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The Effects of Natural Weathering on the Mechanical and Thermal Properties of rPP/MAH-g-PP/Bamboo Textile Waste Composites

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Abstract

The increasing amount of plastic and textile waste has intensified the need for sustainable composite materials made from recycled sources. The study investigates the natural weathering effects on the mechanical and thermal properties of MAPP-compatibilized bamboo textile waste-reinforced recycled polypropylene composites. The objectives were to characterize alkali-treated bamboo textile waste fibers and to evaluate the mechanical and thermal properties of MAPP-compatibilized bamboo textile waste-reinforced recycled polypropylene composites. Alkali treatment was conducted using NaOH to modify fiber surfaces followed by composite fabrication through internal mixing and compression molding with fiber loadings of 5, 15, and 25 wt%. Characterization of fibers was carried out using FTIR and SEM. Mechanical properties were tested through tensile testing on Young's modulus, tensile strength, and elongation at break while thermal behavior was tested using thermogravimetry analysis and differential scanning calorimetry. Natural weathering exposure was conducted for 7 days. Results showed that alkali treatment effectively removed surface impurities and increased roughness of fiber surface, enhancing the fiber-matrix interaction. Unweathered composites showed better tensile properties with increasing fiber loadings while weathered composites were weaker due to photo-oxidative degradation and moisture ingress. TGA analysis shows reduction in initial degradation temperature and peak decomposition temperature for weathered composites, while DSC analysis indicated reduced melting enthalpy and increasing crystallinity. The composite containing 15 wt% fiber loading exhibited the best balance between performance and practicality of use compared to the composite containing 5 and 15 wt%. It can be concluded that natural weathering adversely effects the mechanical and thermal properties of bamboo textile waste-reinforced recycled polypropylene for long-term

performance, highlighting the need for further stabilization for outdoor applications.

1. Introduction

Due to the buildup of plastic waste in landfills and natural ecosystems, the fast expansion of plastic manufacture in the past few decades has raised serious environmental issues. Polypropylene (PP) is one of the most used thermoplastic polymers due to its low density, strong mechanical qualities, chemical resistance, and ease of production. A significant portion of the world's plastic waste is composed of PP where it makes up about 19.1% of all plastic waste produced worldwide [1]. Additionally, PP is the second most utilized plastic across the globe after polyethylene and is predominantly disposed of in landfills [2].

A potential approach to lessen the reliance on virgin polymers and minimize the environmental effect is by utilizing recycled polypropylene (rPP). However, polymer degradation resulting from repeated processing and recycling cycles such as oxidation, chain scission, and crystallinity changes limit the use of rPP in products requiring high-performance in outdoor settings [3]. These degradation processes weaken the mechanical properties, thermal stability, and long-term durability of rPP which restricts it use in harsh or extended service conditions, especially in outdoor settings where materials are subjected to UV radiation, moisture, and temperature fluctuations.

A possible method to counteract these detrimental effects is the addition of natural fiber reinforcements such as bamboo textile waste from the textile industry that utilizes bamboo fibers to produce garments and apparel. Despite its potential, this waste stream is extremely underutilized, contributing to more solid waste problems. Repurposing bamboo textile waste as a reinforcing ingredient in natural fiber-reinforced rPP composites is a sustainable option that adheres to the principles of circular economy. However, poor interfacial adhesion between the hydrophilic bamboo textile waste fibers and the hydrophobic rPP matrix causes inefficient stress transfer, moisture ingress, and degradation of the mechanical and thermal properties of the composite frequently limits its effectiveness.

The addition of maleic anhydride-grafted polypropylene (MAPP) is frequently used to enhance the fiber-matrix interaction in PP-based composites. There has been few research on the long-term weathering effects on the MAPP-compatibilized bamboo textile waste-reinforced rPP composites despite numerous studies have shown how effective MAPP is in improving the mechanical and thermal properties of natural fiber-reinforced PP composites. It is yet unclear how recycling-induced deterioration, compatibilization, natural fiber reinforcing, and environmental weathering interact with each other. Thus, there is a glaring lack of knowledge regarding how environmental weathering affects the mechanical and thermal characteristics of rPP composites reinforced with bamboo textile waste, especially those treated with MAPP. To assess the robustness, dependability, and possible outdoor use of such sustainable composite materials, it is imperative to close this gap.

2. Research Methodology

2.1 Fabrication of rPP/MAH-g-PP/bamboo textile waste composites

rPP was obtained from local recycling centres located in Pagoh, Johor. The collected rPP was washed with water and detergent to remove impurities and left to dry at room temperature. The dried rPP was chopped into manageable pieces and grinded into powder. White bamboo textile waste was obtained from local stores in the form of sheets of fabric. The bamboo textile waste was cut into small 1 cm x 1cm to allow it to easily brake into individual fibers when soaked during alkaline treatment. The cut bamboo textile waste was soaked in 5 wt% NaOH solution for 2 hours. The bamboo textile waste fibers were rinsed with distilled water until a neutral pH was observed at the discharge water.

Three formulation designs were made with different bamboo textile waste fiber loadings as shown in Table 1. The rPP, MAPP, and bamboo textile waste fibers were compounded into a composite using an internal mixer set at 180°C for 10 minutes. The composites were grinded into small and manageable pieces using a grinder machine before compressed into square-shaped sheets using a compression molding machine set at 220°C and compressed for 10 minutes. The square sheets were cut into dumbbell-shaped specimens adhering to the ASTM D638 standard measuring 155 mm long, 19 mm wide at the heads, and 6 mm wide at the middle, narrow section using a laser cutter machine.

Table 1 *Formulation matrix used in this study*

Formulation ID	rPP, wt%	Bamboo Textile Waste Loading, wt %	MAPP, wt%
rBTW-5	90	5	5
rBTW-15	80	15	5

rBTW-25	70	25	5

2.2 Characterization of bamboo textile waste fibers

The characterization of alkali-treated bamboo textile waste fibers was conducted to confirm the effects of alkali treatment towards the bamboo textile waste fibers. A scanning electron microscope (SEM) was employed to analyze the surface microstructure of the treated and untreated bamboo textile waste fibers to compare and highlight the differences between them. The SEM images produced were also used to confirm the removal of hemicellulose and lignin from the surface of the bamboo textile waste fibers after alkali treatment which implies a successful treatment.

