International Journal of
Composite and Constituent Materials

ISSN: 2456-5237
Volume 10, Issue 2, 2024
July–December
DOI (Journal): 10.37628/IJCCM

https://journalspub.com/journal/ijccm/

Research IJCCM

Physico-Mechanical and Degradation Properties on Agro-Waste Based Polymer Composites Reinforced with Banana Bunch Fiber

Haydar U. Zaman[1], Md. Abu Sayed[2,*]

Abstract

The usage of banana bunch fibers in polymer composite parts for the automotive, aerospace, and construction industries is growing. As people grow more aware of the danger of synthetic fibers, banana bunch fibers are being used in an increasing variety of sectors. It is important to recognize that humans depend on the Earth for survival, not the other way around. This understanding drives scientists and policymakers to seek alternatives to traditional materials, prioritizing environmentally friendly options for a more sustainable future. Better thermomechanical properties, less carbon dioxide emissions, ease of manufacturing, biodegradability and recycling potential, and improved compatibility with human health are just a few of the sustainable features that make banana bunch fibers superior to synthetic materials. As a result, fibers from banana bunches are frequently used to modify polymers. In this study, polypropylene (PP) composites reinforced with banana bunch fiber (BF) were fabricated using compression molding. In some applications, stearic acid (SA) was used as a coupling agent, while in others, it was not applied. Raw banana BF was used to construct composites with filler loading levels ranging from 10 to 40 weight percent. The mechanical properties of the resulting composites were evaluated through a series of tests. Composites reinforced with 30% fiber showed the best mechanical performance based on fiber loading. SA was chemically added to increase banana BF and boost its compatibility with the polymer matrix. When compared to the untreated composites, the mechanical properties of the banana BF-reinforced composites that underwent SA treatment were better. To gain a further understanding of the fiber-matrix adhesion, the researchers utilized scanning electron microscopy (SEM) on the tensile fractured samples. This technique provided detailed images to analyze the interaction between the fibers and the polymer matrix. These photos demonstrated how the SA treatment improved the banana bunch fiber's adherence to the PP matrix. The composites were also examined for their moisture absorption capacity and their ability to simulate weathering conditions. These tests aimed to assess the durability and environmental resilience of the materials.

***Author for Correspondence**
Md. Abu Sayed
E-mail: mdabu0856@gmail.com

[1]Assistant Professor, Department of Physics, National University of Bangladesh Institute of Radiation and Polymer Technology, Bangladesh Atomic Energy Commission, Savar, Dhaka, Bangladesh
[2]Assistant Professor, Department of Chemistry, National University College of Bangladesh

Received Date: October 02, 2024
Accepted Date: October 11, 2024
Published Date: October 14, 2024

Citation: Haydar U. Zaman, Md. Abu Sayed. Physico-Mechanical and Degradation Properties on Agro-Waste Based Polymer Composites Reinforced with Banana Bunch Fiber . International Journal of Composite and Constituent Materials. 2024; 10(2): 33–43p.

Keywords: Composite, stearic acid, banana bunch fiber, polypropylene, mechanical properties

INTRODUCTION

On composite materials that use natural fibers to strengthen thermoplastics, there has been a lot of research and development done all around the world. These materials are already commercially available, particularly within the automotive industry, where they are gaining traction for various applications [1–3]. Natural fibers are a plentiful source of materials that are frequently less expensive, have superior mechanical qualities, and may be found all over the world, though they are more common in tropical regions. Natural fibers are frequently utilized in place of synthetic fibers in several applications due to their low density, low cost, renewability, and biodegradability. Recently, researchers have been concentrating on the use of natural fibers as reinforcement in polymeric matrices. Natural fibers would be healthier to use than synthetic fibers if environmental factors were considered. For a number of natural fibers, including jute, cotton, abaca, bamboo, coir, flax, hemp, and sisal, the use of natural fibers in thermoplastic matrices has been proven. Currently, the packaging, automotive, and construction industries use these fibers [4, 5].

Many different natural fibers have been researched for usage in the industry at this time, including jute, coir, wheat, banana, sisal, barley, wood, oats, and flax [6–8]. They are rapidly developing into viable alternatives to synthetic materials in a range of uses, including building materials and vehicle parts [9, 10]. Banana fiber also has a high TS, is resistant to rot, and has a unique flexural strength that is comparable to glass fiber [11]. After the fruits mature, banana plants that are still alive can simply be harvested for their fiber. The use of banana bunch fibers (empty fruit) as reinforcing polymers is a topic that is not covered in great depth in literature. These banana fibers are developing materials for composite production because of their high rate of transformation from agricultural waste to products with significant commercial value. Banana empty fruit bunch fiber (BF) was chosen since it is commonly available and takes only 10 months for a banana to mature. To find a useful application for the banana empty fruit bunch, considerable research and development efforts must be done. This will unquestionably help address environmental concerns related to the disposal of banana fibrous waste as well. Banana is the first natural fiber to pass the stringent requirements for materials used on the exterior of motor vehicles due to its reputation for resilience to factors like stone impact, weather exposure, and wetness [12]. In tropical regions, it is typical to find agricultural plants like banana trees. Banana fiber is a byproduct of the banana industry that can be utilized for industrial applications without the need for extra funding. The revolutionary use of banana fiber by Daimler Chrysler in underfloor protection for passenger automobiles has led to an increase in the use of banana fiber-reinforced composites in modern society [13]. The use of banana fibers as a reinforcing agent in thermoplastics like polyethylene (PE) and polypropylene (PP) has been demonstrated in a number of studies on banana fibers [14, 15]. The material PP, which is a subset of thermoplastic engineering polymers, has several crucial and practical characteristics, including a high Vicat softening point, good flex life, sterilizability, good surface hardness, and good scratch and abrasion resistance. When utilized in applications requiring typical temperatures, PP has outstanding and desired physical, thermal, and mechanical qualities, hence it was chosen as the composite’s matrix. Additionally, it holds a substantial market share in wood plastic composites, has a low specific density, and does not pollute when burned [16–18].

