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Eco-Friendly Materials for Temporary Use in Architecture and Decorations

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Abstract

This paper introduces the development of ecologically friendly composite materials for decoration and architectural purposes. The composites designed comprised degradable polylactic acid (PLA) and sugarcane bagasse fiber (SC) derived from the bioplastics and sugar industries. The SC reinforcement was examined for impurity treatment and composite formation using hot compression molding at 200 ± 10°C. Two processing methods were studied: (1) random dispersion of SC at 0, 2, 4, 6, 8, and 10 wt%, and (2) single and double-layer SC composite sheets made with 6 wt% SC. The physical and mechanical properties of the PLA-SC composites were evaluated through the morphologies and flexural properties (ASTM C293), thermal conductivity (ASTM C518), and biodegradation assessment (ISO 16929:2021). Results revealed that impurities in SC were effectively removed using an alkaline sodium bicarbonate solution followed by boiling in a 5% vinegar solution. Increasing SC contents reduced the weight, density, and thermal conductivity (k-value) of the PLA-SC composites compared to those representing single and double layers of SC. Additionally, this approach enhanced the flexural properties of the composites. Random dispersion with 10 wt% treated SC yielded the best results among the tested methods, making it the optimal approach for sustainable decoration and architectural materials.

Keywords: Green Composites; Ecologically Friendly Products; Natural Fibers Reinforce Plastics; Green Architecture Materials.

1. Introduction

Materials for many purposes, such as medical, automotive, and everyday use, are concerned with environmental impacts. These include materials in architectural works, decorations, and construction. Using ecologically friendly materials gains benefits in terms of sustainable building certification regarding LEED or TREE. The LEED-certified green building is a global program that recognizes sustainable buildings, while the TREE on buildings program has been applied to certify sustainable buildings in Thailand. The two certifications have the same criteria for building materials & resources that are categorized in building and materials reuse, as well as low-emitting materials. The research was conducted to introduce ecologically friendly material produced from natural resources. Therefore, a bioplastic-cellulose composite was in focus.

The application of bioplastic-cellulose composites is growing due to their environmental benefits, sustainability, and potential to replace petroleum-based plastics. Key focuses are improving mechanical, thermal, and barrier properties for

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packaging, medical, automotive, and construction applications. Material improvements include compatibility and performance enhancements, nanotechnology, and sustainability. Moisture sensitivity, cost, and scalability present challenges, but research focuses on cost-effective manufacturing and improving processing methods [1-3]. To reduce environmental impacts, the sustainable material in this paper incorporates biodegradable plastics, polylactic acid (PLA), and renewable fibers, sugarcane fiber (SC). PLA derives from renewable resources such as corn and sugarcane. Its natural decomposition significantly reduces landfill waste and minimizes carbon footprints. Innovative home construction, such as canal homes in Amsterdam, uses bioplastic-cellulose composite materials, customized shades, and structures through 3D printing. They offer a sustainable alternative to traditional building products, reduce carbon footprints, and provide energy-efficient benefits. Interiors and everyday items use bioplastics, which contribute to eco-friendly, aesthetically pleasing homes and reduce environmental impact [4, 5]. SC, particularly bagasse, is a significant by-product of the sugar industry. Estimated global production of 513 million tons annually results from generating approximately 0.3 tons of bagasse for every ton of sugarcane processed. Despite its abundance, improper disposal of a large portion of this biomass leads to environmental issues such as air pollution from incineration or uncontrolled decomposition. SC exhibits a composition similar to wood fibers. Its structural components include 45% cellulose, 28% hemicellulose, 20% lignin, 5% sugar, 1% minerals, and 2% ash. The composition of SC makes it suitable for bio-composites, biofuels, and sustainable materials. Its high cellulose content affects the SC structure, making it suitable for creating durable composite materials, similar to wood fibers, when treated appropriately [6-8].

Chemical treatments with sodium hydroxide, sulfuric acid, sodium hypochlorite, and acetic acid are integral to improving the physical and chemical properties of natural fibers, which are suitable for applications such as composites, biofuels, and textiles. These treatments enhance the mechanical properties, water resistance, and enzymatic digestibility of fibers, making them more efficient for industrial use. However, carefully controlling the treatment conditions is essential to avoid excessive degradation and preserve the strength and functionality of the fibers [9].

This study aims to identify the most effective technique for treating impurities and surfaces of SC while maintaining their cellulose structure. Reinforcement PLA with SC using hot compression molding was examined for the effectiveness of SC reinforcement properties and optimized methods to create a sustainable panel material for architecture, comparable to materials currently in use such as fiberboards, composites, and engineered wood products, as oriented strand board (OSB) and gypsum boards.

2. Research Methodology

This study explores the most effective processing methods for decorative and architectural composite panels. The raw materials were selected from the group of environmentally and ecologically friendly materials. The focus was on degradable plastic, polylactic acid (PLA), and natural fiber, sugarcane bagasse, for the hot compression molding process. Two preparation and processing steps were investigated for (1) sugarcane bagasse treatment for essential cellulose and (2) compression molding conditions for an optimal processing method. The following details are of the materials and methods used in the research. Figure 1, shows the flowchart of the research methodology through which the objectives of this study were achieved.

