavior not observed in composites with varying BL fiber sizes.

The internal morphology of PBS composites was examined using X–ray tomographic microscopy (XTM), enabling detailed visualization of their three–dimensional structure. The XTM analysis revealed distinct internal structural differences between composites reinforced with BS and BL fibers. Reinforced BS fiber composites demonstrated superior fiber dispersion and reduced porosity, both of which contributed to improved tensile strength and increased Young's modulus. These enhancements were further supported by FTIR analysis, as well as SEM and optical microscopy characterizations, which confirmed that alkali treatment effectively enhanced the interfacial interaction between banana fibers and the PBS matrix. In contrast, the higher porosity observed in BL fiber composites contributed to reduced elongation at fracture and lower impact

strength. While composite hardness aligned with XTM, but elongation at break varied minimally.

Based on the findings of this study, future research could focus on exploring coupling agents or compatibilizers to minimize porosity and enhance mechanical integrity, particularly in BL fiber–reinforced composites. It would also be valuable to assess these biocomposites using a biodegradation test. Investigating the thermal behavior to achieve composite crystallinity could provide deeper insights into material stability. Additionally, incorporating other natural fibers to develop hybrid composites may offer opportunities to tailor properties for diverse applications.

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Author Contributions

S.U., M.U., J.N., and P.P. conducted the experiments; K.N., K.M., and C.T. coordinated the project; P.S., S.U., and K.N. prepared the graphs and tables; P.S., S.U., and M.U. analyzed the data and manuscript writing. The findings were discussed, and the manuscript was reviewed by all authors.

Conflicts of Interest

The authors declared that no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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