Due to the interaction or attraction between the hydroxyl groups of fiber components and water molecules, both natural and banana BF exhibit strong hydrophilicity. The interactions between fiber and water start in the noncrystalline zone and move into the crystalline region. Hygroscopic materials including cellulose (noncrystalline, crystalline), and hemicellulose absorb water by hydration, a process involving accessible hydroxyl groups. The exothermic event that takes place when a cellulose molecule absorbs a water molecule results in the production of cellulose hydrate, which serves as a catalyst for further absorption [19, 20]. The use of fiber as reinforcement in composite materials is constrained due to the high moisture sensitivity of lignocellulosic fiber, which also causes dimensional instability. Natural fibers typically have low interfacial properties with the polymer matrix because of their hydrophilicity, which limits their efficacy as reinforcing agents. The fiber interface is optimized by taking into consideration chemical alterations and chemical coupling agents. Most chemicals that act as chemical coupling agents have two purposes. In the first step, the hydroxyl groups of the cellulose are reacted with, and in the second step, the functional groups of the matrix are reacted with [21]. Some chemical alterations to the fibers, such as acetylation, mercerization, methylation, cyanoethylation, benzoylation, and permanganate treatment, can lessen their propensity to absorb moisture [22–24].

Stearic acid (SA) has also been acknowledged as a coupling agent in addition to the coupling agents. It has not yet undergone a thorough analysis of its full potential as a coupling agent. Using SA-coated zeolite as the filler, Kim et al. created PE composites [25]. The SA coating on the zeolite's surface increased the flexibility of the polymer matrices. In order to comprehend the intumescence mechanism better, Bellayer et al. [26] created SA-treated $CaCO_3$-LLDPE composites. When the heat stress during burning was high, $CaCO_3$ was able to diffuse effectively inside the LLDPE matrix because of SA, which helped to encourage the creation of a coherent network. An extensive survey of the literature reveals that SA has not yet been investigated as a coupling agent for cellulosic fiber composites. As a result, this work's objective was to investigate the usage of SA as a coupling agent in the development of composites comprised of banana and PP. In the current work, a thorough analysis has been done to determine how mechanical properties, such as tensile, bending, and impact properties, change when banana fiber-reinforced PP composites are made via compression molding. Banana BF that has been treated with PP and SA will be used in this endeavor to create composite materials. Also covered is how fiber loading affects the morphological and mechanical characteristics of banana BF-reinforced PP.

EXPERIMENTAL

Ingredients

In the current study, reinforcement was created using banana empty fruit BF, a type of bast fiber that was locally available in Pahang village, Kuantan, Malaysia. Currently, BF is a waste product of banana farming that is either not used correctly or is only used in part. Banana fiber was extracted from the dried-up fruit cluster of the banana plant. A mature banana bunch was cut into four pieces, transversely sliced, and fed into a machine that removed fiber after being cut to a length of 50 cm. After extraction, the fibers were exposed to the sun for two hours. Short nonwoven fibers (5–7 mm) called BFs were used in this investigation. The thermoplastic polymer PP was provided by Titan Polymer (Malaysia) Sdn. Bhd. as homopolymer pellets with a density of 0.91 g/cm^3 and a melt flow index of 24 g/10 min (230°C/2.16 kg). Commercial-grade chemicals were employed to treat the surfaces of the fibers.

Methods

Making of Composites

The fibers from the bananas were meticulously separated by hand, the adhering pith, if any, was taken out, and the fibers were then uniformly cut to a length of 150 mm. The superfluous material was removed from the well-separated fibers by soaking them in acetone for 30 minutes at room temperature. Before the samples were weighed in the necessary amount, they were air-dried after washing. In the mixture, SA toluene predominates (1: 10: 10 (w/w/w)) over acetone. In the combination, SA was dissolved. Banana fibers were thinly laid on a metal tray, and then a 1:3 (w/w) solution was applied. The tray was kept standing and covered with aluminum foil for two hours at room temperature while the solvent mixture was allowed to evaporate. Banana fibers that had been coated with SA were also dried for 48 hours at a constant temperature of 60°C in the oven. About 6 g of heated PP granules were pressed between two steel plates in a hot press (Carver, INC, USA, Model 3856) to create one PP sheet. 180°C was utilized to operate the press. For two minutes, steel plates were subjected to a pressure of 7 MPa. The plates were then allowed to cool in a different press for three minutes while being kept at ambient temperature and seven MPa of pressure. The PP sheet that resulted was cut to the precise dimensions (150 × 120 × 0.25 mm^3) for composite construction. The fibers were then randomly arranged in a mold with the dimensions 150 × 120 × 0.25 mm^3 with PP sheets sandwiched between them. To create composites with varying fiber loading, such as 10–40 wt%, five layers of pre-weighted PP sheets were sandwiched between four layers of fibers. This sandwich was squeezed for five minutes at 190°C and 10 MPa to create composites. The composite sample comprised of steel plates was then chilled using a separate press (Carver Laboratory Press, USA, Model 2518) operating in a cooling environment.