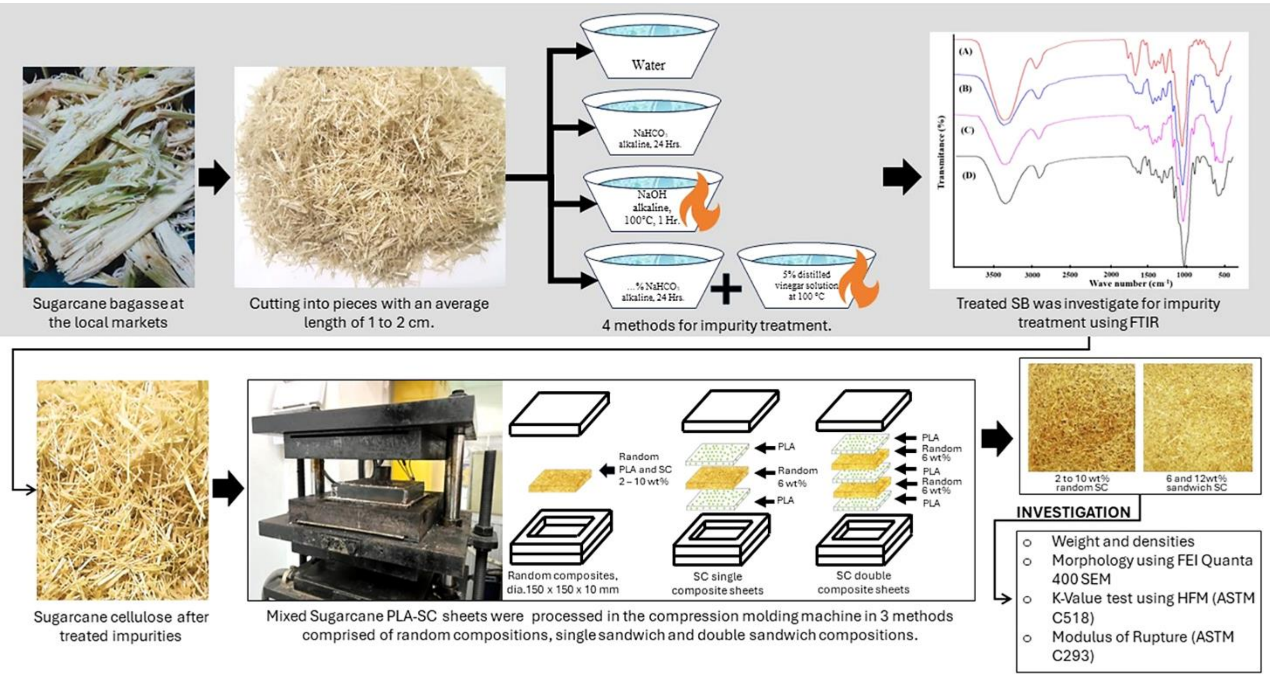

Figure 1. Workflow briefly shows the preparation and processing steps

2.1. Materials

Polylactic acid (PLA) as a polymer matrix was procured from Nature Works LLC, Minnesota, United States, with a 1.24 g/cm³ density, a melt flow rate (MFR) of 6 g/10 min, and a melting temperature of 210 ± 8°C. Sugarcane bagasse as a reinforcement was the waste from the extraction of sugarcane juice. Subsequently, the bagasse was cleaned in the water at room temperature and dried, then cut into pieces with an average length of 1 to 2 cm.

2.2. Material Treatment Methods

Sugarcane bagasse contains numerous impurities and requires an optimal treatment method to remove surface impurities and extract cellulose (SC). The surface treatment of natural fibers markedly improves the interfacial adhesion between the fibers and the matrix, resulting in enhanced composite characteristics [10]. The SC extractions were compared by four distinct methods regarding the alkaline agent groups composed of sodium hydroxide (strong alkaline), sodium bicarbonate (mild alkaline), and distilled vinegar (neutralizes alkaline). Those methods consisted of (A) soaking in water, (B) soaking in a sodium bicarbonate alkaline solution for 24 hours, (C) boiling in a sodium hydroxide alkaline solution at 100°C for 1 hour, and (D) soaking in a sodium bicarbonate alkaline solution for 24 hours, followed by rinsing with water, then boiling in a 5% distilled vinegar acid solution at 100°C for 3 hours. Subsequently, the SC was washed with water and dried in a hot air oven at 80°C for 24 hours.

2.3. Sample Forming Methods

The composite samples were prepared in two categories: (1) random dispersion and (2) single and double-layered sheets. The random dispersions comprised 0, 2, 4, 6, 8, and 10 wt% SC reinforcement to the PLA matrix. Each composition was fabricated to hot compression to provide samples with 150 × 150 × 10 mm dimensions. The materials were blended and placed in a stainless-steel mold, preheated at 200 ± 10°C for 15 minutes to melt some PLA. Subsequently, hot compression at 1500 psi with 200 ± 10°C for an additional 20 minutes, followed by cooling to room temperature. For the layered sheets, a single-layer sheet was fabricated using a 6 wt% SC content sheet covering both surfaces with 2 PLA sheets measuring 150×150×10 mm. A double-layer sheet was fabricated using two 6 wt% SC content sheets, covered and bounded by PLA sheets. The total dimensions of a double-layer sheet were also approximately 150×150×10 mm. The single and double-layer sheets were hot-compressed at 1500 psi with 200 ± 10°C for 15 minutes. The forming methods of the random compositions, single and double sheets, are shown in Figure 2.