A Fourier transform infrared spectroscopy (FTIR) was employed to provide qualitative data and to observe structural alterations between the treated and untreated bamboo textile waste fibers by examining the presence of specific chemical bonds such as C-O, C-C, O-H, and C=O bands. The scanning parameters was set between 400 cm^{-1} and 4000 cm^{-1} with a resolution of 4 cm^{-1}. SEM and FTIR analyses will further prove the successful removal of hemicellulose and lignin from the surface of the bamboo textile waste fibers, indicating the effectiveness of the alkali treatment.

2.3 Natural weathering exposure

The fabricated rPP/MAH-g-PP/bamboo textile waste composites were subjected to natural weathering for 7 days in compliance with the ASTM D1435 standard to assess their environmental endurance. The exposure to natural weathering was conducted at Pagoh Campus Residential College, Universiti Tun Hussein Onn Malaysia (UTHM) Pagoh Campus located in Pagoh, Johor, Malaysia with approximate coordinates 2.143986 °N, 102.727890 °E which is a region characterized by a tropical rainforest climate.

The site experiences high solar irradiance, frequent rainfall, high humidity with values often exceeding 80%, and temperatures fluctuations ranging from 22°C to 35°C. This made the site suitable for evaluating the effects of UV radiation exposure and moisture ingress towards the rPP/MAH-g-PP/bamboo textile waste composites. Samples were mounted on an outdoor exposure rack where they were oriented at a 45° angle facing the equator. The exposure rack was installed and exposed in an open area free from shading or obstructions with great airflow and full exposure to sunlight and rain.

2.4 Mechanical properties testing

Tensile characteristics of the rPP/MAH-g-PP/bamboo textile waste composites such as the Young's modulus, tensile strength, and elongation at break were assessed using the ASTM D638 standard. The specimens will be fitted into a universal testing machine (UTM) with a 10kN load cell and a crosshead speed of 5 mm/min. The Young's modulus, tensile strength, and elongation at break of the samples were automatically measured and calculated by the UTM software.

2.5 Thermal properties testing

Thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) were used to determine the thermal characteristics of the rPP/MAH-g-PP/bamboo textile waste composites. The TGA machine was fitted with 7 mg of the composite at different bamboo textile waste fiber loadings, and the temperature range was set at 30°C to 500°C with a heating rate of 10°C/min. The test was conducted in an inert environment using nitrogen gas as the inert gas. The initial decomposition temperature, $T_{10\%}$, peak of decomposition temperature, T_p, and amount of final residue at 500°C of the composites were obtained.

For DSC testing, 6 mg of the composite at different bamboo textile waste fiber loadings were fitted into the DSC machine and heated to 200°C at a rate of 10°C/min. Following the first heating cycle, the samples were cooled at a rate of 10°C/min and heated again to examine the composites' melting and crystallization behavior. The test was conducted in an inert environment using nitrogen gas as the inert gas. The glass transition temperature, T_g, melting temperature, T_m, and the melting enthalpy, ΔHm of each composite were obtained from the DSC thermograph. The degree of crystallinity, χc of the composites was calculated using the Equation 1 where $\mathbf{\Delta H_m^0}$ is the melting enthalpy of 100% pure crystalline PP and $\mathbf{w_f}$ is the weight fraction of the bamboo textile waste fibers in the composite. The $\mathbf{\Delta H_m^0}$ was kept constant at a value of 204 J/g.

$$\chi c\ (\%) = \frac{\Delta Hm}{\Delta H_m^0 (1 - w_f)} \times 100 \quad (1)$$

3. Results and Discussions

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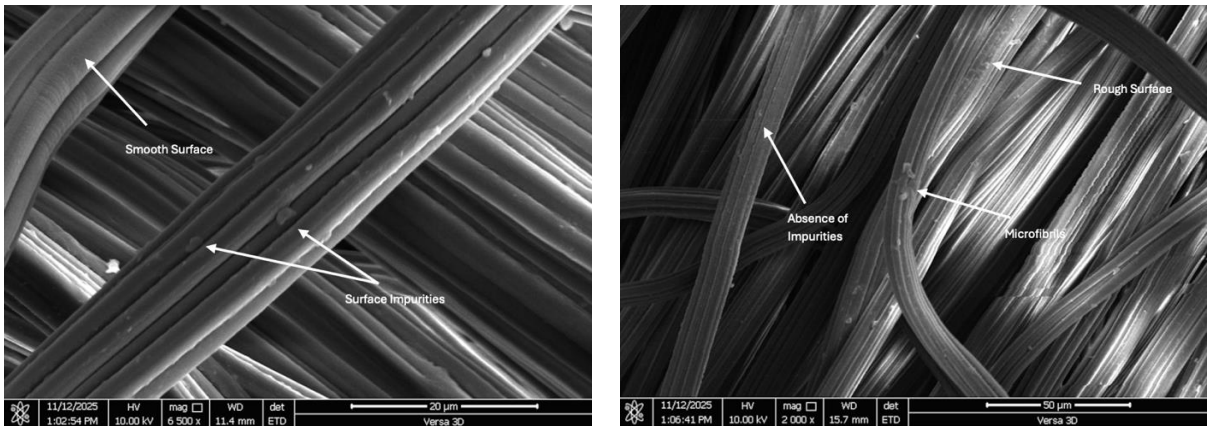
3.1 Morphological analysis of bamboo textile waste fibers

SEM was used to examine the surface morphology of bamboo textile waste fibers to assess the physical changes caused by alkaline treatment. Figure 1 shows the micrograph of (a) untreated and (b) treated bamboo textile waste fibers.



