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EFFECT OF HOT WATER ON THE PHYSICO-MECHANICAL PROPERTIES OF DELEB WOOD (*BORASSUS AETHIOPUM*) REINFORCED RECYCLED POLYPROPYLENE COMPOSITES

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ABSTRACT

This study investigates the use of hot-water-treated Deleb wood (Borassus Aethiopum) as a filler in recycled polypropylene (rPP) for wood–plastic composite (WPC) production. The wood was treated at 140 °C and 2.5 bar, then processed into particle sizes of 75, 150, and 300 μm, with filler loadings ranging from 10–50%. Maleic anhydride grafted polypropylene was used as a compatibilizer, and composites were produced via extrusion and compression molding. Mechanical properties, including tensile strength, modulus, flexural strength, impact energy, elongation at break, and hardness, were evaluated. Results showed that treated wood composites exhibited superior mechanical performance compared to untreated ones, with optimal tensile strength observed at 20% filler loading. Treated samples showed an average improvement of about 29% in tensile strength across particle sizes. However, elongation at break decreased with increasing filler content and was higher in untreated composites. Water absorption increased with filler loading, reaching a maximum at 50% and a minimum at 10%. Overall, hot water treatment improved both mechanical properties and moisture resistance. The method is eco-friendly, cost-effective, and suitable for enhancing WPC performance for outdoor applications without chemical modification.

Keywords: Hot water treatment, *Borassus Aethiopum,* recycled polypropylene, mechanical properties, Water absorption.

INTRODUCTION

The recent surge of waste plastics in the ocean is a clarion call to global researchers, as plastic waste has become ubiquitous (Nuryawan *et al.,* 2020). Plastics are indispensable in everyday life and industry, but they pose a threat to ecosystems and human health (Choi *et al*., 2023). Large volumes of waste plastic products are discarded daily in Nigeria and other parts of the world and are found on streets and in marketplaces, eventually entering the ocean, where the effects of plastic pollution are felt more by marine life. Every year, about eight million tonnes of plastic end up in the oceans (Elhadj & Pierre, 2023). This high volume of plastic waste generated daily is not unconnected to the use of plastics in food packaging, beverage bottles, textile products (synthetic fibres for clothes and ropes), and building materials (e.g., electrical insulation, pipes, and window frames). Although plastic materials offer ease of processing, good ductility, high toughness, excellent chemical resistance, and moldability, their durability and long-term degradation contribute to the high rate of plastic waste generated in the environment (Kim, 2014). If these waste plastics are modified with lignocellulosic materials as reinforcement, new products can be produced with improved properties. Such fibre-reinforced polymers offer higher strength and/or modulus than conventional materials and are exploitable in diverse fields such as automobiles, appliances, and spacecraft (Benzard, 2011; Samyn, 2024). The biodegradability of lignocellulose offers the advantage of being environmentally friendly when employed as a reinforcing filler in the production of wood-plastic composites (WPCs). In addition to this attribute, characteristics such as low density, lightweight nature, renewability, and cost-effectiveness render wood fillers less preferred than conventional alternatives (e.g., glass, carbon, or inorganic fillers). These advantages have increasingly drawn the attention of researchers globally (Benzard, 2011; Yaxine *et al.,* 2023). However, water absorption and fungal decay are among the drawbacks associated with wood fibre-reinforced WPC, which is often used in outdoor applications and hence requires modification (Hosseinaei *et al*., 2011; 2012). Hot water modification of wood has recently gained attention. Ponderosa pine was subjected to hot water extraction (HWE) by Pelaez-Samaniego et al. (2013) and Susanna et al. (2020), who reported that HWE increases resistance to water absorption in wood fibres. Hosseinaei *et al*. (2012) reported the effects of hot-compressed water (HCW) extraction of hemicellulose from southern yellow pine; they observed increased thermal stability of the wood, tensile strength, and water-absorption resistance of composites reinforced with the modified wood. The use of hot-water-modified Deleb tree (Borassus Aethiopum) for the reinforcement of plastic waste or recycled thermoplastics has yet to be investigated. Deleb wood is reported in the literature to be versatile for reinforcing walls and to serve as a rafter for roofing mud houses in rural areas because of its durability and good termite resistance (Acheampong et al., 2022; Boakye *et al.,* 2024). This study, therefore, focuses on the potential of using hot-water-treated Deleb wood powder as a filler in polymer composites and thereafter investigates the absorption resistance and mechanical properties of recycled polypropylene reinforced with Deleb wood powder.