Examination of Morphology

The surface morphology of the composites' tensile fractures, both with and without SA treatment, was examined using a scanning electron microscope (SEM, model JEOL JSM-5310) operating at a voltage of 20 kV. Prior to SEM, the samples were coated with a thin layer of gold (25 nm) using a BAL-TEC SCD 050 sputter coater under vacuum to avoid electrical charge buildup.

Composites' Absorption of Water

The water uptake test in accordance with ASTM D-579-99 was conducted on rectangular specimens with a measurement of 25.4 mm × 6.2 mm. The samples were heated to a temperature of 50 °C for around 24 hours to dry them, after which they were chilled in a desiccator and weighed. After that, each sample was placed for a varied period (up to 30 days) in a beaker that contained 100 cc of deionized water and was kept at room temperature (25°C). After a predetermined amount of time, samples were removed from the beaker, five dry cloth wipes were applied, and then the samples' weights were once again recorded. Following each measurement, the samples were put back into the water. As a result of consuming more water, the samples put on weight, which was calculated as a weight difference and shown as a percentage increase from baseline weight.

Test for Simulated Weathering

A tester (Q-UV-26200, Q-panel Co.) was used to mimic dews and condensation for two hours (45°C ± 2°C), and the UV lamp (313 nm) was used to imitate sunlight for four hours (65°C ± 2°C), all for a total of 300 hours for the composite samples that had not been treated as well as those that had. The samples were weighed, and after drying for 30 minutes in the oven, their mechanical characteristics were assessed. The reliable results are achieved by averaging experimental data from each of the tests, which each entails the examination of at least five different samples.

FINAL FINDINGS AND DISCUSSION

Effect of Banana Concentration on Composites' Mechanical Properties

A significant impact was made on the mechanical properties of the composites by their fiber content (wt%). In Figure 1, the TS and bending strength (BS) values of composites constructed of untreated banana fibers at various fiber loadings are displayed. While TS and BS increased for composites with a 40% higher fiber loading, they decreased (Figure 1). TS and BS were shown to improve by up to 30% more fiber loading. In composites with a 30% banana content that were not treated, the TS and BS were discovered to be 38.1 MPa and 44.2 MPa, respectively.

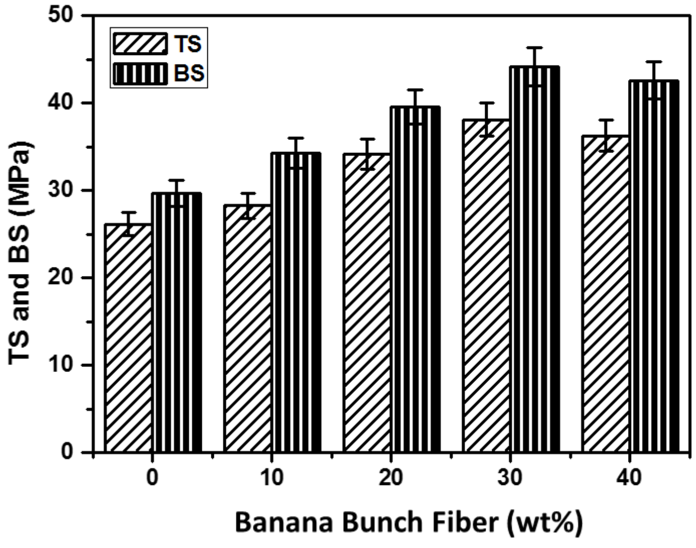

Figure 1. The influence of fiber loading on the bending and tensile strength of PP and banana fiber composites.

Figure 2 displays the findings of a study on the impact of fiber loading on the tensile modulus (TM) and bending modulus (BM) of a banana-PP composite. From 10 to 40% weight percent of PP was loaded with fiber, and both the TM and BM grew gradually. The early reinforcing impact of natural fibers contributed to this increase by allowing stress to be transmitted from the continuous polymer matrix to the dispersed fiber phase [27]. It was discovered that the composites' TM and BM heights were 0.87 and 0.91 GPa, respectively. Figure 3 illustrates the variance in Charpy impact strength (IS) for PP composites augmented with untreated banana fiber as a function of fiber loading. The IS increased when the amount of fiber was increased by up to 30%; however, composites with 40% more fiber showed lower IS values than those with 30% more fiber. The height value of IS was discovered to be 18.3 kJ/m^2 at a composite with 30% banana content. As a result, it was determined that the mixture with a 30% banana content was the best. The TS, BS, TM, BM, and IS of the composites displayed improvements of 45.4%, 48.8%, 45%, 50%, and 44%, respectively, in comparison to virgin PP matrix at 30 wt% banana fiber loading.