(a) **(b)**

Fig. 1 *SEM micrograph of (a) untreated and (b) treated bamboo textile waste fibers*

The surface of the untreated fibers appears relatively smooth and compact, with the presence of several surface impurities and non-cellulosic materials adhered to the fiber surface. These contaminants are frequently linked to elements that are found naturally on bamboo fibers, such as hemicellulose, lignin, waxes, pectin, and leftover textile manufacturing chemicals. The untreated bamboo textile waste fiber micrograph showed a flat and smooth surface morphology indicating little surface roughness which prevents efficient mechanical interlocking when the fibers are integrated into the rPP matrix [4]. Furthermore, contaminants and foreign surface coatings hinders interfacial bonding which lowers the effectiveness of stress transfer between the fibers and polymer matrix [5] [6].

Conversely, treated bamboo textile waste fibers show a surface morphology that is considerably rougher and more textured than its untreated counterpart. The alkali treatment has successfully eliminated a large amount of surface contaminants, exposing cellulose microfibrils caused by fibrillation [7]. The development of surface imperfections improves mechanical locking which aids in fiber-matrix adhesion [4].

3.2 FTIR spectra of bamboo textile waste fibers

FTIR spectroscopy was conducted to investigate the chemical structure and the presence of functional groups in untreated and treated bamboo textile waste fibers. Figure 2 shows the FTIR spectra for untreated and treated bamboo textile waste fibers.

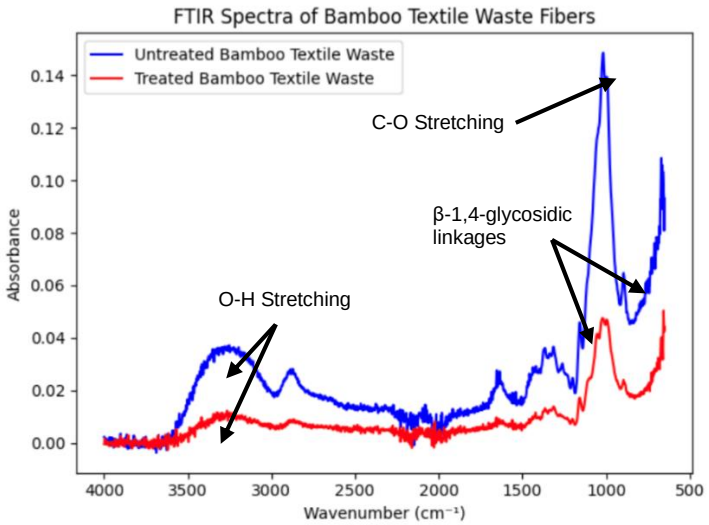


Fig. 2 *FTIR spectra of untreated and treated bamboo textile waste fibers*

In both untreated and treated bamboo textile waste fibers, a broad absorption band was observed at approximately 3600 cm^{-1} to 3200 cm^{-1} which is correlated to the O-H stretching contained in hydroxyl groups present in hemicellulose and cellulose [22]. The untreated bamboo textile waste fibers showed a more intense and broader O-H band with the presence of peaks at around 3483.09 cm^{-1} to 3430.87 cm^{-1}, indicating a higher amount of hydroxyl groups and stronger hydrogen bonding [22]. This aligns with the characteristics of untreated bamboo fibers which are hydrophilic due to the large amounts of free hydroxyl groups present within the fibers.

Conversely, the treated bamboo textile waste fibers showed a large reduction in the intensity and broadness of the O-H stretching band. This significant reduction showed the partial removal of hemicellulose and surface impurities induced by the alkaline treatment. The diminished O-H band showed that the alkaline treatment has successfully reduced the hydrophilicity of the bamboo textile waste fibers which is good for improving the interfacial compatibility with the hydrophobic PP matrix for the composite fabrication process [23].

The presence of weak absorption bands in the region between 3000 cm^{-1} to 2800 cm^{-1} correspond to the C-H stretching vibrations of -CH and -CH_2 groups present in lignin and cellulose [22]. These peaks are present in both the treated and untreated bamboo textile waste fibers spectra, indicating that the polysaccharide backbone of the fibers remain intact even after alkaline treatment. The absence of strong carbonyl C=O absorption at around 1370 cm^{-1} in spectra of treated bamboo textile waste fibers showed the effective partial removal of hemicellulose from the fibers which contains acetyl and ester functional groups that contribute to carbonyl absorption [25].

The fingerprint region of the FTIR spectra between 1500 cm^{-1} to 500 cm^{-1} provides the most significant information regarding structural changes of the bamboo textile waste fibers induced by the alkaline treatment. Both treated and untreated bamboo textile waste fibers show prominent peaks in the range between 1200 cm^{-1} to 1000 cm^{-1} which are the characteristic of C-O and C-O-C stretching vibration of cellulose [24]. Absorptions bands at around 1156 cm^{-1} and 894 cm^{-1}, are attributed to the β-1,4-glycosidic linkages in cellulose, where the peak at 1156 cm^{-1} is associated with glucose ring vibrations, and the peak at 894 cm^{-1} is associated with C-O-C ether linkage of the β-1,4 bond [24]. Peaks shown at around 1042 cm^{-1} to 1016 cm^{-1} correspond to the C-O stretching vibrations of the primary and secondary alcohol groups in cellulose. The treated bamboo textile waste fibers show a more intense and sharper peaks in this region compared to its untreated counterparts. This suggests that the removal of hemicellulose leads to a more ordered, cellulose-rich structure within the bamboo textile waste fibers [24].

Overall, the FTIR spectra show that the alkaline treatment successfully modified the surface chemistry of bamboo textile waste fibers without affecting the cellulose backbone within the fibers. The reduction of the hydroxyl band intensity along with the weakened hemicellulose associated peaks and sharpening of cellulose related peaks indicate a successful removal of non-cellulosic components from the fibers and an increase of cellulose dominance.

3.3 Mechanical properties of rPP/MAH-g-PP/bamboo textile waste composites

To support the discussion on natural weathering effects on the weathered composites, the weather conditions of Pagoh, Johor, Malaysia throughout the exposure period were recorded and summarized as presented in Table 2.