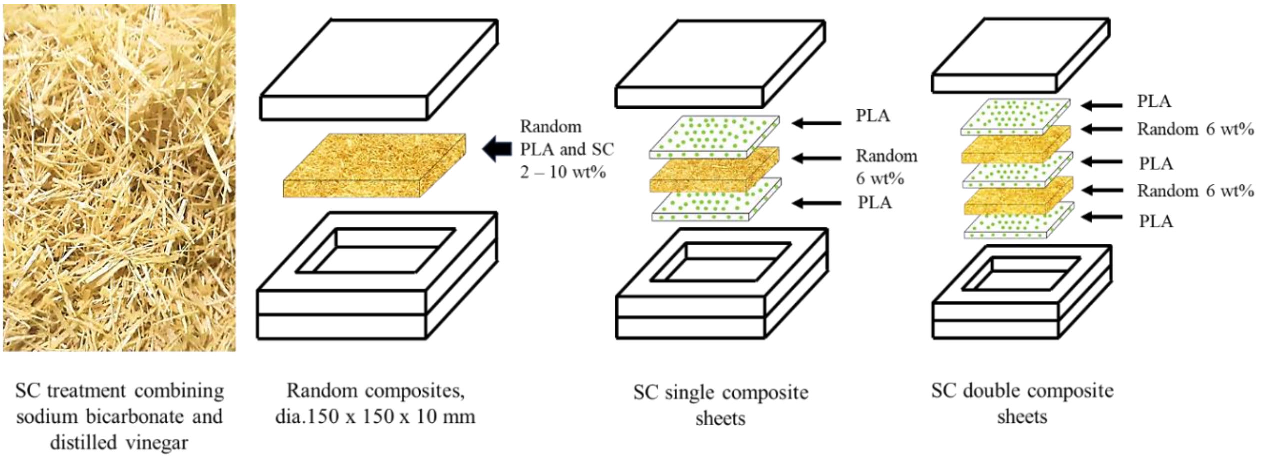

Figure 2. The forming methods of random composition, single and double sheets.

2.4. Testing Characterization and Standards

The sample sheets were examined for their physical and mechanical properties. The physical properties were exhibited in weight, density, morphology, and SC dispersion to PLA. The mechanical properties of thermal conductivity, flexural modulus, and degradation were revealed.

The extraction catalyst morphology was assessed using the FEI Quanta 400 SEM scanning electron microscope alongside a Fourier transform infrared spectroscopy (FTIR) spectrometer to acquire the spectrum. SC dispersion behavior was analyzed using the Leica M205 FCA fluorescence stereo microscope.

The thermal conductivity K-Value was measured using the heat flow meter (HFM), specifically designed for insulating materials, per international standards ASTM C518. The flexural test was conducted utilizing a simple beam with center-point loading (ASTM C293) for a sample measuring 150 × 150 × 10 mm to confirm the modulus of rupture (MOR). The biodegradation testing included a germination and disintegration assessment during composting, adhering to the international standards ISO 16929:2021.

3. Results and Discussion

The results are observed according to the optimal method to remove impurities, lignin, and hemicellulose from SC, the weight percentage of SC to the PLA matrix, and methods in fabrications regarding the physical properties of the PLA-SC composite, as well as flexural modulus and thermal properties.

3.1. Preparation of the Composite Sheets

SC was extracted using four methods to remove lignin and hemicellulose and analyzed for their functional groups using FTIR spectra. The SEM analysis confirmed the SC surface impurity treatment, as shown in Figure 3.