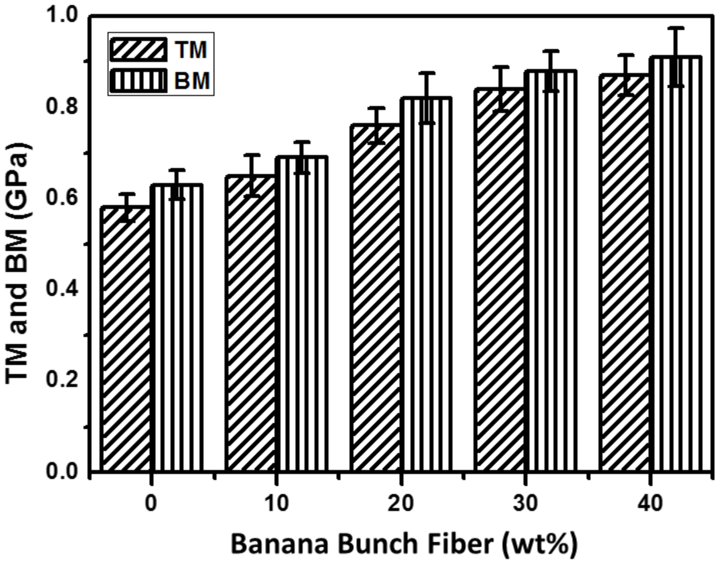

Figure 2. The bending and tensile moduli of banana fiber/PP composites are influenced by the amount of fiber loaded.

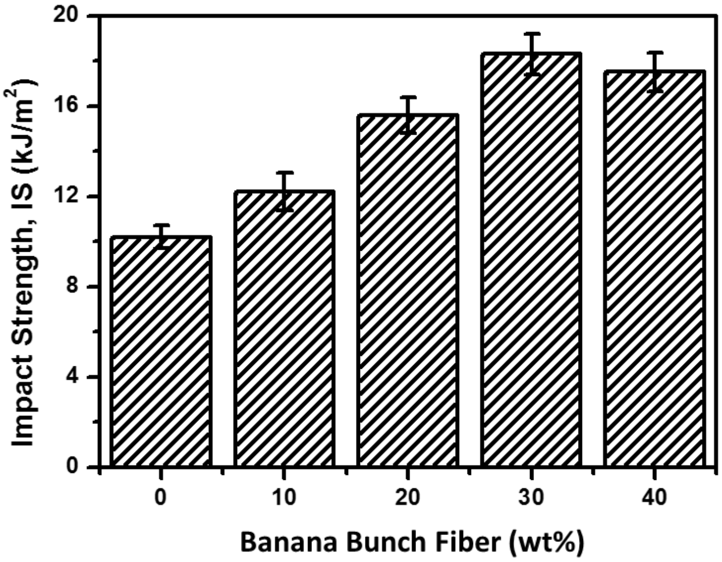

Figure 3. The amount of loaded fiber affects the impact strength of composites constructed of banana fiber and PP.

The improvement in mechanical properties suggests that fibers made of bananas can effectively facilitate stress transition from the matrix due to their uniform cross-sections and high aspect ratios. Because fiber orientation is so important to the performance of the composites at low fiber loading, the level of gain in mechanical performance at low banana fiber loading is less than it is at 30 wt% of banana fiber loading. Poor fiber alignment causes a larger free region for fiber movement at lower fiber loading, which reduces the effective stress transfer from fiber to matrix [28]. Fiber loading at 10% weight percent may not be sufficient to sufficiently reinforce the PP matrix and transmit stress because a minimum critical weight ratio fiber loading is necessary to reinforce the matrix. In this study's research, 30% of the weight of banana fiber loading is the crucial weight percent at which the fibers are adequate to constrain the matrix, produce a uniform distribution of stress, and provide the matrix with helpful reinforcement. It was shown, however, that over 30 wt%, fiber loading decreased the mechanical characteristics of TS, BS, and IS by 5%, 4%, and 5%, respectively. Lack of adhesion between the fibers and matrix, which encouraged the growth of microcracks at the interface, and non-uniform stress transfer caused by fiber aggregation in the matrix may be to blame for the loss in strength at higher fiber loading [28]. In addition, increased fiber loading causes voids to form in the composites because of fiber-fiber agglomeration caused by H-bonding between the fibers. This has an adverse effect on the mechanical properties and causes an uneven distribution of fibers inside the PP matrix. But as fiber loading increased, the TM and BM of PP steadily grew from 10 to 40 wt%, indicating a reinforcing effect. The failure process of fiber-reinforced composites, which involves fracture initiation and propagation in the resin matrix, fiber breaking and pullout, delamination, and disbanding, is reflected in how they react to impacts. The interaction of the fibers with crack development and their function as a stress-transfer medium are responsible for the rise in notched IS. Due to the presence of many fiber ends in the composites, IS was shown to be reduced to a high fiber loading of 40% weight. This could lead to the development of cracks and ultimately the failure of the composite [29]. The failure of composites can be interpreted in terms of the likelihood of fiber aggregation caused by stress concentrations at certain spots, like how cracks propagate more rapidly as a result.

