PROGRESS IN ENGINEERING APPLICATION AND TECHNOLOGY
e-ISSN: 2773-5303

PEAT

Vol. 7 No. 1 (2026) 611-622
https://publisher.uthm.edu.my/periodicals/index.php/peat

Mechanical and Thermal Properties of Bamboo-Cotton Textile Waste Reinforced Recycled Polypropylene Composite for Eco-Packaging Applications

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DOI: https://doi.org/10.30880/peat.2026.07.01.069

Article Info

Received: 12 January 2026
Accepted: 20 February 2026
Available online: 25 May 2026

Keywords

Recycled polypropylene, bamboo-cotton textile waste, natural fiber-reinforced composite, mechanical properties, thermal properties, morphology analysis

Abstract

The growing waste production issues has led to global interest in sustainable materials, particularly in natural fiber-reinforced polymer composites using recycled plastics and textile waste. This study examines the mechanical and thermal properties of a composite made from bamboo-cotton textile waste reinforced recycled polypropylene (rPP), compatibilised with MAPP. The methodology involved alkaline treatment of bamboo-cotton textile waste (BCTW) , followed by composite preparation using internal mixing, compression molding, and laser cutting, varying fiber loadings at 5%, 15%, 20%, and 25%. Characterization was performed using Fourier Transform Infrared Spectroscopy (FTIR) and Field Emission Scanning Electron Microscopy (FESEM). Mechanical assessments included tensile testing for parameters like tensile strength, Young's modulus, and elongation at break, while thermal properties were measured through Thermogravimetric Analysis (TGA) and Differential Scanning Calorimetry (DSC). FESEM results indicated that the chemical treatment enhanced fiber surface roughness, promoting better mechanical interlocking with the recycled polypropylene matrix. FTIR spectra confirmed the successful removal of non-cellulosic components, including cellulose, lignin, and pectin, post-treatment. Thermal analyses showed that the 5% fiber reinforced polymer composite exhibited significant thermal stability with the highest crystallinity. The treated 20% composite achieved the highest tensile strength and Young's modulus, attributed to increased fiber loading, optimizing mechanical performance. However, performance declined beyond 20% due to fiber agglomeration. These results indicate that BCTW-reinforced rPP composites could serve as an effective and eco-friendly alternative to traditional packaging materials.

1. Introduction

In Malaysia, the manufacturing sector has become one of the important sectors that have developed and contributed to the growth of the economy. The textile industry has been a significant part of the manufacturing sector in Malaysia. According to [22], textiles have been widely used, especially in apparels including formal, casual, sports, and leisure wear. Technically, textiles are categorised into several different application categories, including agriculture, geology, packing, medical, hygiene, filters, personal protection, and the automotive industry [4]. The fundamental chemical composition of the fibers leads to such a broad range of commercial applications, increasing the production of textile. Alongside with textile waste, plastic waste is also considered as the third highest waste source globally as its overall amount is increasing in tandem with both per capita consumption and population growth [4]. Furthermore, Malaysia is acknowledged as the world's top importer of plastic waste since 2017 and continually keeps on track on worldwide trends in the use of single-use plastics as well as the total output of plastic waste. This issue has given major challenges to the management system and to the environment. Thus, one of the major plastic wastes produced is polypropylene (PP). PP is a kind of thermoplastic polymer that has been widely used as it is cost-effective, easy to process, and has exceptional properties. Additionally, due to its resistance to natural breakdown, plastics such as PP has become one of the major challenges to waste management which led to the accumulation of plastics waste that pose serious environmental issues over years..

Therefore, the global push toward sustainable materials has led to increased interest in natural fiber-reinforced polymer composites, particularly those utilising recycled plastics and agricultural or textile waste. For instance, the development of bamboo-cotton textile waste reinforced rPP composites helps to overcome and minimise waste management. Moreover, the reinforcement of bamboo-cotton textile waste in rPP composites strives to enhance the performance of the composites and reduce the environmental impact of plastic-based materials which brings technical, economic, and environmental benefits. Thus, it is crucial to investigate the mechanical and thermal properties of the reinforced composites to ensure it is ideal for eco-packaging application. The composites were loaded with various filler content to identify the composites with excellent properties. For characterisation and morphology of the composites, it is necessary to undergo FT-IR spectroscopy and FESEM [3]. A tensile test will be done to examine the composite's mechanical properties. On the other hand, TGA assesses the thermal stability of the composites, while DSC analysis provides insight into the melting and crystallization behaviours of the composite. Moreover, the usage of MAPP as a compatibilizer in the composite blend resulting in improved mechanical and thermal properties, making it potential for wide range of applications in industries [15].

2. Methodology

In this section, the overall experimental methodology is discussed.

2.1 Materials and Chemicals

In this study, the materials used for composite were bamboo-cotton textile waste, recycled PP, maleic anhydride polypropylene (MAPP), meanwhile sodium hydroxide (NaOH) solution, detergent, and distilled water were used for pre-treatment of the textile waste and rPP.

2.2 Fabrication of Alkaline-Treated BCTW-rPP Composite

This subtopic particularly further discusses the fabrication process of the alkaline treated bamboo-cotton textile waste reinforced rPP composite.