Table 2 *Weather conditions of Pagoh, Johor, Malaysia throughout exposure period*

Date & Day	Tmin, °C	Tmax, °C	Weather Condition	Wind Speed Range, km/h	Minimum Humidity, %	Maximum Humidity, %
22 Dec 2025 (Monday)	24	32	Partly cloudy	4 – 13	55	89
23 Dec 2025 (Tuesday)	25	33	Partly cloudy	6 – 9	55	94
24 Dec 2025 (Wednesday)	24	33	Partly cloudy, light rain	6 – 14	56	94
25 Dec 2025 (Thursday)	25	31	Partly cloudy, thunderstorm	5 – 9	66	94
26 Dec 2025 (Friday)	24	31	Partly cloudy, thunderstorm	5 – 8	66	100
27 Dec 2025 (Saturday)	24	28	Thunderstorm	7 – 10	84	100
28 Dec 2025 (Sunday)	24	26	Partly cloudy, light rain	6 – 8	89	100

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The mechanical properties of rPP/MAH-g-PP/bamboo textile waste composites were determined on their Young's modulus, tensile strength, and elongation at break. The test was conducted for composites prior and after exposure to natural weathering for 7 days. Figure 3 illustrates the (a) Young's modulus, (b) tensile strength, and (c) elongation at break data for the composites.

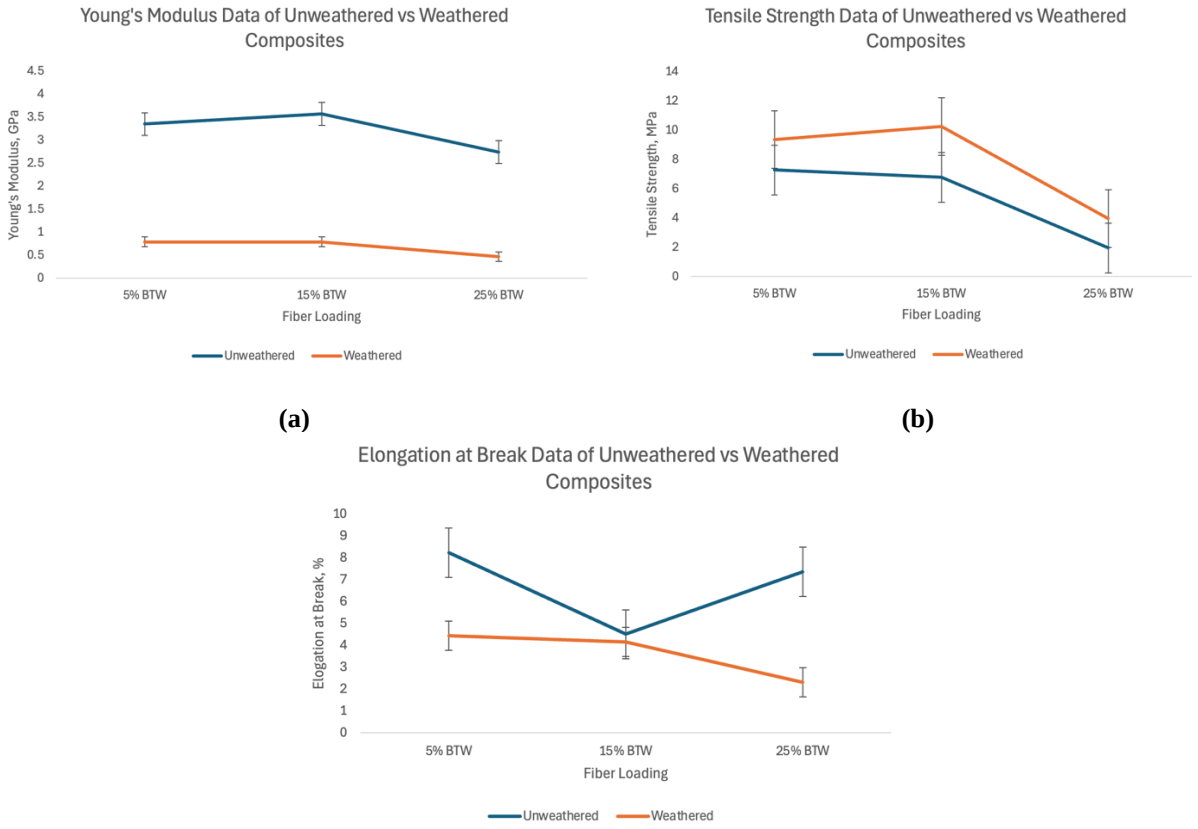


Fig. 3 *The (a) Young's modulus, (b) tensile strength, and (c) elongation at break of rPP/MAH-g-PP/bamboo textile waste composites*

3.3.1 Young's modulus of composites

The Young's modulus of the unweathered rPP/MAH-g-PP/bamboo textile waste composites increased from 3.35 GPa at 5 wt% bamboo textile waste fiber loading to a maximum of 3.57 GPa at 15 wt%, followed by a large decrease to 2.74 GPa at 25 wt%. This value trend showed that moderate incorporation of treated bamboo textile waste fibers successfully enhanced the stiffness of the composite due to better stress transfer efficiency and fiber dispersion within the composite. At higher bamboo textile waste fiber loadings, the decrease in Young's modulus is associated with non-uniform fiber dispersion and morphological defects [8]. This weakens the fiber-matrix adhesion and produces void regions in the composite, further weakening its mechanical properties even when compatibilized with MAPP [9].

Following 7 days of exposure to natural weathering, a large reduction in Young's modulus can be observed in all fiber loadings where it dropped to 0.79 GPa for composites with 5 wt% and 15 wt% and further decreased to 0.47 GPa for the composite with 25 wt% bamboo textile waste fiber loading. This reduction in stiffness was attributed to environmental degradation including ultraviolet (UV) radiation exposure, moisture ingress, and temperature fluctuations. Exposure to UV radiation from sunlight promotes photo-oxidative degradation of the rPP matrix which leads to chain scission reactions. This reduces the molecular weight of the rPP matrix and leads to embrittlement [10].