The Impact of SA Treatment on Composites' Mechanical Properties

The investigation of the coupling agent's effects on the static mechanical properties (TS, BS, TM, BM, and IS) of banana fiber-reinforced PP composites (BFRP) with a 30 weight percent content is displayed in Figures 4 and 5. When comparing all samples' mechanical characteristics to those of unidirectional composites without SA at 30 weight percent fiber loading, an even greater improvement with SA addition was seen. Comparing 30 weight percent reinforced BFRP with SA to 30 weight percent reinforced BFRP without SA resulted in an increase in the maximum TS and BS of the reinforced BFRP of 9 and 7%, respectively (Figure 4). When compared to those of the 30 wt% BFRP composites, it was discovered that the highest IS of unidirectional banana fiber/PP composites improved by 32% because of SA coating treatment on the fiber surface (Figure 4). However, as compared to those of the BFRP composites at 30 wt% fiber loading, the maximum TM and BM of the banana fiber/PP composites were reported to have improved by roughly 26 and 37%, respectively, because of the SA coating treatment on the fiber surface, as shown in Figure 5. The hydrophilic fiber and hydrophobic PP matrix exhibit resultant loss in weak mechanical interfacial adhesion because of hydroxyl and other polar groups on the fiber surface, which is the main factor for untreated BFRP composites to perform less mechanically. Contrarily, when SA was added, it interacted with the hydrophilic banana through its carboxylic group and somewhat increased the surface's hydrophobicity, making the banana surface compatible with hydrophobic PP. When SA is in its acid state, acid-base interactions allow it to engage with the fiber's surface in the right manner. The transmission of stress from the matrix to the fiber is improved by the connection and adhesion between the fibers and matrix, whether via covalent bonding, acid-base interaction (such as H-bonding), or a combination of the two. The SA-provided chain entanglement between the SA and PP chains, the potential covalent interaction between the carboxylic and hydroxyl groups of the banana fiber, and the covalent interaction between the carboxylic and hydroxyl groups of the banana fiber all contribute to the feasibility of effective stress transmission. According to Bisanda and Ansell [30], surface treatment improves natural fiber's adhesive properties by removing hemicelluloses, which creates a rough surface topography and enhances the fiber's mechanical properties as well as its adhesion to the matrix. But as the SA weight percentage increased from 10 to 13 wt%, the mechanical behavior of the BFRP changed. Because the SA chains interact with one another rather than the polymer matrix or the fibers, there is slippage at the interface and a resultant loss in mechanical performances [29].

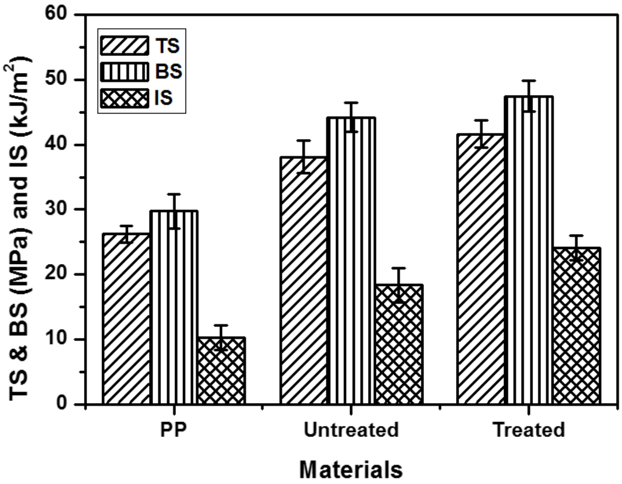

Figure 4. Tensile, bending, and impact resistance of banana-PP composites with and without treatment.

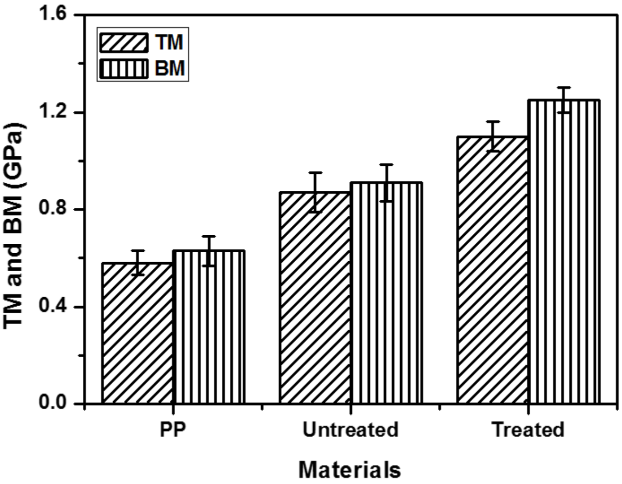

Figure 5. Tensile and bending moduli of banana-PP composites with and without treatment.

Characteristics of the Fractured Surface

To better comprehend the fracture mechanism, SEM pictures of the tensile surfaces of the composite samples were collected. To evaluate how an SA impacts the interphase of the composites, SEM examination of the fracture surfaces of the composites can be used. Tensile fractographs for treated and untreated composites with a 30-weight percent fiber loading is shown in Figure 6(a, b). The application of tensile stress caused the fibers to bunch up into bunches and numerous holes were formed after fiber pullout from the matrix, as can be seen in Figure 6(a), which illustrates how poorly scattered the fibers were in the untreated fiber composites. In contrast, better adhesion and fiber dispersion were seen in treated fiber composites (Figure 6(b)), which decreased the amount of fiber pullouts and voids because the fibers did not fully come out of the matrix. Additionally, the fractured surfaces were more equally distributed than they were in the case of the fiber composites that had not been treated. The lignocellulosic banana fiber's hydrophilic surface was treated with SA coating chemicals prior to being employed to create unidirectional banana fiber/PP composites. Better adherence between the fiber and matrix was obtained because of the interaction between the SA's carboxylic group and the banana's hydroxyl group (–OH). The mechanical characteristics of these composites were improved.