2.2.1 Collection and Alkaline Treatment of the BCTW

Firstly, the bamboo-cotton textile waste (BCTW) collected from the recycling center undergoes a cleaning process using water and detergent to eliminate dust, oil, or paint. After cleaning, the textiles are rinsed with distilled water and air-dried to remove moisture. The dried BCTW is then uniformly cut into smaller pieces, ranging from 1 to 5 mm in length, to ensure equal exposure during subsequent chemical processes, enhancing fiber dispersion in the polymer matrix. Following this, the textile pieces are soaked in a 2% sodium hydroxide (NaOH) solution for at least 3 hours to remove hemicellulose, lignin, and surface impurities, after which they are dried in a drying oven at 60°C for approximately 3 hours.

2.2.2 Preparation of the BCTW Reinforced Recycled PP Composites

The recycled PP that are obtained and collected from local waste are washed with hot water and detergent to remove impurities such as dirt, oils and greases, and labels and adhesives. The rPP pieces are allowed to completely dry thoroughly through air-drying. The steps are purposely to eliminate moisture content from the polymer matrix as it affects the degradation of it during melt processing. After that, the treated rPP were crushed into small flakes or granules, typically about 5 to 10 mm, using a grinder. This process mainly helps for uniform feeding into the internal mixing, in order to obtain a homogeneous composite mixture [18]. Hence, Table 1 and 2 depicts the composition of each sample of the composite.

Table 1 *Untreated BCTW reinforced rPP composite designation*

Sample	Designation	rPP (wt%)	BCTW (wt%)	MAPP (wt%)
rPP/BCTW 5	P/5%	90	5	5
rPP/BCTW 15	P/15%	80	15	5
rPP/BCTW 25	P/25%	70	25	5

Table 2 *Alkaline-treated BCTW reinforced rPP composite designation*

Sample	Designation	rPP (wt%)	BCTW (wt%)	MAPP (wt%)
rPP/BCTW 5	P/A5%	90	5	5
rPP/BCTW 10	P/A10%	85	10	5
rPP/BCTW 15	P/A15%	80	15	5
rPP/BCTW 20	P/A20%	75	20	5
rPP/BCTW 25	P/A25%	70	25	5

2.2.3 Internal Mixing Process

After alkaline treatment, materials such as rPP pellets or flakes, bamboo-cotton textile, and MAPP compatibiliser are weighed based on varying compositions of composite samples with textile loadings of 0%, 5%, 10%, 15%, 20%, and 25% by weight. This variation helps to differentiate the properties of each sample. To ensure that the bamboo-cotton textile fibers are evenly embedded in the rPP matrix, the mixture is melted and blended in an internal mixer set at 180°C-200°C and a speed of 60 rpm to avoid degradation. Once the set temperature is attained, rPP pellets are added to the mixer. After 2 minutes, MAPP compatibiliser is introduced, followed by the textile pieces after a further 2 minutes. The MAPP compatibiliser is crucial for enhancing the interfacial adhesion between the hydrophilic textile fibers and the hydrophobic polymer matrix. After mixing for a total of 10 minutes, the composite mixture is discharged from the mixer and allowed to cool down.

2.2.4 Compression Molding Process

Once the composite mixture has cooled, it is crushed into small pellets for easier handling before being prepared for compression molding. This process occurs in a hot compression molding machine utilizing a square steel mold measuring 250 mm x 250 mm x 4 mm, at a temperature of 190°C. The top plate is heated to 210°C, while the bottom plate remains at 190°C. After reaching the designated temperatures, the crushed composite is evenly distributed in the mold for structural integrity. The mold is then placed on the heated plate and maintained under a minimal pressure for 10 minutes. Subsequently, it is subjected to a cold press while maintaining constant pressure until the plate cools to 60°C. Finally, it cools for 24-48 hours before any additional processing or testing.

2.2.5 Laser Cutting Process

In order to go through mechanical testing by using UTM, the sample needs to be cutted into a dumbbell shape, according to ASTM D638 standard. The method that had been used to cut the composite was through laser cutting method at speed of 10 mm/S. (unit) using 1200 W of rated power and rated voltage of 50-60 Hz.

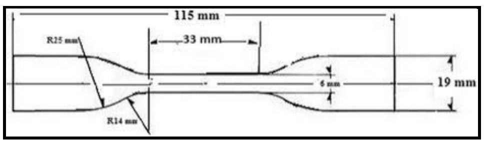


Fig. 1 *Dimensions of tensile test specimen under ASTM D638*

2.3 Characterisation of the Reinforced Composites

During this research, several characterisation analysis including Fourier Transform Infrared (FT-IR) Spectroscopy and Field Emission Scanning Electron Microscopy (FESEM) were done before and after alkaline treatment of the bamboo-cotton textile waste.

2.3.1 Fourier Transform Infrared (FT-IR) Spectroscopy

The procedure began with sample preparation, where a small amount of the textile sample was ground with potassium bromide (KBr) and compressed into a translucent pellet using a hydraulic press. To conduct an FT-IR analysis, the instrument is kept stabilized. The spectrometer is powered on and allowed to warm up to ensure thermal stability of the instrument. To eliminate atmospheric interference, the nitrogen purge gas flow was verified and confirmed that the internal optics has no presence of moisture. Once the hardware and sample were ready, and the control software was initialised, the diagnostic routine was performed.