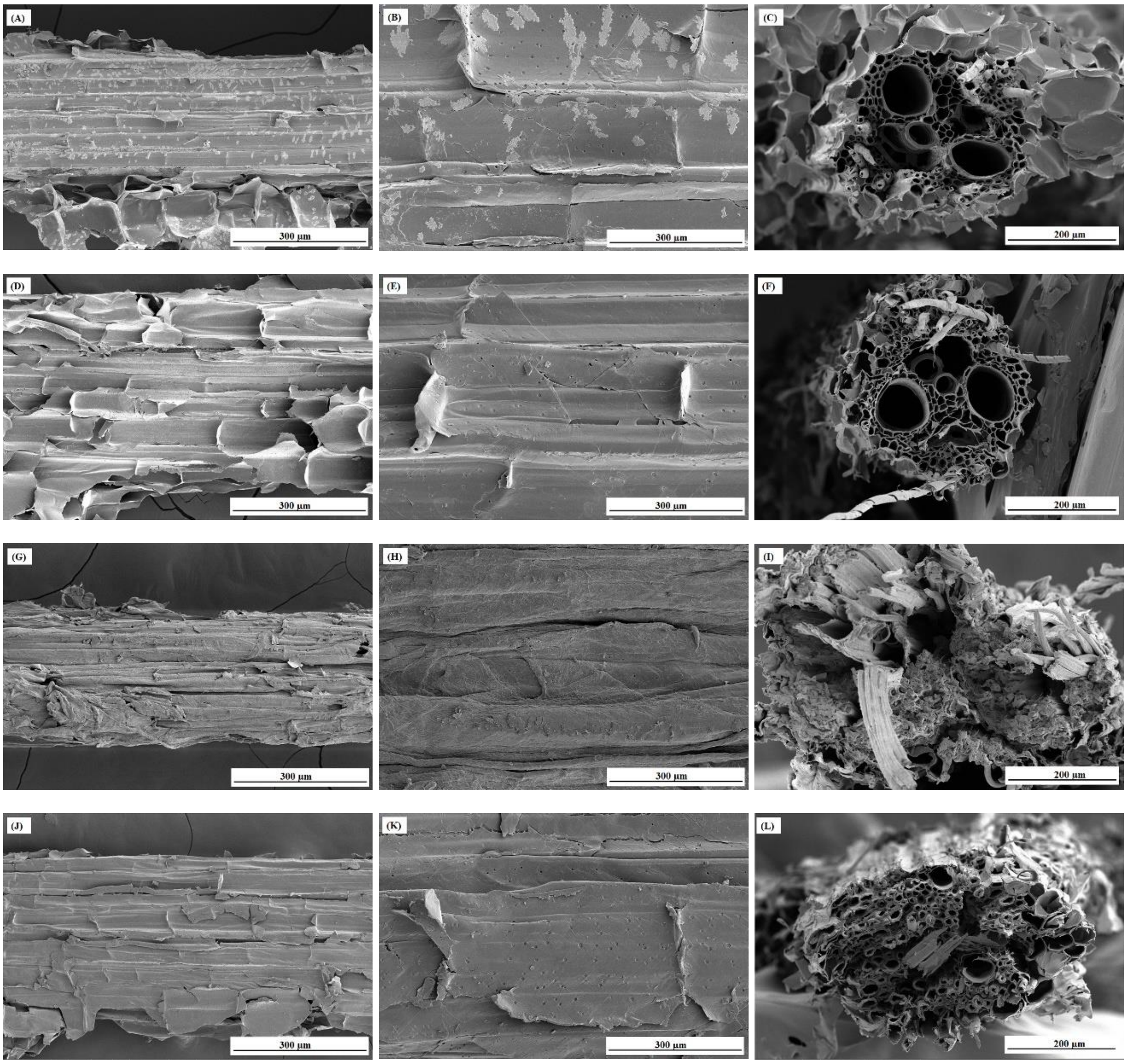

Figure 3. The morphology and surface of SB fibers were extracted using the following methods: (A–C) soaking in water, (D–F) soaking in NaHCO3 alkaline solution, (G–I) boiling in NaOH alkaline solution, and (J–L) soaking in NaHCO3 alkaline solution followed by boiling in 5% distilled vinegar acid solution.

Figure 3 (A–C) shows that SC treated by soaking in water retains the surface impurities along the cell wall. Figure 3 (D–F) demonstrates that soaking in $NaHCO_3$ efficiently treated the surface and reduced impurities. It was similar to SC treated by boiling in NaOH, as shown in Figure 3 (G-I), but the SC (G-I) illustrates the decomposition of the cellulose structure. Figure 3 (J-L) demonstrated that extraction by soaking in $NaHCO_3$, followed by rinsing with water and boiling in 5% distilled vinegar solution, ensures significantly reduced surface impurities on the cell wall with roughness using a non-toxic solution [11]. This method resulted in less cellulose degradation compared to treatment with NaOH solution.

The SC surface treatments for four different extraction methods need to confirm the removal of the lignin and hemicellulose after the treatment process. The functional groups of lignin and hemicellulose were ensured treatment using FTIR spectra as presented in Figure 4.

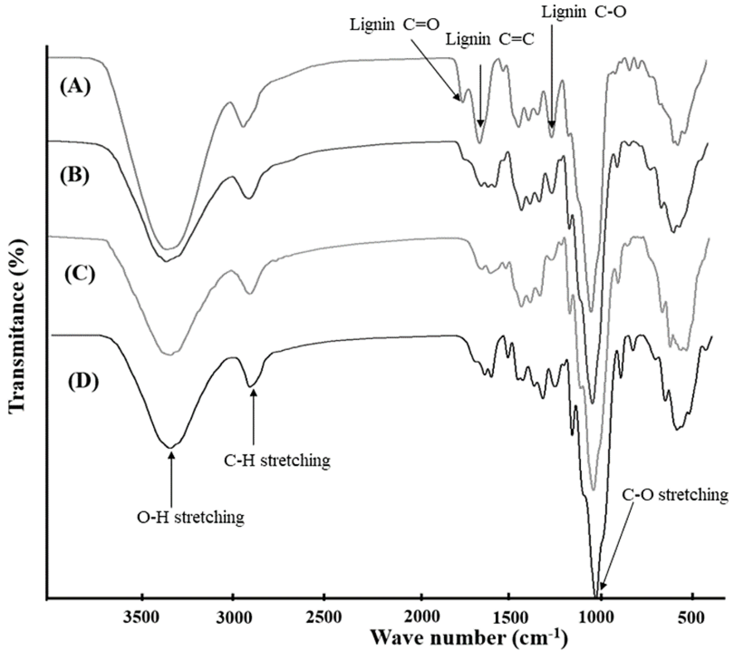

Figure 4. FTIR spectra of SC treatment using different methods: (A) soaking in water, (B) soaking in sodium bicarbonate solution, (C) boiling in a sodium hydroxide solution, and (D) soaking in sodium bicarbonate solution, followed by rinsing with water and boiling in the distilled vinegar solution.