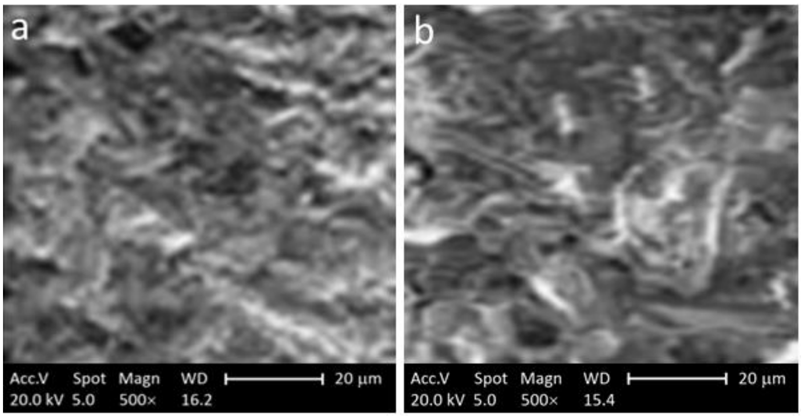

Figure 6. Under a scanning electron microscope, banana fiber composites that have not been treated with SA (a) and that have been treated with SA, (b) exhibit the tensile fracture surfaces.

Composites' Absorption of Water

It is generally known that lignocellulosic-based composites' ability to absorb water results in unfavorable dimensional changes in the finished product [31]. Additionally, rapid debonding, delamination, and structural integrity loss brought on by water absorption may result in a decline in the material's mechanical properties [32]. The TS of the composite falls as the water immersion times increase [33]. When tested with water immersion, the quantity and kind of lignocellulosic filler have a big impact on how much water lignocellulosic-based composites can absorb. It is predicted that lignocellulosic composites, like banana fiber, may absorb more water as a result.

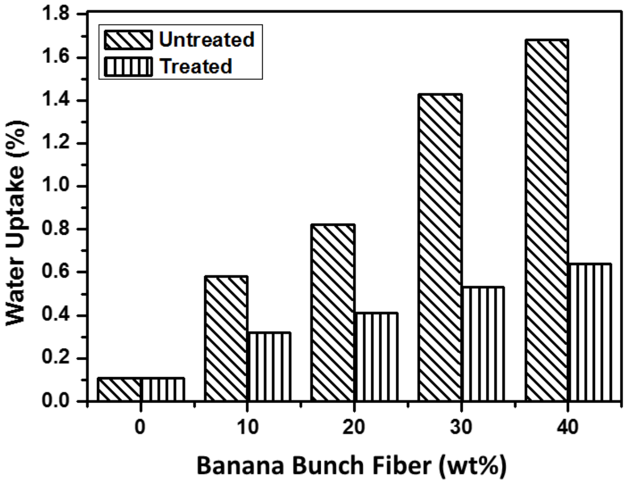

Figure 7. Banana fiber/PP composites with various fiber loading and SA treatments exhibit variable water absorption.

Figure 7 displays the water uptake properties of the produced composites in relation to fiber loading. Only composite samples that had not received SA treatment were included in the comparison to produce more accurate results. Water absorption (%) of the untreated composite increased as fiber loading increased to 40% of its weight [34]. The untreated composite sample could absorb water at a rate of around 1.68% at a 40% fiber loading, whereas the treated composite sample could only do so at a rate of about 0.64%. Researchers found that SA pretreatment reduced the water content of composites compared to untreated composites. Possible causes of this include the functional group’s polarity. A hydroxyl group, a polar compound that is present in the cellulose molecule of virgin banana fiber, is responsible for absorbing moisture from the surrounding air. The carboxylic group of SA is more polar than the hydroxyl group, in comparison. Since less water was absorbed as a result, the pretreated composites’ dimensional stability may have improved.

REPLICATING THE EFFECTS OF WEATHERING

To evaluate the deteriorating features of the environment, the weathering effect was used. Analyzing the impacts of weathering on several physical parameters involved two composite samples, one without SA treatment and the other with SA. In this scenario, samples that had been treated and samples that had not were subjected to a rigorous weathering test that lasted 300 hours and alternated between mimicking sunlight and simulating wetness. In the weather tester, many techniques including a strong mercury or xenon arc, water spray, and humidity control were employed. Every so often, the samples’ tensile characteristics, notably their TS and TM, were measured to see how much they had changed. Table 1 displays the missing TS and TM values. For the untreated sample, the highest TS loss throughout the longest observation period was approximately 15.6%, compared to roughly 10.2% for the treated sample with SA. Similarly, the greatest TM loss was 13.9% in the untreated sample, but it was 8.2% in the treated sample. The weather test revealed that the treated samples retained their tensile qualities even after being subjected to severe weathering for 300 hours, in contrast to the untreated samples, which lost their tensile properties (TS and TM).