2.3.2 Field Emission Scanning Electron Microscopy (FESEM)

As for the FESEM test, a sample preparation was done by cutting the textile into small pieces. The samples then were kept in a drying oven at 60°C for 24 hours to ensure complete moisture content removal. Next, the specialised aluminium stub was sterilised and mounted the sample onto it. The samples were securely mounted on the stub using conductive carbon tape or adhesive, and placed into the FESEM's vacuum chamber. The region that wanted to be analysed was spotted and analysed under 2000x and 6500x magnification.

2.4 Mechanical Testing of the Reinforced Composite

To determine the mechanical properties of the reinforced rPP composites, a tensile test has been done. The tensile tests were done by using a universal testing machine (UTM) according to the standard of ASTM D638 at FKMP laboratory. The dimensions of the composite sample were 4 mm thickness, 6 mm width, and 33 mm gauge length. Few dumbbell-shaped composite samples with varying textile loadings including pure PP, rPP, and the 5%, 15% and 20% of untreated and alkaline-treated BCTW-rPP composite, respectively. The samples were tested under a stress of 10kN and recorded the data.

2.5 Thermal Testing of the Reinforced Composite

For thermal testing, there are two types of analysis that have been done which include Thermogravimetric Analysis (TGA) and Differential Scanning Calorimeter (DSC) test.

2.5.1 Thermogravimetric Analysis (TGA)

To perform TGA testing, a careful selection and cleaning of the sample pan was done to prevent cross-contamination from the previous run. A small amount of the textile and composite samples are weighed ranging from 5 to 20 milligrams. The samples then were loaded into the pan and placed onto the balance assembly inside the furnace. The samples were performed at a heating rate of 10°C/min with temperature range from 200°C to 500°C.

2.5.2 Differential Scanning Calorimetry (DSC) Testing

To ensure a precise measurement of heat flow during DSC analysis, samples were prepared carefully and ensured instrument stabilization. Next, the samples were cutted into small pellets and a small amount of it weighed ranging from 5 to 10 milligrams. The samples then were placed into a specialized aluminium pan. The pan was sealed using a crimping press to ensure the mass remained constant throughout the run. Therefore, the samples were performed with the range of temperature from 0°C to 200°C and rate of heat at 25°C/min.

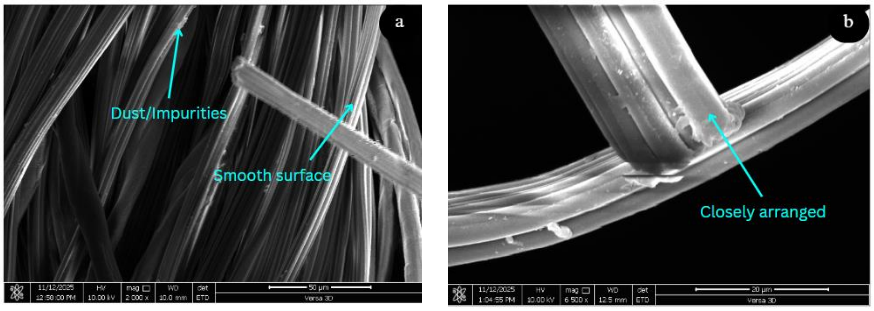
3. Results and Discussion

3.1 Characterisation Analysis

In this section, the characterisation analysis of the untreated and alkaline-treated BCTW through FESEM testing and FT-IR spectroscopy was discussed.

3.1.1 Morphological Analysis of Untreated BCTW

Fig. 2 (a) and (b) illustrate the surface morphology and structural characteristics of untreated BCTW at magnifications of 2000x and 6500x, respectively. At 2000x magnification, Fig. 2 (a) reveals a smooth surface lacking visible roughness, attributed to natural constituents such as cellulose, hemicellulose, lignin, lubricants, and waxes that layer the textile surface. These materials inhibit exposure of underlying cellulose microfibrils, leading to poor mechanical bonding between adjacent fibers [8]. Under 6500x magnification, Fig. 2 (b) shows minor surface irregularities on the fibers, likely due to residual impurities present in untreated fibers. This results in low surface roughness and energy, rendering the fibers suboptimal for reinforcement in polymer composites, as such characteristics diminish mechanical performance. Composites utilizing untreated fibers exhibit inadequate adhesion to the epoxy matrix, resulting in fiber pull-out during mechanical testing [2].

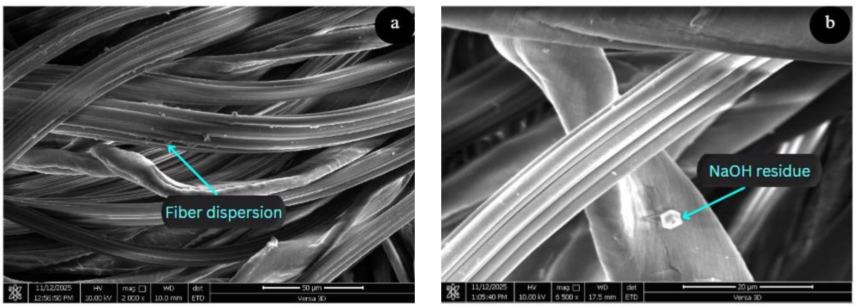


(a) (b)

Fig. 2 *Surface morphology of untreated BCTW at (a) 2000x magnification; (b) 6500x magnification*