Simultaneously, moisture ingress through the hydrophilic bamboo textile waste fibers weakens the fiber-matrix interface even further which causes debonding and formation of microfractures within the composite. This effect is most severe at higher bamboo textile waste fiber loadings where increased fiber contents increase the number of pathways for moisture to penetrate and accelerates deterioration [11]. Additionally, the bamboo textile waste fibers swell when absorbing moisture from the surroundings which causes internal stress within the fiber-matrix interface [12].

3.3.2 Tensile strength of composites

The tensile strength of unweathered rPP/MAH-g-PP/bamboo textile waste composites decreased progressively with the increasing amount of bamboo textile waste fiber loadings from 7.29 MPa at 5 wt% to 6.78 MPa at 15 wt% and further down to 1.96 MPa at 25 wt%. This reducing trend showed that even though the addition of bamboo textile waste fibers may increase the stiffness of the composite, it does not necessarily improve the tensile strength of the composite itself. At higher bamboo textile waste fiber loadings, stress-concentration areas associated with fiber agglomeration and poor interfacial adhesion becomes dominant, leading to premature failure under tensile loading during testing [9].

In contrast, after exposure to natural weathering for 7 days, the tensile strength of the composites showed a different trend compared to their unweathered counterparts. The composite containing 15 wt% bamboo textile waste fiber loading exhibit the highest tensile strength at 10.25 MPa, followed by the 5 wt% composite at 9.36 MPa while the 25 wt% composite retained the lowest tensile strength at 3.98 MPa. The increase in tensile strength from 5 wt% to the 15 wt% composite after exposure to natural weathering for 7 days may be attributed to the rPP matrix embrittlement induced by photo-oxidation [10]. As the rPP matrix become stiffer and reduced in ductility, higher stresses can be sustained by the composite even though the overall toughness of the composite is reduced.

The inferior tensile strength exhibited by the composite with 25 wt% bamboo textile waste fiber loading showed the detrimental effects of excessive fiber loading under exposure to natural weathering. Severe fiber-matrix debonding combined with fiber swelling and microfractures due to moisture ingress accelerates the degradation of the composite [11] [12]. Results indicated that the composite containing 15 wt% bamboo textile waste fiber loading was able to provide the most favorable and promising balance between reinforcement efficiency from bamboo textile waste fibers and structural integrity both prior and after exposure to natural weathering.

3.3.3 Elongation at break of composites

The elongation at break of the rPP/MAH-g-PP/bamboo textile waste composites showed a non-linear trend with the increasing amount of bamboo textile waste fiber loading. The composite containing 5 wt% bamboo textile waste fiber loading displayed the highest elongation at break at 8.25%, exhibiting greater ductility due to the abundance of the rPP matrix. The elongation at break decreased to 4.51% at 15 wt% suggesting that the rPP polymer matrix chain mobility was restricted caused by the bamboo textile waste fiber reinforcement. The elongation increased to 7.36% at 25 wt% which may be associated with ununiform deformation and bamboo textile waste fiber pull-put occurring before the actual fracture of the composite occurs.

After exposure to natural weathering for 7 days, all composites showed a large reduction in elongation at break suggesting that they have become brittle. The elongation at break values decreased to 4.44%, 4.17%, and 2.32% for composites containing 5 wt%, 15 wt%, and 25 wt% bamboo textile waste fiber loadings, respectively. The reduction of elongation at break values may be attributed to the photo-oxidative degradation of the rPP matrix that limits plastic deformation [10]. Additionally, moisture ingress causes moisture-induced interfacial debonding which reduces the effective stress transfer distribution throughout the composite, leading to an earlier fracture under tensile loading [11] [12]. The most severe loss of elongation at break was observed in the composite containing 25 wt% bamboo textile waste fiber loading, indicating that high fiber loadings only worsen the brittleness of the composite after exposure to natural weathering.

3.4 Differential scanning calorimetry data of composites

DSC analysis was conducted to investigate the thermal transitions of rPP/MAH-g-PP/bamboo textile waste composites at different bamboo textile waste fiber loadings. The analysis emphasized on the glass transition temperature, T_g, melting temperature, T_m, melting enthalpy, ΔHm, and degree of crystallinity, χc of the composites which gives insights about the crystalline structure, polymer chain mobility, and the impact of fiber loading towards the composite's thermal properties. Table 3 shows the list DSC data obtained for the rPP/MAH-g-PP/bamboo textile waste composites, composing of the T_g onset, T_g midpoint, and T_g endset, T_m, ΔHm, and χc across all fiber loadings.

Table 3 *DSC data for the rPP/MAH-g-PP/bamboo textile waste composites*

Formulation ID	T_g Onset, °C	T_g Midpoint, °C	T_g Endset, °C	T_m, °C	ΔHm, J/g	χc, %
rBTW-5	35.01	35.63	36.09	123.16	-41.38	21.35
rBTW-15	21.86	22.53	23.12	122.61	-46.27	26.68
rBTW-25	23.23	25.26	25.64	121.96	-41.87	27.37

3.4.1 Melting temperature of composites

The T_m corresponds to the amount of thermal energy required to disrupt the crystalline structures of the rPP matrix. The melting peaks for the composites containing 5 wt%, 15 wt%, and 25 wt% bamboo textile waste fiber loadings were determined to be 123.2°C, 122.6°C, and 122.0°C, respectively. The comparatively small range of melting temperatures suggests that the crystalline lattice structure of the rPP matrix is not altered by the addition of the bamboo textile waste fibers [13]. This implies that for all fiber loadings, the crystalline structure of rPP maintain their structural integrity and chemical stability with minimal effects to the T_m of the composites [14].

3.4.2 Melting enthalpy and crystallinity trends

The ΔHm corresponds to the amount of thermal energy absorbed during melting and is directly related to the calculation of the degree of crystallinity, χc of the composites. The ΔHm of the rPP/MAH-g-PP/bamboo textile waste composites were determined to be -41.38 J/g, -46.27 J/g, and -41.87 J/g while the χc showed an increasing trend at 21.35%, 26.68%, and 27.37% for composites with 5 wt%, 15 wt%, and 25 wt% bamboo textile waste fiber loadings, respectively.