MATERIALS AND METHODS

The recycled Polypropylene (rPP) used in this study was PP black, Batch No: 05PP011, supplied in May 2014 by MYPLAS (Pty) Ltd, Stellenbosch, South Africa. Deleb wood was obtained from local merchants in Zaria, Nigeria. The wood logs were mulched into chips and pulverized into a small particle size. These wood particles were subjected to hot water treatment (HWT) at 140 °C and

[a] pressure of 2.5 bar for 2 hours. The wood-to-water ratio in a 5-litre-capacity stainless-steel cylindrical reactor was 1:4 in a closed system. After 2 hours, the heating was stopped, the mixture was allowed to cool, and the content was filtered and oven-dried at 70 °C for 24 hours.

Proximate Analysis
The treated and untreated wood samples of *B. Aethiopum* were taken to the National Animal Production Research Institute (NAPRI) laboratory centre, Shika, Zaria, where quantitative and qualitative analyses of the wood were conducted and recorded, as shown in Table 2, using Van Soest fibre analysis.

Samples Preparation
The untreated and treated woods were further milled, using Jaw crusher and ball milling machines (Retsch Masch, Nr 70992 GMbH & CO. and Kera b.v. Soeter berg Overveld 057748 Holand) respectively, then sieved using impact Laboratory sieve (ISO 3310-1:2000, bs 410-2000) to obtain 75, 150, and 300 μm particle sizes as fillers, weighed according to the planned percentage weight (10, 20, 30, 40 and 50 %) and the corresponding complementary percentage weight of rPP polymer as shown in Table 1 were weighed and bagged respectively. Subsequently, the maleic anhydride-grafted polypropylene (MAPP) was weighed equally, bagged, and kept for the next stage (extrusion process).

Table 1: rPP and Wood Formulations

S/NO	Composite Sample code	Plastic forms (%)	Plastic content (%)	Wood flour content (%)	Coupling agent (%)
1	rPP100	recycled	100	0	0
2	rPP85utW10	recycled	85	10	5
3	rPP75utW20	recycled	75	20	5
4	rPP65utW30	recycled	65	30	5
5	rPP55utW40	recycled	55	40	5
6	rPP55utW50	recycled	45	50	5

Where, r = Recycled, PP = Polypropylene, u = Untreated, t = Treated, W = Wood

Compounding and Extrusion
The recycled polypropylene treated and untreated *B. Aethiopum* wood of 75, 150, and 300μm particles, respectively, were mixed and compounded using a customized single screw extruder machine. The extruder machine consists of a single screw with a length of 55 cm and a diameter of 2.5 cm, i.e., a length-to-diameter ratio of 22:1, at a rotational speed of 100 rpm. The Screw has a conical tip towards the die, reducing flight depth. The machine has two heating zones that can be controlled separately. The extruding temperatures used were 180 °C and 160 °C for compounding. The polymer, the wood sample, and MAPP were fed into the Hooper; the materials were simultaneously transported to the heating zone (180 oC at the rear end and 160 oC at the forefront), where the polymer was melted and mixed with wood content and later forced through the die to form pellets of WPC. The pellets collected from the machine die were reintroduced into the Hooper for proper mixing, and the process was repeated 3 times to obtain the final homogeneous composite pellets. The same procedure was repeated for all the weighed samples.

Compression Molding
The extruded pellets of Deleb wood/rPP at particle sizes of 75, 150, and 300μm were fed into a two-roll mill machine according to ASTM 15-672, with the mixture introduced into the heated rollers at 180 °C, where it melted and flowed after mixing for 5 minutes. The mixed material was collected and subsequently placed in a metal mold measuring 150 x 100 x 5 mm (length, width, and thickness, respectively), and then pressed on a compression molding machine at 180 °C for five (5) minutes. Thereafter, cold-pressed at room temperature for three (3) minutes and a pressure of 4Pa. The composites were removed from the machine and kept for future analysis. The pressing was carried out in the polymer processing laboratory at the Department of Polymer Technology (Nigerian Institute of Leather and Technology, Zaria). Composite Sheets were thereafter cut into various dimensions for characterization.