3.1.2 Morphological Analysis of Treated BCTW

Fig. 3 (a) and (b) present the surface morphology of alkaline-treated BCTW at magnifications of 2000x and 6500x, respectively. Significant morphological changes were observed in Fig. 3 (a), where the fiber bundles are more loosely packed and separated due to alkaline treatment, which partially removes binding agents like hemicellulose, lignin, pectin, and wax. This treatment renders the fiber textile rougher and more irregular, primarily due to the exposure of cellulose microfibrils. Such changes enhance fiber dispersion in composite matrices by reducing the compactness of the bundles. Fig. 3 (b) further stresses this improved surface modification, showing distinct fiber dispersion and increased surface roughness linked to the removal of protective layers. [24] indicate that alkaline treatment fosters better mechanical interlocking in composites and that treated fibers exhibit superior mechanical performance compared to untreated ones [7]. Notably, traces of NaOH were observed on the textile's surface, likely from insufficient rinsing. Overall, the surface morphological analysis via FESEM suggests that alkaline-treated BCTW is more advantageous, as it facilitates the removal of natural impurities and results in improved fiber separation and surface texture, contributing to better mechanical properties.



(a) (b)

Fig. 3 *Surface morphology of alkaline-treated BCTW at (a) 2000x magnification; (b) 6500x magnification*

3.1.3 Fourier Transform Infrared Spectroscopy Analysis of Untreated and Alkaline-Treated BCTW

Fig. 4 illustrates the FT-IR spectroscopy analysis comparing spiral peaks of untreated and alkaline-treated BCTW, highlighting the effects of alkaline treatment on chemical transformations in textiles. The analysis reveals distinct shifts in functional group peaks, indicating structural changes. Both spectra show absorption peaks at 3200-3400 cm-1, corresponding to the stretching of hydroxyl (O-H) groups in cellulose, hemicellulose, and lignin. The alkaline treatment reduces peak intensity, suggesting moisture removal and increased exposure of cellulose hydroxyl groups. In the region of 2850-2920 cm-1, peaks correlate with methyl (C-H) groups, while the 1720-1740 cm-1 range indicates carbonyl (C=O) stretching, confirming the loss of hemicellulose and pectin [21]. Notably, the reduced intensity of peaks around 1630-1650 cm-1 signifies the removal of hemicellulose and lignin, while peaks near ~1030 cm-1 reflect stretching vibrations of C-O and C=C groups linked to glycosidic bonds in cellulose. Overall, the spectral differences between untreated and alkaline-treated BCTW indicate increased cellulose purity and crystallinity post-treatment, essential for enhancing material density and improving the mechanical properties of resulting composite materials [19].

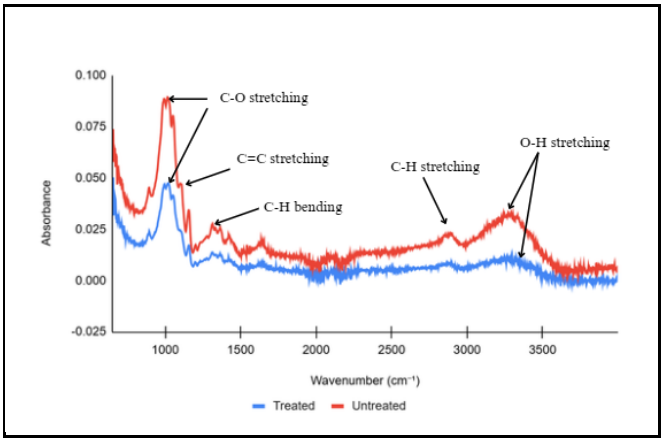


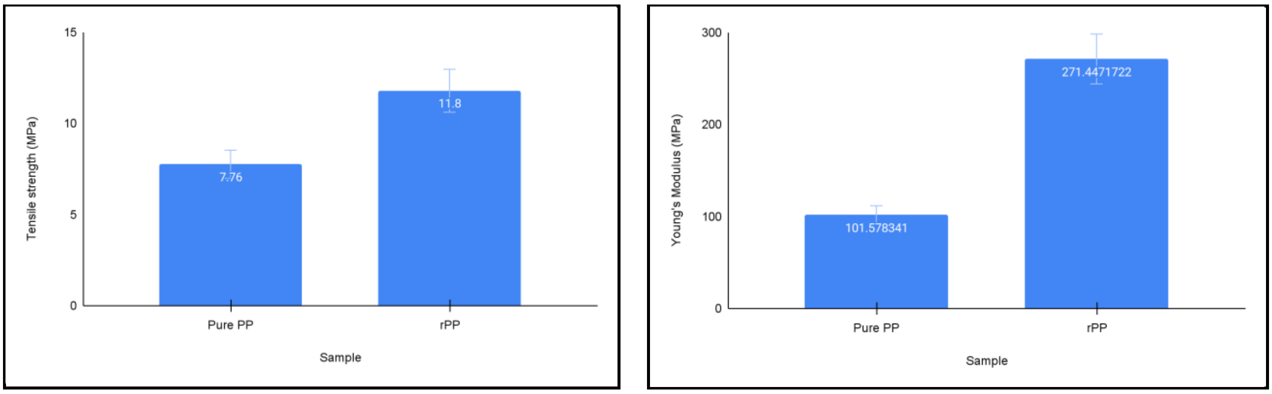
Fig. 4 *FT-IR analysis of untreated and alkaline-treated BCTW*

3.2 Mechanical Properties

In this section, the mechanical analysis such as tensile strength, Young's modulus, and elongation at break of pure PP, rPP, and various content of both alkaline-treated and untreated BCTW reinforced polypropylene composite are discussed.