Figure 4 depicts the absorption peak observed through the treated SC. The absorption peak observed around 1728 cm^{-1} was derived from the C=O stretching vibration of carboxylic groups of hemicellulose and lignin. The C=C stretching vibration of the aromatic ring in lignin contributes to the absorption peak observed around 1637 cm^{-1}. The absorption peak observed around 1246 cm^{-1} is due to the C–O stretching vibration of the aryl group in lignin [12]. The spectra show that methods (B), (C), and (D) have been affected by reducing the lignin at 1728 cm^{-1} (C=O) and 1637 cm^{-1} (C=C). The method (D) showed significantly better decomposition of C–O stretching vibration (1246 cm^{-1}) than other methods. This study confirms that alkali treatment increases fiber roughness, exposes cellulose, and enhances bonding with hydrophobic polymers [11, 13, 14]. Then, this research chose the method (D) of soaking in sodium bicarbonate solution, followed by rinsing with water and boiling in vinegar solution, because SC significantly exhibited less decomposition and hemicellulose and lignin were ideally removed, confirmed by FTIR spectra [12, 15].

3.2. Physical Properties of the Composites

The composite sheets fabricated from treated SC were examined for their effectiveness as the SC content increased by 0, 2, 4, 6, 8, and 10 wt% to PLA. Figure 5 shows visible SC dispersions tend to be uniform when SC content increases. The textures of the composites resemble the Oriented Standard Board (OSB). The uniform dispersion of the 10 wt% SC sheet looks smooth and fine to the touch, resembling the single and double-layer sheets illustrated in Figure 6.

Figure 5. Characteristics of random dispersions PLA-SC Composites

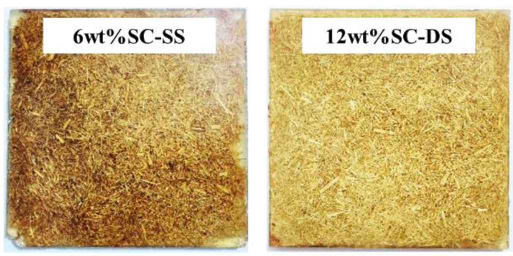

Figure 6. characteristics of single and double sandwich PLA-SC Composites

The composites exhibited weights between 9.2467 to 10.0693 kg/m² with densities ranging from 980.4689 to 1043.9783 kg/m³, as shown in Table 1. These are similar to 9 mm MDF, which weighs approximately 9.0278 kg/m². Compared to other materials, as shown in Table 2, the composites are lighter than a wood-cement board with 8 to 10 mm thicknesses, weighing approximately 10.4167 kg/m² to 13.8889 kg/m². However, the composites are heavier than 10 mm plywood, 10 mm OSB, and 12 mm gypsum board, which weigh approximately 5.2083 kg/m², 7.0546 kg/m², and 7.200 kg/m², respectively.

Table 1. Physical properties of PLA-SC composites

	Thickness (m)	Width (m)	Length (m)	Weight (kg)	Density (kg/m³)	Weight (kg/m²)
Neat PLA	0.0091	0.1498	0.1487	0.2305	1135.1485	10.3478
2 wt%	0.0092	0.1504	0.1491	0.2121	1032.4568	9.4583
4 wt%	0.0096	0.1490	0.1500	0.2094	980.4689	9.3691
6 wt%	0.0095	0.1486	0.1505	0.2185	1029.4585	9.7700
8 wt%	0.0097	0.1507	0.1491	0.2165	990.1842	9.6353
10 wt%	0.0097	0.1494	0.1493	0.2246	1043.9783	10.0693
Single sandwich	0.0094	0.1500	0.1500	0.2112	1006.2199	9.3867
Double sandwich	0.0093	0.1489	0.1494	0.2057	1000.3209	9.2467

Table 2. Physical properties of Plywood, MDF boards, OSB boards, Wood-cement board, and Gypsum board [16-22]

	Thickness (m)	Width (m)	Length (m)	Weight (kg)	Density (kg/m³)
Plywood	0.010	1.200	2.400	0.2–0.8	500–800
MDF (Medium-Density Fiberboard)	0.009	1.200	2.400	0.3–0.6	700–850
OSB (Oriented Strand Board)	0.009	1.220	2.440	0.4–0.7	650–750
Wood-cement board	0.008	1.200	2.400	0.5–0.8	900–1500
Gypsum board	0.009	1.200	2.400	4–6	0.15–0.23

3.3. Morphological analysis of the PLA-SC Composites

A fluorescence stereoscope was used to confirm the dispersion behavior of SC fiber in the PLA matrix. Figure 7 shows low contents of 2wt% and 4wt% SC to PLA, revealing non-uniform dispersion. At a concentration of 6wt% and higher, SC to PLA demonstrates a noticeable decrease in the distance between SC as the SC content increases. It indicated a more uniform dispersion of SC [23, 24]. The layered compositions of SC single and double-layer sheets, as shown in Figure 8, illustrate that the single is in the middle of the composite sheet, while the double sheet reveals the gap between the two SC layered sheets.