Tests
FTIR Analysis
The Fourier transform infrared (FTIR) spectroscopic analysis of the *B. Aethiopum* wood particles was studied using FTIR Thermo Scientific Nicolet (iS10). Both treated and untreated samples were subjected to this test to investigate the effect of hot water treatment on peak intensity and certain functional groups of Deleb wood.

Water Absorption Test
Water absorption tests were conducted in accordance with ASTM D570-98, in which each specimen was weighed, recorded, and immersed in water in a container for 24 hours at 23±2 °C. The sample was removed, the surface water was wiped off using a dry cloth, and the sample was weighed again to determine the weight gain using a weighing balance. The sample was returned to the water container, and these procedures were repeated for 32 days. Percentage water absorption was calculated and recorded using this formula in equation (1).

$$\text{Water absorption (\%)} = {(Wf - Wi)}/_{Wi} \times 100 \qquad (1)$$

Where, Wi = Initial weight and W_f = final weight of the specimen.

Tensile Strength
Tensile properties of each composite were determined according to ASTM D 638 standard with a gauge length of 40 mm and load force of 100 KN. The sample's dimensions of 100 × 10 × 5 mm were tested using a Tensile Strength Testing machine (Model TM2101-T7, Shanghai Rixine Electronic Co., Ltd., Shanghai Rixine Technology, China) with a crosshead speed of 2 mm/min. The reading was automatically recorded and calculated by the instrument's software. At least 3 specimens were tested for each composite blend and property. Tensile properties obtained from this test were tensile strength, elongation at break, and tensile modulus.

Flexural Strength
A three-point bending test was performed in accordance with ASTM D790 to measure the flexural properties of the composites

using a Tensiometer (Lonroy, LC008). A maximum load of 100 KN and cross-head speed of 5 mm/min were applied, and loading continued until fracture, and values of flexural strengths were recorded automatically. The dimension of the sample was 100 × 30 × 3 mm in length, width, and thickness, respectively. The test was conducted by positioning the specimens horizontally in the machine's sample compartment, with at least 3 specimens tested for each composite blend.

Impact Test

The Impact energy test was conducted with a Charpy Impact Testing Machine, Cat. No. 412 (Model No. 6957), capacity of 15 Joules) According to ASTM-E23 standard, with a notch depth of 0.5 mm and a notch base radius of 0.25 mm. Samples were tested at room temperature by a single swing of the pendulum hammer using Norwood. The specimen size was 100 × 11 × 5 (mm). Each sample was placed on the vice and clamped firmly. The pendulum hammer was raised to the required height, then released to strike the sample at once. Then, the impact energy absorbed by the specimen was recorded. The impact energy of the samples, in Joules per square metre, was recorded for 3 specimens per composite blend.

Hardness Test

The hardness test was conducted using a Microvickers Hardness Tester (MV1-PC, Mh-v CM, Serial No: 07/2012-1329) with a maximum capacity of 0.3 Kgf (150 HV) in accordance with ASTM E-384. The test was carried out at a temperature of 23 ± 2 ºC. The specimen dimension was 30 × 10 × 3 (mm). The specimen was mounted in a specimen compartment, and the indentation point was focused. Three different points were indented on each specimen, and the hardness values were recorded. The average of the three readings was calculated and recorded.