3.2.1 Mechanical Properties of Pure and Recycled Polypropylene

Figure 5 (a) and (b) display a bar chart demonstrating significant differences in properties between pure polypropylene (PP) and recycled polypropylene (rPP). Young's modulus, a measure of a material's resistance to elastic deformation, indicates that rPP possesses higher tensile strength and Young's modulus than pure PP. This enhancement in rPP is attributed to increased crystallinity achieved through repeated thermal cycles during the recycling process, where mechanical and thermal stresses lead to chain scission, resulting in shorter polymer chains [11]. Shorter chains tend to have greater mobility, allowing them to reorganize into crystalline structures more easily, further augmented by the presence of fillers or nucleating agents that contribute to increased crystallinity and material stiffness [9]. Conversely, Figure 6 showcases an analysis of elongation at break, assessing the ductility of both materials. Pure PP exhibits a higher elongation at break compared to rPP, indicating that pure PP is ductile and capable of substantial plastic deformation. In contrast, rPP is described as brittle, as chain scission results in shorter chains that are unable to maintain entanglement under tension, leading to immediate fracture upon reaching their limits [11].



(a) **(b)**

Fig. 5 *(a) Tensile strength; (b) Young's modulus of pure and recycled PP*

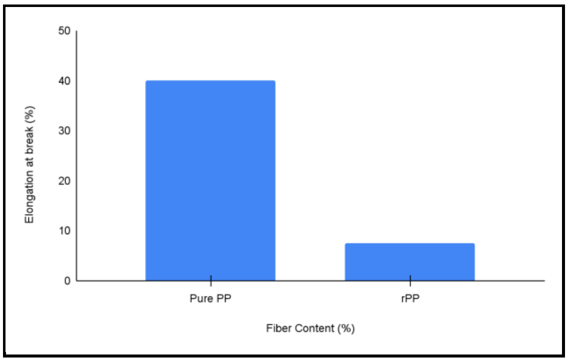
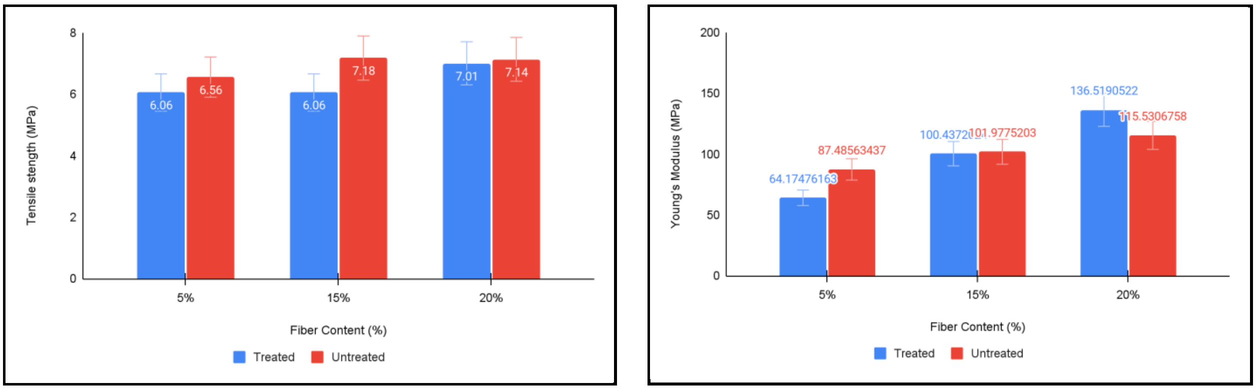


Fig. 6 *Elongation at break between pure and recycled PP*

3.2.2 Mechanical Properties of Untreated and Alkaline-Treated BCTW Reinforced rPP Composite

Fig. 7 (a) illustrates the tensile strength comparison between untreated and alkaline-treated BCTW reinforced rPP composites with varying fiber textile loadings, showing that 20% BCTW reinforcement yields higher tensile strength than 5% and 15%. This is attributed to effective stress transfer due to better fiber distribution in the composite matrix. MAPP plays a crucial role in enhancing mechanical strength by reducing fiber pull-out through robust chemical bonding with fiber surfaces [20]. Conversely, untreated rPP composites display unexpected high tensile strength, likely due to an uneven fiber-rPP ratio after alkaline treatment, which increases fiber weight loss and leads to poor adhesion during compression molding. The alkaline-treated composites show significant tensile strength improvement due to enhanced fiber-matrix adhesion.

Fig. 7 (b) presents the Young's modulus findings, indicating that both untreated and alkaline-treated BCTW-rPP composites exhibit increased stiffness with higher fiber content, with the alkaline-treated 20% composite achieving the highest Young's modulus. This increase is linked to the removal of natural surface components like hemicellulose and lignin, which facilitates better mechanical interlocking at the fiber-matrix junction, thereby enhancing rPP's elastic deformation resistance [23]. Meanwhile, Fig. 8 compares elongation at break, revealing that the 5% BCTW-rPP composite possesses the highest elongation before fracture, while composites with higher fiber contents (15% and 20%) show reduced elongation. This reduction is due to the increased rigidity of the fiber textiles, which restricts rPP molecular mobility and contributes to brittleness. Additionally, higher BCTW weights lead to weak interfacial bonding, making fibers prone to pull-out upon elongation. Alkaline treatment causes higher strength and stiffness but decreases the elongation at break due to increased fiber brittleness [10].