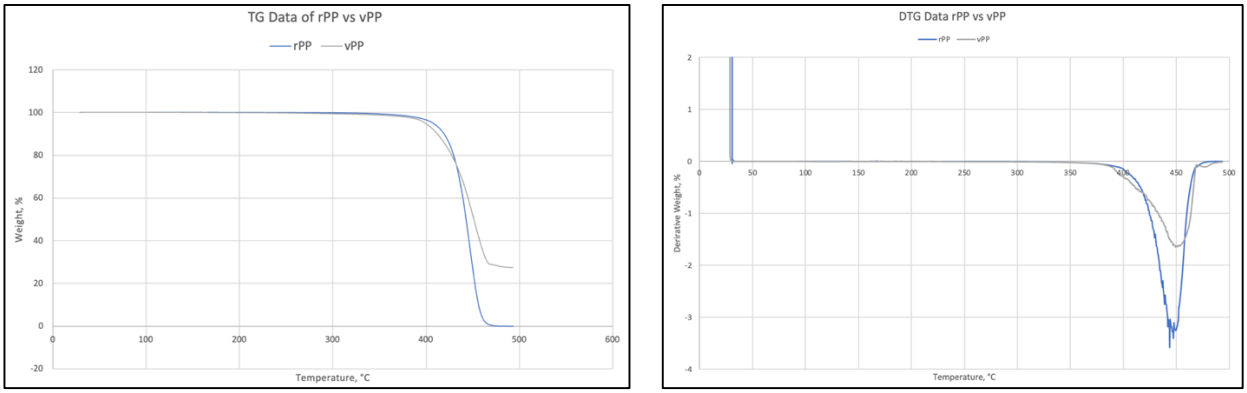
Natural fibers like bamboo textile waste fibers can act as nucleation sites during the cooling of the composites, also known as nucleating agents [15]. In semi-crystalline polymers like PP, crystallization is initiated by the formation of ordered regions called nuclei which will then grow into larger crystalline structures. The surface of bamboo textile waste fibers were suitable sites for rPP polymer chains to begin organizing into crystalline regions. Therefore, a higher fiber loading increases the number of nucleation sites available during solidification of the composites, increasing its χc value [16]. This was exhibited the composite containing 25 wt% bamboo textile waste fiber loading having the highest χc value while the composite with 5 wt% showing the lowest χc value. However, the extent of crystallinity is largely moderated by the mobility of the polymer chains in which beyond a certain amount of fiber content in the composite, the χc value will plateau due to the restriction of rPP matrix chain movement and fiber agglomeration [17].

3.5 Thermogravimetric analysis

In this section, the thermogravimetric analysis was focused on investigating the thermal decomposition of virgin PP (vPP) and rPP, untreated and treated bamboo textile waste fibers, including the rPP/MAH-g-PP/bamboo textile waste composites prior and after 7 days of exposure to natural weathering.

3.5.1 Thermogravimetric analysis of virgin and recycled PP

Figure 4 illustrates the (a) TG curve and (b) DTG curve while Table 4 shows the initial decomposition temperature, $T_{10\%}$ and peak of decomposition temperature, T_p of vPP and rPP. $T_{10\%}$ refers to the temperature at which the sample loses 10% of its initial weight, while T_p refers to the maximum negative peak of the DTG curve.



(a) **(b)**

Fig. 4 *The (a) TG curve and (b) DTG curve for vPP and rPP*

Table 4 *Degradation temperatures of vPP and rPP*

Sample	$T_{10\%}$, °C	T_p, °C
vPP	412.03	455.28
rPP	419.23	449.46

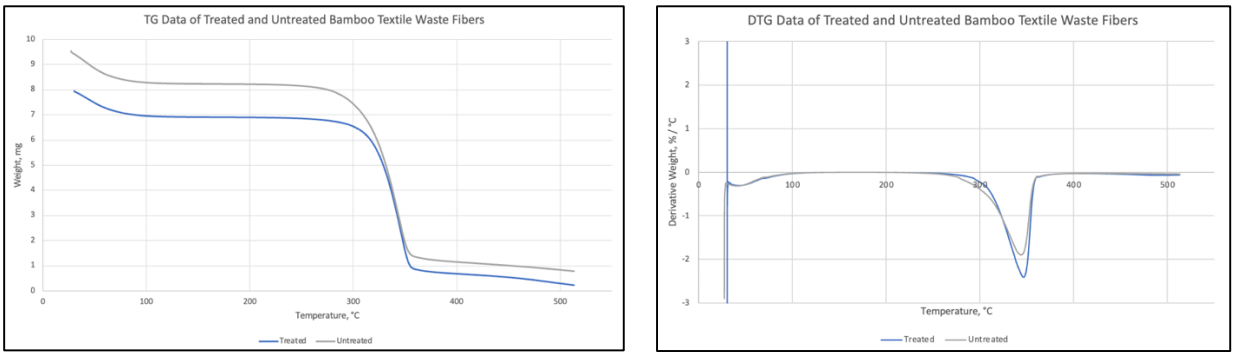
The TG curve of rPP remains relatively stable at lower temperatures, indicating that rPP possess a good thermal resistance to temperatures up to around 350°C to 380°C. However, the onset of major degradation occurs slightly earlier compared to vPP. A rapid and steep loss of mass was observed in temperatures between 380°C to 460°C, corresponding to the thermal decomposition of the rPP backbone. The DTG curve for rPP exhibits a broader peak compared to vPP, indicating a less uniform degradation process. This degradation behavior is commonly associated with the presence of contaminants, impurities, additives, and effect of chain scission occurring throughout the recycling process of rPP.

Conversely, vPP shows a more thermally stable curve where its TG curve shows minimal mass loss before the main degradation stage. This shows that vPP is relatively pure and has minimal traces of contaminants or impurities. The primary degradation of vPP occurs at a slightly higher temperature range between 400°C to 480°C, exhibiting better thermal stability. The DTG curve of vPP also presents a sharper and more defined peak, exhibiting a more homogenous and controlled degradation process.