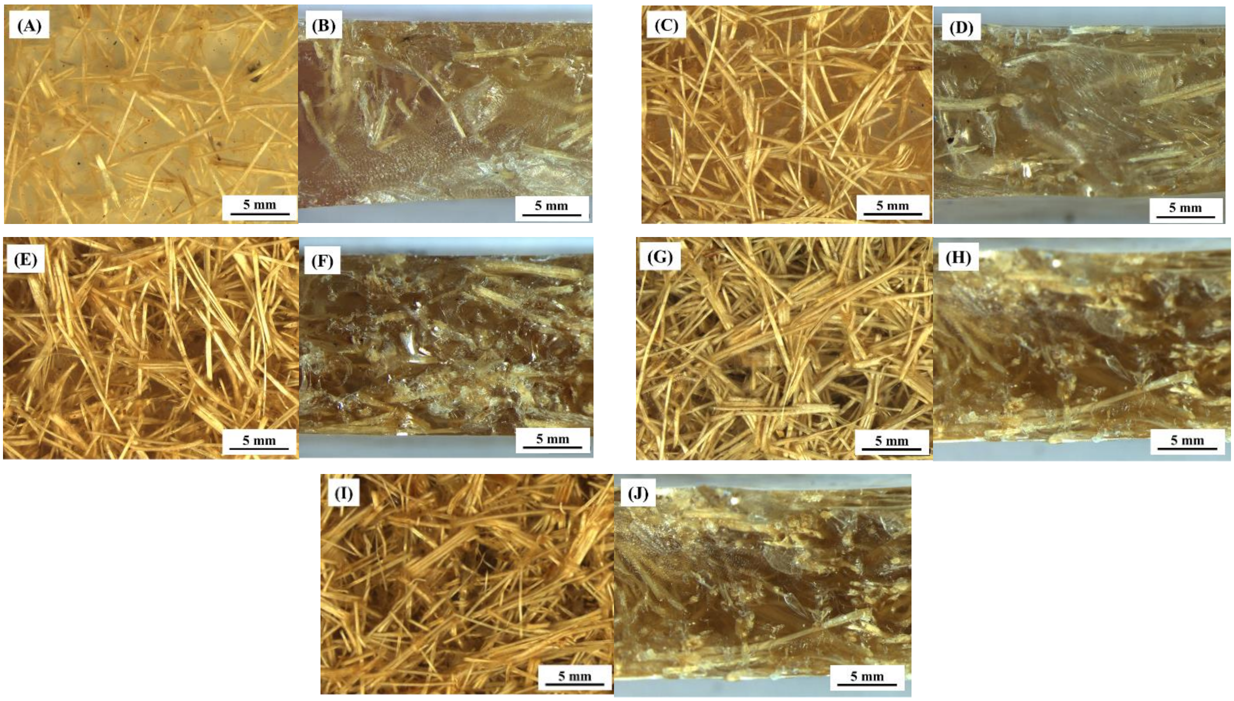

Figure 7. SC dispersions of the composites with top and cross-sectional view of the composites based on random dispersion, (A–B) 2wt%SC-R, (C–D) 4wt%SC-R, (E–F) 6wt%SC-R, and (G–H) 8wt% SC-R, (I-J) 12wt%SC-R

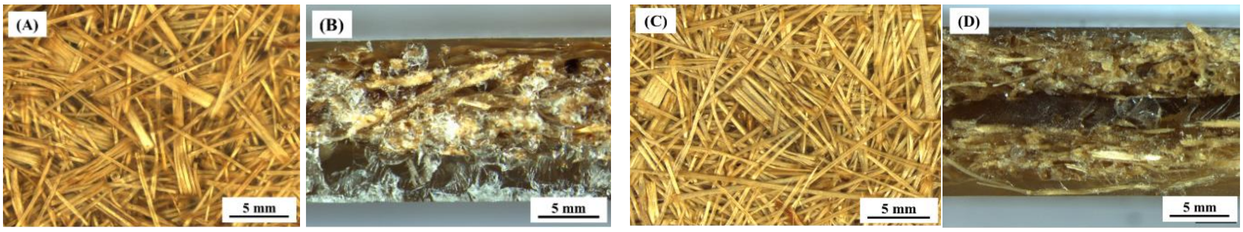

Figure 8. Top and cross-sectional view of the single and double layering of SC sheets, (A–B) single-layer sheet and (C–D) double-layer sheet

3.4. Mechanical and Thermal Properties of PLA-SC Composites

The dispersion of SC in PLA significantly impacted the mechanical and thermal properties of the composites. These properties promote a practical essential when selecting or using the material.

Mechanical properties in this paper were demonstrated in terms of Modulus of Rupture (MOR). The results were regarding ASTM C293 applying a center-point loading system to measure the MOR of the composites, as shown in Figure 9.