(a) **(b)**

Fig. 7 (a) *Tensile strength; (b) between untreated and alkaline-treated BCTW-rPP composite*

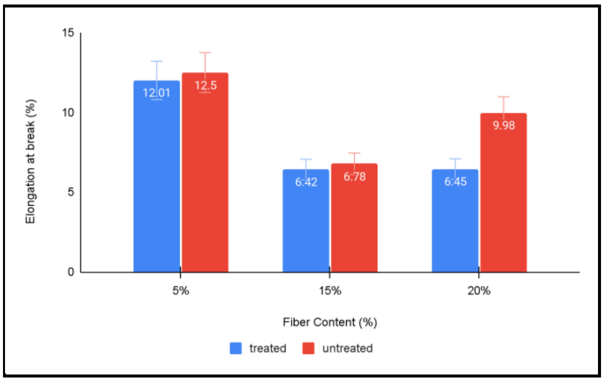


Fig. 8 *Elongation at break between untreated and alkaline-treated BCTW-rPP composite*

3.3 Thermal Properties

In this section, the thermal analysis of pure PP, rPP, and untreated and alkaline-treated BCTW reinforced rPP composites through differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA) are discussed.

3.3.1 Differential Scanning Calorimetry Analysis of rPP, Untreated and Alkaline-Treated BCTW-rPP Composite

Table 3 compares melting temperatures, heat of fusion, and crystallinity degrees between rPP, untreated, and alkaline-treated BCTW reinforced rPP composites at varying fiber contents. The melting temperature (Tm) remains stable across all samples, but lower than pure polypropylene (~160-170°C), indicating thermal stability is affected by chemical treatment and fiber loading (5%-25%) due to chain scission. The degree of crystallinity (Xc) shows more variability, while rPP exhibits the highest crystallinity at 46.1%, attributed to high temperatures and shear during processing leading to shorter polymer chains [11]. For treated BCTW-rPP composites, the 5% fiber loading shows the highest crystallinity at 31.2%, which declines to 17.5% with increasing fiber content. This indicates that lower fiber contents allow BCTW to act as effective nucleating agents, while higher contents inhibit polymer chain mobility and crystal growth. Untreated samples with 15% BCTW show a crystallinity of 30.71%, suggesting that alkaline treatment enhances nucleation at lower fiber content by removing non-cellulosic materials. It is noted that the crystallinity of rPP can exceed that of pure PP due to the increased mobility of degraded chains forming crystals [9].

Table 3 *DSC data of rPP, untreated and treated BCTW-rPP composites*

Sample	**rPP**	**Treated BCTW-rPP**			**Untreated BCTW-rPP**		
		5%	**15%**	**25%**	**5%**	**15%**	**25%**

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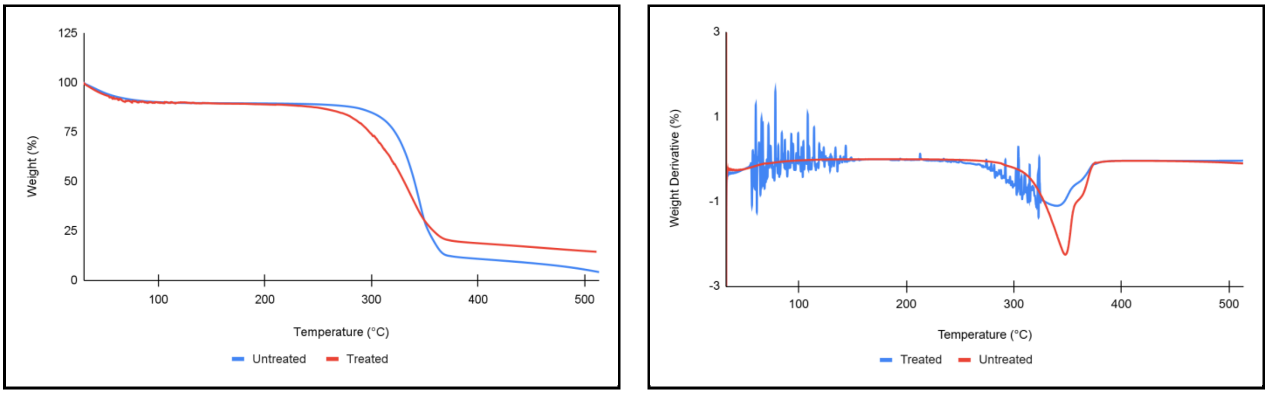
Melting Temperature (℃)	121.88	122.17	122.14	122.03	122.29	121.97	121.91
Heat of Fusion (J/g)	57.35	65.13	59.19	36.52	52.88	63.57	44.13
Degree of Crystallinity (%)	46.1	31.2	28.3	17.5	25.55	30.71	21.32