Additionally, the $T_{10\%}$ value of rPP is slightly higher than vPP, indicating the difference to initial thermal degradation in both samples. This behavior may be attributed to the presence of additives such as stabilizers added during the production of PP products. In contrast, the T_p value of vPP is slightly higher than that of rPP, exhibiting better overall thermal stability of vPP compared to its recycled counterpart. The reduced value of T_p in rPP may be associated with degradation, structural defects, and chain scission induced during its production and recycling process. This analysis showed that rPP still showed good thermal resistance though exhibiting a slightly inferior thermal stability compared to vPP.

3.5.2 Thermogravimetric analysis of untreated and treated bamboo textile waste fibers

Figure 5 illustrates the (a) TG curve and (b) DTG curve while Table 5 shows the $T_{10\%}$ and T_p values of the untreated and treated bamboo textile waste fibers.



(a) **(b)**

Fig. 5 *The (a) TG curve and (b) DTG curve for untreated and treated bamboo textile waste fibers*

Table 5 *Degradation temperatures of untreated and treated bamboo textile waste fibers*

Sample	$T_{10\%}$, °C	T_p, °C
Untreated	69.39	346.91
Treated	62.37	343.75

The TG curve of both untreated and treated bamboo textile waste fibers show a similar degradation characteristic of lignocellulosic materials. An initial mass loss occurring at temperatures below 100°C was correlated to the evaporation of absorbed and trapped moisture within the fibers due to the hydrophilic nature of the bamboo textile waste fibers [18] [19]. This was followed by a stable region with minimal mass loss up to around 270°C, indicating that there was minimal thermal degradation of the bamboo textile waste fibers before the onset of decomposition of the fibers occurs.

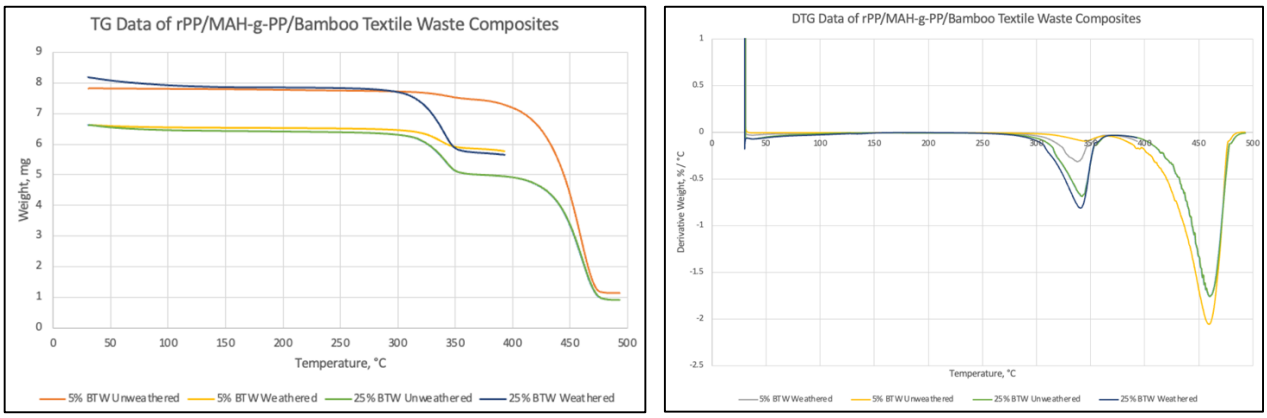
As the temperature increased above 280°C, a major mass loss was observed for both samples until around 360°C. This stage occurs due to the thermal degradation of cellulose and hemicellulose that mainly constitutes the bamboo textile waste fibers. It was observed that the untreated bamboo textile waste fibers exhibit a slightly lower mass loss compared to its treated counterpart, suggesting the presence lignin and inorganic components that are more thermally stable. Conversely, the treated bamboo textile waste fibers showed a larger mass loss, exhibiting improved decomposition efficiency due to the removal of surface impurities and non-cellulosic material during alkaline treatment.

The DTG curve of untreated bamboo textile waste fibers showed a less defined and broader peak in comparison to its treated counterpart. The broader peak showed the overlapping degradation involving cellulose, hemicellulose, and lignin. In contrast, the treated bamboo textile waste fibers showed a well-defined peak and was sharper, suggesting a more uniform degradation process dominated by cellulose. This shows the alkaline treatment successfully reduced the amount of hemicellulose and lignin from the surface of the bamboo textile waste fibers.

Additionally, the treated bamboo textile waste fibers exhibited a higher $T_{10\%}$ value compared to its untreated counterpart. This showed that the alkaline treatment made the bamboo textile waste fibers more resistant to early-stage thermal degradation. Additionally, the T_p value of treated bamboo textile waste fibers was higher than that of the untreated bamboo textile waste fibers, exhibiting and improved overall thermal stability. The results proved that alkaline treatment successfully enhanced the thermal performance of bamboo textile waste fibers, making it a beneficial reinforcement in thermoplastic composites.

3.5.3 Thermogravimetric analysis of rPP/MAH-g-PP/bamboo textile waste composites

Figure 6 illustrates the (a) TG curve and (b) DTG curve while Table 6 shows the $T_{10\%}$ and T_p values along with the amount of final residue of the rPP/MAH-g-PP/bamboo textile waste composites prior and after exposure to natural weathering for 7 days.



(a) **(b)**

Fig. 6 *The (a) TG curve and (b) DTG curve for rPP/MAH-g-PP/bamboo textile waste composites*

Table 6 *Degradation temperatures and amount of final residue of rPP/MAH-g-PP/bamboo textile waste composites*

Sample ID	Weathering Duration, days	$T_{10\%}$, °C	T_p, °C	Final Residue, %
rBTW-5	0	408.57	460.06	14.627
	7	345.85	337.50	87.148
rBTW-25	0	327.70	344.71	13.739
	7	320.15	340.58	69.025

The TG curves for the unweathered rPP/MAH-g-PP/bamboo textile waste composites containing 5 wt% and 25 wt% bamboo textile waste fiber loadings showed the typical double-stage thermal degradation profile of PP-based natural fiber composites. An initial mass loss at temperatures below 100°C was observed for both composites and is attributed to the evaporation of absorbed moisture due to the hydrophilic nature of the bamboo textile waste fibers during the fabrication process of the composites [18] [19]. This initial mass loss is more pronounced for the composite containing 25 wt% bamboo textile waste fiber loading where a higher amount of fiber loading allows for more moisture absorption. Above 100°C, both composites remained thermally stable until around 300°C, indicating that the composites were able to withstand conventional thermoplastic processing temperatures without premature degradation.