RESULTS AND DISCUSSION

Characterization of *Borassus Aethiopum*

FTIR Analysis of the untreated and treated Deleb wood particles was evaluated, and the effect of chemical modification on the Deleb wood was observed using FT-IR Spectroscopy and proximate analysis. The comparison of the FT-IR spectra of the untreated and the treated Deleb wood particles in Figure 1 shows a reduction in O-H stretching intensity. The shifting of the peaks from 3335 cm-1 in untreated to 3308 cm-1 in treated Deleb wood was observed. This may be attributed to the disruption of the hydrogen bond between the O-H groups of cellulose and hemicellulose and the reduction of the -OH group associated with some of the removed hemicellulose present in the wood structural particles (Lawal et al., 2023; Gumel & Tijjani, 2015). Peaks at 2923 cm^{-1} for the untreated and 2896 cm^{-1} for the treated Deleb wood spectra may have originated from C-H stretching of the aliphatic group, and the reduction in their stretching intensity indicates the removal of hemicellulose (Jayamani *et al*., 2020). The absorption peak at 1732 cm^{-1} in the untreated wood was observed to have reduced to 1722 cm^{-1} in the treated spectra. They were associated with carbonyl C=O stretching of acetyl and attributed to the asymmetric deformation of lignin in the treated wood. The band at 1237 cm^{-1} is attributed to the stretching vibration of C-O groups present in lignin and hemicellulose structure. Weakening of this peak at 1229 cm-1 in the treated spectra confirmed the removal of hemicellulose (Jin *et al.,* 2022). This observed peak reduction, attributed to reduced hemicellulose, typically supports the reduction observed in the proximate analysis result shown in Table 2, where the reduction in hemicellulose decreased from 10.72% in the untreated to 8.62% in the treated wood. However, the peaks at 1602 cm-1 and 1596 cm-1 in the untreated and treated Deleb wood, respectively, were attributed to the C=C stretch, which also showed a reduction in intensity. Tjeerrdsma and Militz (2005) reported that it is possible to hydrolyze hemicellulose preferentially in a mild heat treatment of wood in an acid medium because hemicellulose is hydrolyzed more easily than cellulose. They added that the course of acidity is attributed to the formation of carbonic acid during thermolysis and is a function of time and temperature. Carbonic acid catalyzes the depolymerization of hemicellulose (Kubovsky *et al.,* 2020). This process of using HWT to remove hemicellulose often reduces hygroscopicity but improves durability, dimensional stability, and resistance to biological degradation of the treated woods (Zhang *et al.,* 2017).

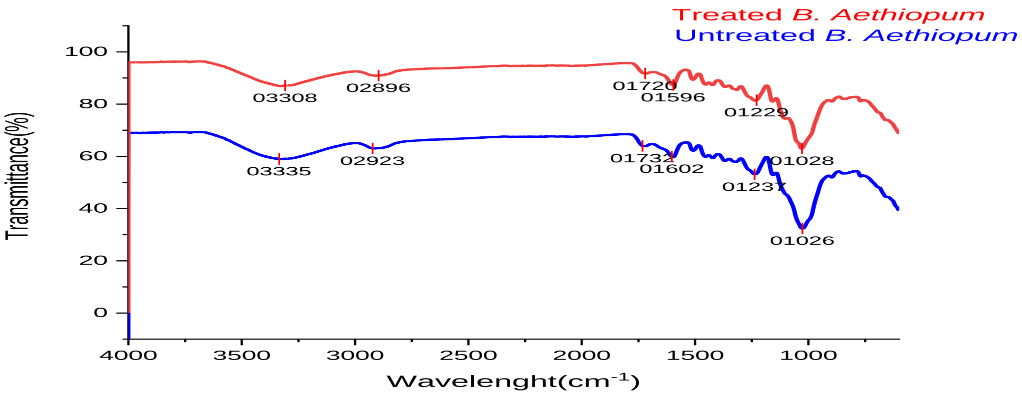

Figure 1: FT-IR Spectra of untreated and treated *Borassus Aethiopum* (Deleb wood)

Table 2: Proximate analysis results for treated and untreated Deleb Wood

	Description										
	Deled Wood	**%DM**	**%ASH**	**%EE**	**%CF**	**%CP**	**%NDF**	**%ADF**	**%LIGN**	**%HEMI CEL**	**%CELULOSE**
1	Treated	89.31	1.12	2.56	75.64	2.31	89.31	80.69	16.25	8.62	64.44
2	Untreated	95.46	3.74	8.83	29.45	11.56	63.43	52.73	13.61	10.70	39.12

Where, DM = Dry Matter, ASH = Ash Content, EE = Ether Extracts, CF = Crude Fibre, CP = Crude Protein, NDF = Neutral Detergent Fibre, ADF = Acid Detergent Fibre, LIGN = Lignin and HEMI CEL = Hemicellulose