Table 1. During a weather simulation, the composites’ tensile strength (TS) and tensile modulus (TM) declined.

Materials	Degradation Time (hr)	Degradation in Medium	
		LTS (%)	LTM (%)
UBPC	50	7.3 ± 0.5	8.1 ± 0.3
	100	10.2 ± 0.4	9.2 ± 0.5
	150	12.1 ± 0.6	11.3 ± 0.4
	200	14.5 ± 0.7	13.2 ± 0.6
	300	15.6 ± 0.6	13.9 ± 0.8
TBPC	50	3.3 ± 0.06	4.2 ± 0.4
	100	5.2 ± 0.08	5.9 ± 0.5
	150	6.9 ± 0.06	7.1 ± 0.7
	200	8.8 ± 0.08	7.9 ± 0.6
	300	10.2 ± 0.7	8.2 ± 0.7

Note: UBPC: Untreated banana/PP composite, TBPC: Treated banana /PP composite, LTS: Loss of TS (%), LTM: Loss of TM (%).

CONCLUSION

In this work, the mechanical characteristics of unidirectional composites reinforced with banana fiber on PP at various fiber weight percentages were examined. The hydrophobic PP matrix can be used with banana because, according to the research, SA covers it to make it so. The findings of the study’s experimental component support the following assertion:

1. The TM and BM of the composites continued to rise as the fiber loading increased from 10% to 40%, even though the TS, BS, and IS of the composites increased as the fiber loading rose from 10% to 30%.
2. The results of the mechanical characteristics revealed that the treated banana fiber reinforced composites had TS, BS, TM, BM, and IS values that were higher than those of virgin PP and

even higher than those of raw composites.

3. The improved tensile properties demonstrated by the composites with SA-treated banana fiber could be attributed to changes in the fiber’s structural properties as well as changes in the fiber/matrix interfacial properties in the case of strength, as shown by SEM micrographs of the fracture surface of the composites.
4. The water uptake behavior of the treated composite was substantially less pronounced than that of the untreated composite. Simulated weathering experiments showed that, in terms of the amount of time required for their degradation, the TS and TM of the treated sample may be lower than those of the untreated sample.

REFERENCES

1. Rana A, Mandal A, Mitra BC, Jacobson RE. Short jute fiber-reinforced polypropylene composites: Effect of compatibilizer. J Appl Polym Sci. 1998;69(2):329–338. doi: 10.1002/(SICI)1097-4628(19980711)69:2<329::AID-APP14>3.0.CO;2-R.
2. Tajvidi M, Ebrahimi G. Water uptake and mechanical characteristics of natural filler–polypropylene composites. J Appl Polym Sci. 2003;88(4):941–946. doi: 10.1002/app.12029.
3. Zhou XP, Li RKY, Xie XL, Tjong SC. Reinforcement of polypropylene using sisal fibers grafted with poly (methyl methacrylate). J Appl Polym Sci. 2003;88:1055–1064. doi: 10.1002/app.11818.
4. Mohanty AK, Misra M, Drzal LT. Sustainable bio-composites from renewable resources: opportunities and challenges in the green materials world. J Environ Polym Degrad.. 2002;10:19–26. doi: 10.1023/A:1021013921916.
5. Puglia D, Biagiotti J, Kenny JM. A review on natural fibre-based composites-Part II: Application of natural reinforcements in composite materials for automotive industry. J Nat Fibers. 2005;1(3):23–65. doi: 10.1300/J395v01n03_03.
6. Nikmatin S, Hermawan B, Irmansyah I, Indro MN, Sukardan MD, Umam R. Kinematics and dynamics of the ballistic impact behavior for an oil palm empty fruit bunch fiber reinforced bio-composite. Bioresources. 2020;15(3):6123–6134.
7. Zaman HU, Khan MA, Khan RA. Banana fiber-reinforced polypropylene composites: A study of the physico-mechanical properties. Fibers Polym. 2013;14(1):121–126. doi: 10.1007/s12221-013-0121-8.
8. Roy JK, Akter N, Zaman HU, Ashraf KM, Sultana S, Shahruzzaman, et al. Preparation and properties of coir fiber-reinforced ethylene glycol dimethacrylate-based composite. J Thermoplast Compos Mater. 2014;27(1):35–51. doi: 10.1177/0892705712439568.
9. Nourbakhsh A, Ashori A, Tabari HZ, Rezaei F. Mechanical and thermo-chemical properties of wood-flour/polypropylene blends. Polim Bull. 2010;65(7):691–700. doi: 10.1007/s00289-010-0288-8.
10. Zaman HU, Khan RA, Khan MA, Beg H. Physico-mechanical and degradation properties of biodegradable photografted coir fiber with acrylic monomers. Polim Bull. 2013;70(8):2277–2290. doi: 10.1007/s00289-013-0950-z.
11. Zeng H, Leng J, Gu J, Sun H. Modeling the thermomechanical behaviors of short fiber reinforced shape memory polymer composites. Int J Mech Sci. 2020;166:105212. doi: 10.1016/j.ijmecsci.2019.105212.
12. Hintermann M. Automotive exterior parts from natural fibers. RIKO-2005. 2005.
13. Bledzki AK, Faruk O, Jaszkiewicz A. Cars from renewable materials. Kompozyty. 2010;10:282–288.
14. Kumar S, Misra R. Analysis of banana fibers reinforced low-density polyethylene/poly (Є-caprolactone) composites. Soft Mater. 2007;4:1–13. doi: 10.1080/15394450600823040.
15. Venkateshwaran N, Elayaperumal A. Banana fiber reinforced polymer composites-a review. J Reinf Plast Compos. 2010;29(15):2387–2396. doi: 10.1177/0731684409360578.
16. Romero JRR, Albano C, Davidson E, Poleo R. Effects of gamma irradiation on polypropylene, polypropylene+ high density polyethylene and polypropylene+ high density polyethylene+ wood flour. Mater Res Innov. 2001;4(5):294–300. doi: 10.1007/s100190000104.