3.3.2 Thermogravimetric Analysis of Untreated and Alkaline-Treated BCTW

Fig. 9 (a) compares the thermal gravimetric (TG) behavior of untreated and alkaline-treated BCTW, revealing initial weight loss under 100°C attributed to evaporation of adsorbed water. The untreated BCTW demonstrates a clear onset of degradation due to higher moisture retention from hydrophilic components like hemicellulose, lignin, waxes, and surface impurities [14]. In contrast, the alkaline-treated BCTW shows reduced weight loss in this range, indicating lower moisture retention after the removal of impurities and partial elimination of hemicellulose, leaving a cellulose-rich residue with increased crystallinity. This leads to a main degradation phase observed between 300°C to 400°C, marked by the depolymerization of cellulose chains [19]. [9] emphasizes that the removal of non-cellulosic components raises the activation energy for thermal decomposition. Fig. 9 (b) illustrates the differential thermal gravimetric (DTG) curve, where the treated BCTW presents significant variations at lower temperatures due to residual moisture effects from the alkaline treatment. Across 250°C to 400°C, the untreated BCTW shows a sharper peak, indicating rapid cellulose degradation, while the treated BCTW has a broader peak, reflecting a slower weight loss rate potentially linked to structural modifications [21]. Both samples attain thermal stability beyond 400°C, signaling slow degradation of lignin and char formation [14].

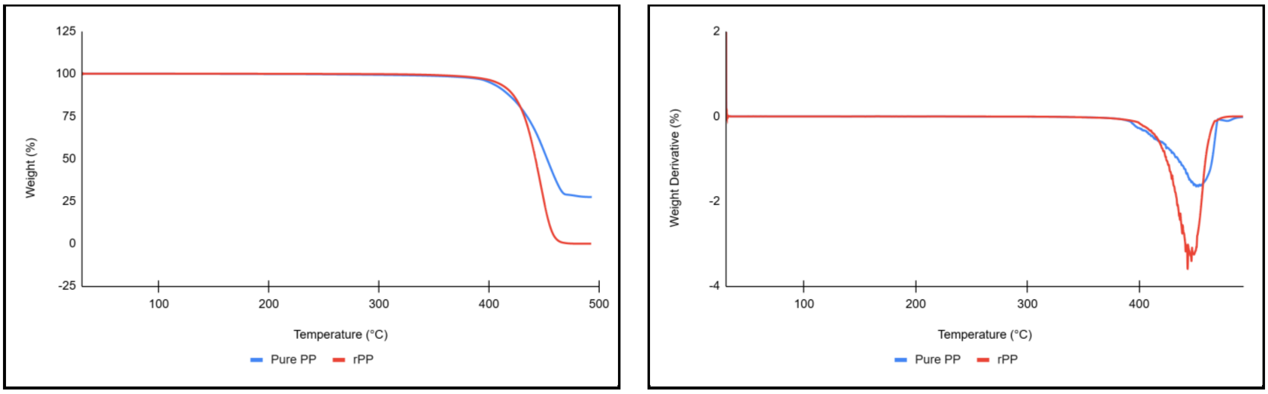


(a) **(b)**

Fig. 9 *(a) TG curve, (b) DTG curve of untreated and alkaline-treated BCTW*

3.3.3 Thermogravimetric Analysis of Pure and Recycled Polypropylene

Fig. 10 (a) shows the TG curve of pure PP and rPP that highlights the percentage of weight loss of a material. The graph shows the rate of weight loss begins at a temperature of ~400°C. A sharp decline can be observed on rPP samples indicating an earlier onset of degradation. This suggests that chain scission has reduced the energy barrier for thermal decomposition [1]. By approximately ~450°C, the rPP has achieved complete volatilization. Meanwhile, pure PP exhibits a gradual slope of decomposition and exhibits char formation at approximately 25-30% at ~500°C. [14] stated that the remaining residue at the end of TGA analysis is mainly carbonaceous char and inorganic ash. This indicates that pure PP may contain inorganic fillers or other components that do not volatilize at these temperatures. Fig. 11 (b) demonstrates the DTG curve of pure PP and rPP. At approximately 420-440°C, the rPP exhibits a sharp peak indicating a very high rate of weight loss, while pure PP shows a more shallow and broad peak with a slightly lower T_{maz} compared to rPP, followed by plateau. This implies that pure PP has a more complex degradation environment which is caused by the presence of additives that shift the kinetics of chain scission.