The first stage of mass loss occurs between 300°C to 350°C which corresponds to the thermal decomposition of the bamboo textile waste fibers present in the composites followed by a second stage of mass loss between 390°C to 450°C attributed to the thermal degradation of the rPP matrix. The composite containing 5 wt% bamboo textile waste fiber loading showed higher thermal stability as evidenced by a higher $T_{10\%}$ and T_p value in contrast with the composite containing 25 wt% bamboo textile waste fiber loading. This behavior is correlated to the larger

proportion of the rPP matrix which is more thermally stable in addition with the more effective encapsulation of bamboo textile waste fibers within the composite [18].

The DTG curves confirm this behavior of the unweathered composites, where the dominant DTG peak of the unweathered composite containing 5 wt% bamboo textile waste fiber loading appears at higher temperatures and corresponds to the maximum degradation rate of the rPP matrix. Conversely, the DTG peak of the composite containing 25 wt% bamboo textile waste fiber loading shifted slightly to lower temperatures and appear broader, showing increased contribution from bamboo textile waste fiber degradation.

For the composites exposed to natural weathering for 7 days, the TG curves reveal various noticeable changes in terms of thermal stability when compared to its unweathered counterparts. It should be noted that the TGA analysis of the weathered composites was conducted only up to 400°C. Therefore, the discussing of thermal behavior and residual mass were limited to this temperature range. Within this range, both composites exhibited an earlier onset of mass loss and reduced thermal stability.

The shifting of TG curves towards lower temperatures were mainly caused by UV radiation from sunlight and moisture ingress. The reduction in $T_{10\%}$ and T_p values of the weathered composites is correlated to the photo-oxidative degradation induced by UV radiation which consequently causes polymer chain scission. The formation of shorter polymer chains reduces the overall molecular weight, therefore lowering the amount of energy required for volatilization and causes earlier onset of degradation [19]. Additionally, the incorporation of MAPP as the compatibilizer played an important role in mitigating the adverse effects of natural weathering exposure by improving the interfacial adhesion and interaction between the rPP matrix and the bamboo textile waste fiber loadings, making the composites more resilient and stable compared to composites without the incorporation of compatibilizers [20] [21].

4. Conclusion and Recommendations

This study successfully evaluates the effects of natural weathering on the mechanical and thermal of rPP/MAH-g-PP/bamboo textile waste composites. The FTIR spectra obtained of untreated and treated bamboo textile waste fibers confirmed the partial removal of hemicellulose, lignin, and other surface impurities following alkali treatment. Morphological analysis of the treated and untreated bamboo textile waste fibers using SEM revealed a cleaner and rougher fiber surface. These changes in morphological characteristics indicated an improved surface preparation for enhanced mechanical interlocking between the bamboo textile waste fiber and the rPP matrix.

Tensile testing using a UTM showed that composites not subjected to natural weathering exposure showed a higher Young's modulus with increasing fiber loading, indicating increased stiffness due to reinforcement of fibers. However, after 7 days of exposure to natural weathering, a significant reduction in Young's modulus and elongation at break was observed for all fiber loadings caused by photo-oxidative degradation of the rPP matrix and deterioration of the fiber-matrix interfacial bonding. Tensile strength showed mixed behavior with moderate fiber loadings showing improved strength after exposure to natural weathering possibly caused by matrix stiffening, while higher amounts of fiber loadings showed embrittlement and interfacial debonding. This emphasized the need for a precise and optimized amount of bamboo textile waste fiber loadings in the composite for best mechanical performance.

TGA analysis showed a decrease in the $T_{10\%}$ and T_p value after exposure to natural weathering, especially for the composite with 5 wt% bamboo textile waste fiber loading which indicates reduced thermal stability due to photo-oxidative degradation, moisture ingress from the environment, and interfacial deterioration. Composites with a higher fiber loading showed degradation behaviors dominated by bamboo textile waste fibers, resulting in smaller shifts in degradation temperatures. DSC analysis revealed only small changes in T_m after exposure to natural weathering which suggest that crystalline regions of the rPP matrix remained mostly intact. However, a noticeable reduction in ΔHm values was observed indicating that the crystalline order was disrupted caused by polymer chain scission and damage due to oxidation. The degree of crystallinity rises due to the higher amounts of fiber loading providing more nucleation sites for crystallization of the rPP matrix to occur during the cooling phase.

In conclusion, bamboo textile waste can be effectively utilized as a sustainable reinforcement material for rPP when combined with alkaline treatment and compatibilization with the addition of MAPP. However, exposure to natural weathering significantly compromises the mechanical and thermal properties of the composites. Based on the data obtained from this study, the composite containing 15 wt% bamboo textile waste fiber loading exhibited the best balance between performance and practicality of use in the real world. Although the 5 wt% composite exhibited superior resistance to thermal and environmental degradation, its reinforcement effect was limited due to the low amount of bamboo textile waste fibers. In contrast, the composite containing 25 wt% bamboo textile waste fiber loading suffered from severe embrittlement and interfacial degradation, making it unsuitable for practical uses in the real world. While the composites exhibited large potential for indoor or semi-structural uses, additional stabilization strategies such as UV blocking, application of protective coatings, and optimized fiber loadings are recommended to enhance the overall durability for long-term use in the outdoors.

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Conflict of Interests

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contributions

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Ahmad Fareez Zulhaqeem, Mazatusziha Ahmad, Reazul Haq Abdul Haq;* ***data collection:*** *Ahmad Fareez Zulhaqeem;* ***analysis and interpretation of results:*** *Ahmad Fareez Zulhaqeem, Mazatusziha Ahmad;* ***draft manuscript preparation:*** *Ahmad Fareez Zulhaqeem. All authors reviewed the results and approved the final version of the manuscript.*

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