17. Karian H. Handbook of Polypropylene and Polypropylene Composites, Revised and Expanded. CRC Press; 2003.
18. Herrera-Franco P, Valadez-Gonzalez A. A study of the mechanical properties of short natural-fiber reinforced composites. Compos BEng. 2005;36:597–608. doi: 10.1016/j.compositesb.2005.04.001.
19. Bledzki A, Al-Mamun A, Lucka-Gabor MM, Gutowski V. The effects of acetylation on properties of flax fibre and its polypropylene composites. Express Polym Lett. 2008;2(6):413–422.
20. Pizzi A, Eaton N. The structure of cellulose by conformational analysis. Part 5. The cellulose Ii water sorption isothermXS. J Macromol Sci Chem. 1987;24:1065–1084.
21. Bledzki A, Gassan J. Composites reinforced with cellulose based fibres. Prog Polym Sci. 1999;24(2):221–274. doi: 10.1016/S0079-6700(98)00018-5.
22. Sreekala M, Thomas S. Effect of fibre surface modification on water-sorption characteristics of oil palm fibres. Compos Sci Technol. 2003;63(6):861–869. doi: 10.1016/S0266-3538(02)00270-1.
23. John MJ, Francis B, Varughese KT, Thomas S. Effect of chemical modification on properties of hybrid fiber biocomposites. Compos - A: Appl Sci Manuf. 2008;39(2):352–363. doi: 10.1016/j.compositesa.2007.10.002.
24. Li X, Tabil LG, Panigrahi S. Chemical treatments of natural fiber for use in natural fiber-reinforced composites: A review. J Environ Polym Degrad. 2007;15(1):25–33. doi: 10.1007/s10924-006-0042-3.
25. Kim H, Biswas J, Choe S. Effects of stearic acid coating on zeolite in LDPE, LLDPE, and HDPE composites. Polymer. 2006;47(11):3981–3992. doi: 10.1016/j.polymer.2006.03.068.
26. Bellayer S, Tavard E, Duquesne S, Piechaczyk A, Bourbigot S. Mechanism of intumescence of a polyethylene/calcium carbonate/stearic acid system. Polym Degrad Stab. 2009;94(5):797–803. doi: 10.1016/j.polymdegradstab.2009.01.032.
27. Patil Y, Gajre B, et al. Effect of maleic anhydride treatment on steam and water absorption of wood polymer composites prepared from wheat straw, cane bagasse, and teak wood sawdust using novolac as matrix. J Appl Polym Sci. 2000;77(13):2963–2967. doi: :10.1002/1097-4628(20000923)77:13<2963::AID-APP20>3.0.CO;2-0.
28. Karmaker A, Hoffmann A, Hinrichsen G. Influence of water uptake on the mechanical properties of jute fiber-reinforced polypropylene. J Appl Polym Sci. 1994;54:1803–1807. doi: 10.1002/APP.1994.070541203.
29. Sanadi AR, Caulfield DF, Jacobson RE, Rowell RM. Renewable agricultural fibers as reinforcing fillers in plastics: mechanical properties of kenaf fiber-polypropylene composites. Ind Eng Chem Res. 1995;34(5):1889–1896. doi: 10.1021/ie00044a041.
30. Bisanda E, Ansell MP. The effect of silane treatment on the mechanical and physical properties of sisal-epoxy composites. Compos Sci Technol. 1991;41(2):165–178. doi: 10.1016/0266-3538(91)90026-L.
31. Mwaikambo LY, Martuscelli E, Avella M. Kapok/cotton fabric–polypropylene composites. Polymer Testing. 2000;19(8):905–918. doi: 10.1016/S0142-9418(99)00061-6.
32. Jiang L, Hinrichsen G. Flax and cotton fiber reinforced biodegradable polyester amide composites, 2. Characterization of biodegradation. Angew Makromol Chem. 1999;268:18–21. doi: 10.1002/(SICI)1522-9505(19990701)268:1<18::AID-APMC18>3.0.CO;2-T.
33. Danjaji I, Nawang R, Ismail H, Ishak ZAMM. Degradation studies and moisture uptake of sago-starch-filled linear low-density polyethylene composites. Polym Test. 2002;21(1):75–81. doi: 10.1016/S0142-9418(01)00051-4.
34. Yang H-S, Kim H-J, Park H, Lee B-J. Water absorption behavior and mechanical properties of lignocellulosic filler–polyolefin bio-composites. Compos Struct. 2006;72:429–437. doi: 10.1016/j.compstruct.2005.01.013.