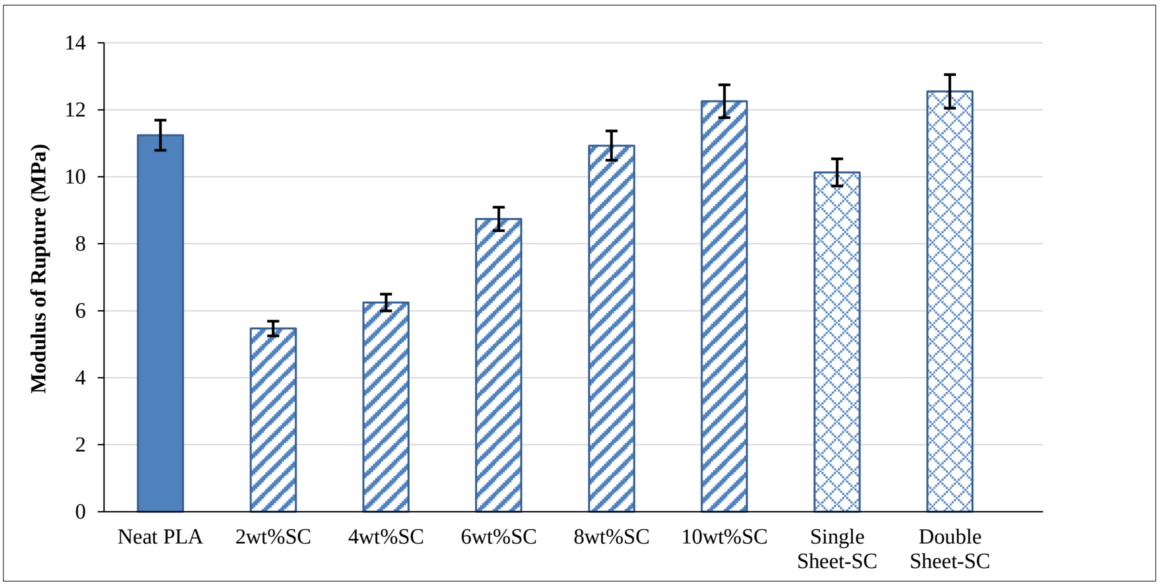

Figure 9. Modulus of Rupture (MOR) of the composites with different SC random dispersion 0-10 wt%, single-layer sheet, and double-layer sheet

Figure 9 reveals a material's resistance to bending stresses. The MOR values of the composite typically range from 5.470 to 12549 MPa. These ranges were more likely to be made of gypsum boards, which illustrated the MOR, typically ranging from 6 to 10 MPa, depending on board composition, reinforcement, and manufacturing process [10]. The insufficient strength of the fiber-matrix adhesion impedes effective load transfer, reducing the material's flexural strength [4]. This was due to the dispersed SC within the PLA matrix, which created an interfacial bond between the SC and PLA. Increasing SC content resulted in an increase in MOR compared to neat PLA. At 2, 4, and 6 wt% SC to PLA, the MOR was measured at 5.470, 6.246, and 8.742 MPa, which is lower than the neat PLA (11.241 MPa). At 10 wt% SC, the MOR was measured at 12.256 MPa, which is higher than the neat PLA. The reduced distance between the fiber and matrix and well-distributed, as shown in Figures 7 and 8, effectively strengthened the bond between the reinforcement and the matrix. Considering the layering sheets, the double-layer sheet yielded the highest MOR of 12.549 MPa. The single-layer sheet yielded 10.131 MPa, similar to but lower than the neat PLA. This examines increasing the number of layers augmented the fiber fraction, enhancing the reinforcing of the composite [23, 24].

In this research, the thermal conductivity was measured to observe heat insulation properties. The thermal conductivity of the K-value of the composites is presented in Figure 10. The study found that the single and double-layer sheets presented the highest thermal conductivity, approximately measured at 0.12330 W/m·K, 11.08% higher than neat PLA measured at 0.1100 W/m·K. At 2 and 4 wt%, SC showed results similar to the layering sheets. The 6, 8, and 10 wt% SC illustrated the lowest K-Value similarly measured at 0.1100 W/m·K. Increasing SC to PLA decreased the K-value for the random dispersion. This suggests that SC dispersion enhances the thermal insulation properties of the composites depending on SC content. This shows significant improvement in heat transfer performance, which is linked to the fibrous structure that aids in thermal conduction from the SC sheet [25, 26]. The K-values are identical to plywood, medium-density fiberboards (MDF), and oriented strand board (OSB), as shown in Table 3, demonstrating K-values of approximately 0.1100 to 0.1300 W/m·K, currently in use.