Proximate Analysis

Table 2 presents the various components of B. Aethiopum, with the percentage composition of lignin, hemicellulose, and cellulose shown. Before hot water treatment, lignin, hemicellulose, and cellulose accounted for 13.61%, 10.70%, and 39.13% of the wood, respectively. After hot-water treatment, 16.25%, 8.62%, and 64.44% were obtained for lignin, hemicellulose, and cellulose, respectively. The value of the hemicellulose component of *B. Aethiopum* was observed to have reduced significantly. A reduction from 10.7% to 8.62% was observed. The percentage reduction of hemicellulose content and other matters may have probably increased the percentage content of Lignin and Cellulose in the treated wood, this is in agreement with the previous study by Palaeze- Samaniego *et al*., (2013) who reported that, the relative content of lignin has been elevated in the treated bark of pine wood sequenced to the removal of hemicellulose when the bark of pine wood was subjected to hot water extraction. Heat treatment of wood at high temperature (120-140 ºC) depolymerizes hemicellulose but has little or no effect on lignin (Teng-chun *et al*., 2017). HWT reduced hemicellulose but relatively increased the lignin content (Table 2), this increased the hydrophobicity of the treated wood because lignin (aromatic rings) possesses hydrophobic characters making the wood more compatible with the matrix, increased the resistance to water ingress, which may have culminated to higher physical and thermal stability of the treated Deleb wood/rPP over the untreated Deleb wood/rPP composites. Arwinfar *et al. (2016) reported that Beach wood was thermally treated (steam/saturated steam) at different severities (120-180 ºC, 30-120 min) and then used as a filler in polypropylene with a* coupling agent. They discovered that the thermal treatment caused structural changes: outer fibres had a coating of amorphous lignin, better embedding broken fibre ends, and fewer voids when treated at 150 ºC for 30 minutes, indicating optimal compatibility between wood flour and polymer, and that mechanical properties improved under those conditions. It thus suggests that heat/hot-water treatments that preserve or mobilize lignin (making it more amorphous) help improve fiber-matrix compatibility, thereby enhancing strength and reducing defects in wood-plastic composites.