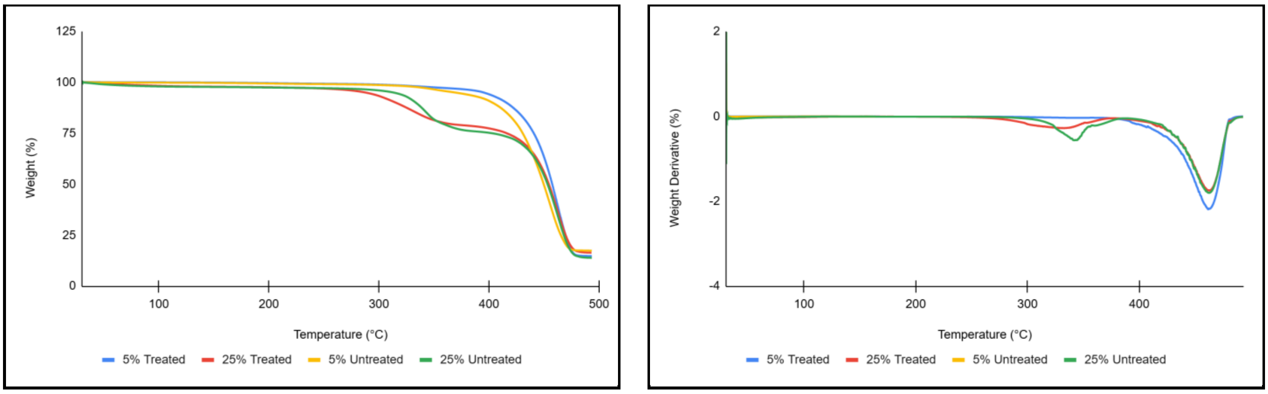
(a) **(b)**

Fig. 10 *(a) TG curve, (b) DTG curve of pure PP and rPP*

3.3.4 Thermogravimetric Analysis of Untreated and Alkaline-Treated BCTW-rPP Composite

Figure 11(a) presents the thermogravimetric (TG) curves of untreated and alkaline-treated BCTW reinforced rPP composites, elucidating their thermal behavior across varying conditions. The alkaline-treated 5% BCTW reinforced rPP composite shows minimal weight loss below 100°C due to residual moisture evaporation, while the polymer matrix ensures thermal stability at low fiber loading. Significant degradation occurs between 380-450°C, associated with polypropylene (PP) thermal decomposition. In contrast, the untreated 5% BCTW composite demonstrates good thermal stability at lower temperatures, but experiences substantial weight loss between 310-460°C, indicating the thermal influence of the rPP matrix and the minimal residues from lignocellulosic fibers impacting char formation. This enhancement can be attributed to the addition of MAPP, which strengthens the chemical bond at the fiber-matrix interface, leading to a slight delay in weight loss [14]. The alkaline-treated 25% BCTW reinforced rPP composite reveals a more intricate degradation pattern with noticeable weight loss below ~270°C, indicative of cellulose and hemicellulose thermal decomposition from the treated BCTW. The degradation shows major weight losses beginning at approximately 290°C, tapering to complete weight loss around ~480°C. The untreated 25% BCTW reinforced rPP composite exhibits a similar thermal degradation behavior to its alkaline-treated counterpart, demonstrating thermal stability below 270°C as lignocellulosic components decompose.

Figure 11(b) illustrates the derivative thermogravimetry (DTG) curve indicating weight loss rates, with peaks correlated to the degradation rate of specific components. The alkaline-treated 5% BCTW reinforced rPP composite shows superior thermal stability, marked by a large DTG peak at ~470°C, signifying effective removal of amorphous components via alkaline treatment. This treatment enhances the crystallinity of natural fibers and shifts the degradation onset to higher temperatures [14], [16]. The alkaline-treated 25% composite showcases distinct thermal decomposition behavior, with prominent degradation peaks between 290°C to 390°C, followed by a gradual decline around ~450°C related to fiber textile weight loss. This peak results from α-cellulose degradation, suggesting improved thermal stability due to the removal of low molecular weight compounds [13], [16]. For the untreated 5% BCTW reinforced rPP composite, the DTG curve reflects an earlier degradation onset due to untreated hemicellulose starting to degrade between 210-270°C, leading to wider initial peaks. Poor interfacial bonding is attributed to a lack of chemical modification, accelerating the degradation of the polymer matrix [12], [14]. The untreated 25% BCTW reinforced rPP composites display a broad peak at ~340°C, indicating rapid weight loss due to untreated fiber components like cellulose and lignin, which diminish thermal resistance due to high moisture content and active pyrolysis from significant fiber loading [6].



(a) **(b)**

Fig. 11 *(a) TG curve, (b) DTG curve of untreated and alkaline-treated BCTW-rPP composite*

4. Conclusion

In conclusion, the present work has effectively signified using bamboo-cotton textile waste (BCTW) as reinforcement into recycled polypropylene (rPP) matrix for developing an eco-packaging sustainable material. Existing industrial textile and plastic waste could be technically incorporated, resulting in composites with maintained mechanical and thermal properties. Meanwhile, alkaline (NaOH) treatment of BCTW is one of the significant contributions towards its improvement because it removes amorphous components such as lignin and hemicellulose from FTIR and FESEM analysis, on making it rougher fiber surface. This modification, combined with the addition of a MAPP compatibilizer, significantly enhanced the mechanical interlocking and interfacial bonding between the fibers and the matrix. The 20% BCTW loading was also found to be the best trade-off for mechanical properties, as we achieved in this way maximum tensile strength before agglomeration of fibers above that concentration. Thermal studies using TGA and DSC also revealed that alkaline treatment enhanced the thermal resistance of the composites to be compatible with common processing methods. Finally, through the avoidance of textile and plastic waste in landfills and less dependency on virgin polymers, this work contributes to moving from a linear to a circular economy. The BCTW-reinforced rPP composites are a competitive, environmental-friendly substitution of traditional packaging materials and lay down solid groundwork for upcoming innovations in eco-friendly technology. By successfully upcycling industrial waste into high-value applications, this research contributes significantly to circular economy goals and provides a practical framework for sustainable material engineering.

Acknowledgement

I would like to express my sincere gratitude to my project supervisor, Dr. Mazatusziha binti Ahmad, for her continuous support, invaluable guidance, and constructive feedback throughout this research journey. I want to thank Universiti Tun Hussein Onn Malaysia (UTHM) for providing financial support and an ideal research environment to accomplish this project.

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