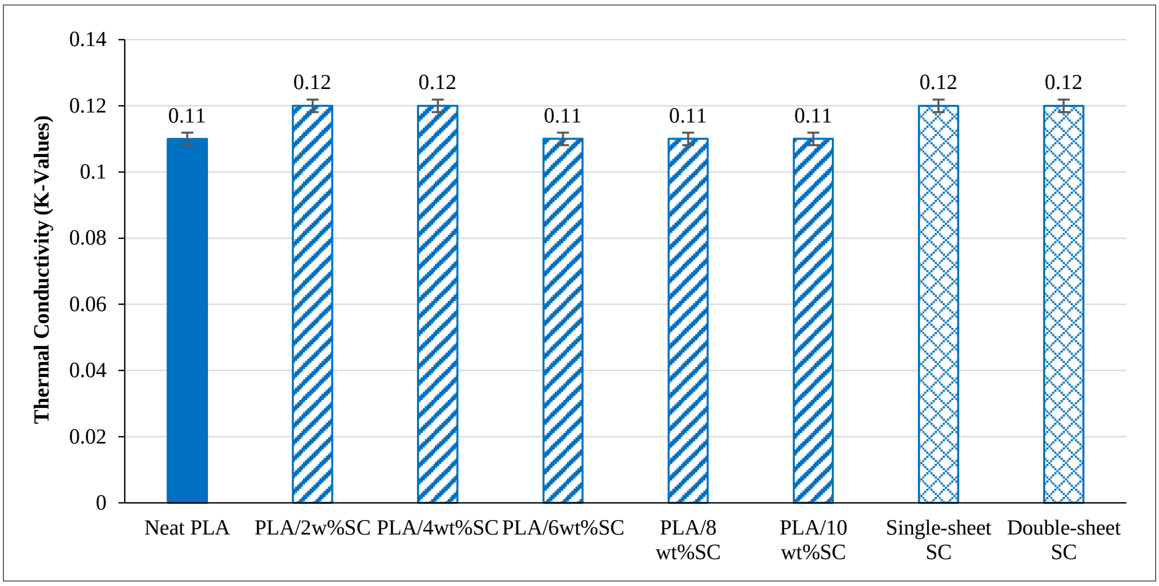

Figure 10. The K-value of neat PLA, Random, and Sandwich PLA-SC composites

Table 3. Comparative properties and applications of common construction and composite materials [16-22]

Material	Weight (kg)	Density (kg/m³)	MOR (MPa)	K-Value (W/m·K)	Applications
Plywood	0.2–0.8	500–800	6–12	0.11–0.13	Flooring, cabinetry, wall panels
MDF (Medium-Density Fiberboard)	0.3–0.6	700–850	6–12	0.10–0.12	Furniture, doors, decorative panels
OSB (Oriented Strand Board)	0.4–0.7	650–750	6–8	0.11–0.13	Subflooring, wall sheathing, roofing
Wood-Cement Board	0.5–0.8	900–1500	8–12	0.13–0.17	Cladding, wet area tiles
Gypsum Board	0.2–0.4	600–700	4–6	0.15–0.23	Interior walls, ceilings
Natural Fiber Composites	0.3–0.6	900–1100	6–12	0.10–0.12	Sustainable construction panels
Fiberboards (MDF/HDF)	0.4–0.6	700–850	8–12	0.11–0.13	Flooring, soundproofing, panels
The result of PLA composites					
Neat PLA	0.2305	1135.15	11.24	0.11	The interior is decorated with flooring, cabinetry, wall panels, furniture, doors, decorative panels, and sustainable construction panels.
PLA/2w%SC	0.2121	1032.46	5.47	0.12	
PLA/4wt%SC	0.2094	980.47	6.25	0.12	
PLA/6wt%SC	0.2185	1029.46	8.74	0.11	
PLA/8 wt%SC	0.2165	990.18	10.93	0.11	
PLA/10 wt%SC	0.2246	1043.98	12.26	0.11	
Single sandwich	0.2112	1006.22	10.13	0.12	
Double sandwich	0.2057	1000.32	12.55	0.12	

4. Conclusion

The physical and mechanical properties of the composite revealed that SB impurities can be treated using a natural alkalized solution, common household chemicals such as baking soda and distilled vinegar. It effectively removed surface impurities, hemicellulose, and lignin from the SC while keeping the cellulose content, different from NaOH extraction, which illustrates the decomposition of the cellulose's surface. Reinforcing the treated SC in PLA significantly improved the properties of the resulting composites. The research observed that the weights and densities of the composites at random dispersion of 2 wt% to 8 wt% were identically comparable to panel materials currently in use. The composites exhibited much better mechanical properties, modulus of rupture, and thermal conductivity. Increased SC content tended to increase the modulus of rupture (MOR). At 10 wt% SC, the modulus of rupture (MOR) is consistent with the neat PLA. According to the morphology, the dispersion behavior of the SC indicates a uniform dispersion when SC increases. It was effective PLA and SC bonding. The single- and double-layer compositions demonstrated a good mechanical property of MOR, which was comparable to neat PLA. Considering in terms of thermal properties, it indicated increasing SC content of random SC enhances the thermal insulation of random dispersion composites. The utilization of PLA-SC composites, as illustrated in Table 3, revealed the comparative characteristics and applications of prevalent building and composite materials. In conclusion, the composite can be applied to interior decoration, including flooring, cabinetry, wall panels, furniture, doors, ornamental panels, and sustainable building panels. The advantage lies in its minimal weight, while the Modulus of Rupture (MOR) and K-values remain comparable.

5. Declarations

5.1. Author Contributions

Conceptualization, W.C. and A.M.; methodology, W.P. and W.C.; software, W.P. and W.C.; validation, B.C., S.P., and P.T.; formal analysis, W.C., A.M., and P.T.; investigation, W.P. and W.C.; resources, W.C. and A.M.; data curation, W.C. and W.P.; writing—original draft preparation, W.P.; writing—review and editing, A.M. and W.C.; visualization, B.C., S.P., and P.T.; supervision, A.M.; project administration, A.M.; funding acquisition, A.M. and W.C. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in the article.

5.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

5.4. Institutional Review Board Statement

Not applicable.

5.5. Informed Consent Statement

Not applicable.

5.6. Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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