Water Absorption

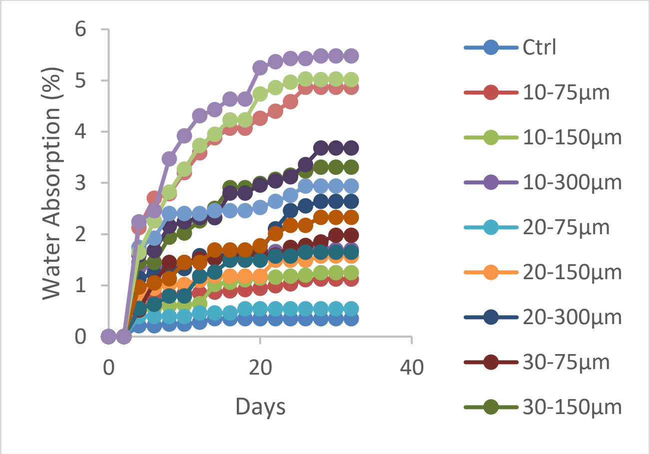

Figure 2 (a): Water Absorption on Treated Wood WPCs

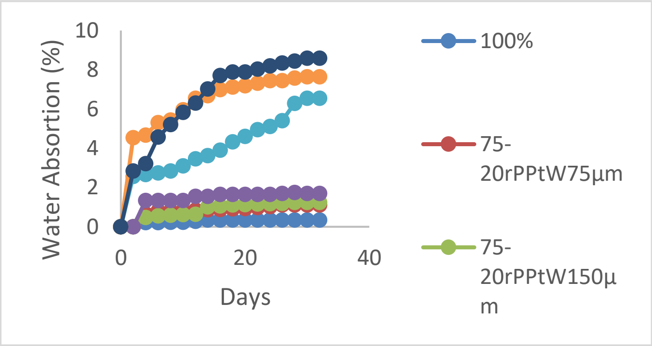

Figure 2 (b): Water absorption for 75µm at 20% filler loading

Figure 2 (a and b) shows the percentage water absorbable capacity of Deleb wood composites. For the first two (2) days, there was no significant water absorption observed for all the treated composites, but there was a progressive increase in water absorption as the number of days increased, and this was observed for 32 days. The hot-water-treated samples showed excellent resistance to water absorption compared to untreated wood composite samples, which had higher absorption percentages; this is in line with the literature. Figure 2 (a) shows the results of all the HWT-treated samples. For easy comparison, the percentage water absorption of 75, 150 and 300 µm at 20 wt % filler loading being the filler loading that gave the optimal performance in mechanical tests for both treated and untreated composite samples is as shown in Figure 2 (b), the water absorption for treated composite at particle sizes of 75, 150 and 300µm were observed to be 1.12, 1.25 and 1.7 % respectively, while the corresponding untreated composites gave water absorption (%) values of 6.56, 7.65 and 8.6 % respectively as well. Apart from the untreated samples showing a higher percentage of water absorption, the absorption capacity increases with increasing particle size. This scenario can best be attributed to the higher porosity of irregular shapes with larger particle sizes, which may have promoted greater ingress of water molecules (Lawal *et al.,* 2023). These results demonstrated that WPCs with hot-water-treated wood particles exhibit higher water resistance and better dimensional stability. These phenomena can be attributed to modifications in the structure and chemical composition of the wood particles, such as the removal of hemicellulose and, probably, an increase in the crystallinity of the cellulose component of the wood. This agrees with the study made by Li *et al*. (2017). Degradation of hemicellulose leads to deacetylation, and the released acetic acid catalyzes hydrolysis of the polysaccharide chain (Kubovsky *et al.,* 2020). Also, the accessible -OH moiety of the lignocellulose was drastically reduced by the removal of hemicellulose and the amorphous portion of cellulose, thereby reducing the water intake and retention potential of the wood structure.

Tensile Strength

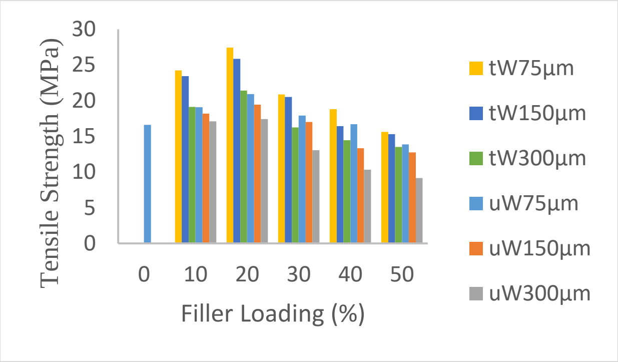

Figure 3: Effect of filler loading and particle size on tensile strength for treated and untreated composites.

Figure 3 shows the effect of hot water treatment (HWT) on tensile strength (TS) of the polypropylene composites. Composites made with hot water-treated wood (tW) exhibited higher values than composites made with untreated wood (uW). This may be attributed to a reduction in the -OH moiety caused by hemicellulose removal during HWT. The wood's chemical composition has therefore been altered, increasing the wood's hydrophobicity and potentially improving the interfacial bond between the wood particles and the matrix (Candelier *et al*., 2016). Composites with filler have higher tensile strength than the control sample (0% filler), but not samples whose filler loading is above 20 wt % (30, 40, and 50 wt %). For all particle sizes, tensile strength increased with increasing filler loading up to 20 wt %, then decreased for both treated and untreated wood composites. The tensile strength values of 20 % filler loading at 75, 150, and 300µm are 27.42, 25.88, and 21.41 MPa, respectively, for treated composites, while the corresponding untreated composites' TS values at the same filler loading and particle sizes were 20.9, 19.43, and 17.41 MPa. The result shows that at particle sizes of 75, 150, and 300µm, there were corresponding increments of 31, 33, and 23%, respectively. The increase in tensile strength may be attributed to the strengthening effect of the filler incorporated into the polymer matrix. Fillers, when integrated into polymeric systems, enhance rigidity and mechanical performance by facilitating efficient stress transfer across the composite interface (Turku *et al.,* 2021). Fillers are usually added to polymeric materials to improve their rigidity and strength. In this study, the optimum filler loading was observed to be 20% weight. At higher filler loading, there was a drastic decrease in TS, which can be attributed to poor filler encapsulation by the matrix for both treated and untreated composites. This effect is often followed by particle agglomeration and poor stress distribution, leading to early failure and a low TS value (Bhaskar *et al*., 2021). It was also observed that a lower particle size supported higher TS, as indicated in Figure 3. This observation may be attributed to the smaller particle size, which provides greater surface area and wettability, thereby enhancing interfacial bonding between the particles and the matrix. Larger particle size, as illustrated in Figure 4, also exhibits a progressive decrease in tensile strength, observably corresponding to an increase in filler particle size within the composite system (Onuoha *et al.,* 2017).

Tensile Modulus

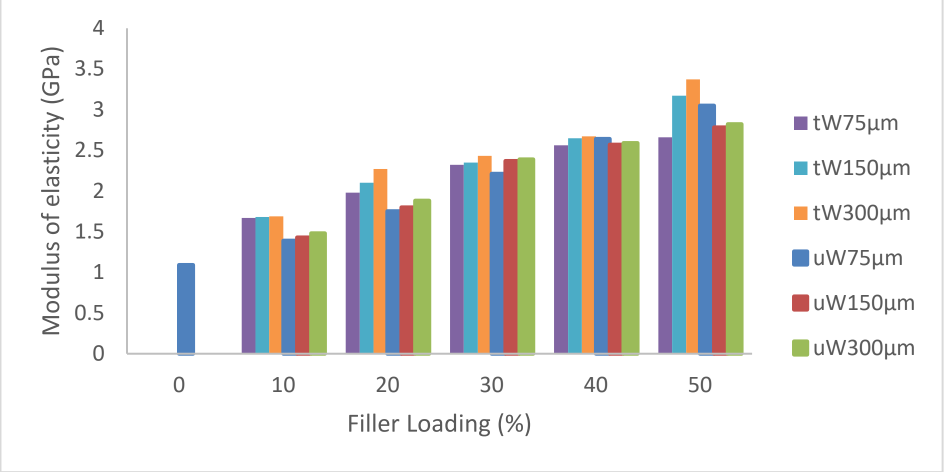

Figure 4: Effect of filler loading and particle Size on Tensile Modulus for treated and untreated composites.

The results of the tensile modulus are shown in Figure 4. The values obtained from HWT samples were higher than those of the untreated sample composites. Generally, the tensile modulus was found to increase with an increase in filler loading and particle size. The range of tensile modulus obtained for the respective particle sizes of 75, 150, and 300 µm is 1.67-3.05, 1.68-3.17, and 1.69-3.37 GPa for treated composites and 1.37-2.66, 1.48-2.78, and 1.48-282 GPa for untreated composites on the same particle sizes, respectively. The treated values are higher than the untreated composites owing to a better interfacial bond between Deleb wood and the rPP matrix, resulting from the removal of hemicellulose and wax contents, which accompanied HWT. Tensile modulus indicates a material's stiffness; incorporating fillers into the polymer matrix increases the stiffness of the composite. This could be attributed to the even dispersion of the filler in the matrix, which efficiently hinders chain movement during deformation. On the other hand, some researchers reported that smaller particles enhance dispersion within the matrix more than larger particles, hence the decreased tensile modulus with increasing particle size, as reported by Onuegbu and Igwe (2011). However, Njoku *et al. (2011) reported that periwinkle particle size within the range of 400 – 1000 µm has a negligible effect on tensile modulus of* Polyester-periwinkle shell particle composites in their study on the effects of variation of particle size and weight fraction on the tensile strength and modulus of periwinkle shell reinforced polyester composite. In this study, a larger particle size was observed to enhance tensile modulus, contrary to the aforementioned scholars. This effect may be attributed to improved stress distribution within the material, as larger particles generally increase material stiffness. This is in line with the study by Edoziuno et al. (2025), which reported on the mechanical and structural performance of hardwood charcoal-reinforced polyester composites, including the effects of particle size and filler loading. In their findings, they showed that larger particle sizes of the charcoal filler yielded a tensile modulus of 906.7 MPa for the 250 µm filler at 10 wt%, while 651.6 MPa was obtained for the 150 µm filler at 20 wt%. They concluded that tensile modulus generally increases with larger filler sizes, although there may be some fluctuations.

Flexural Strength

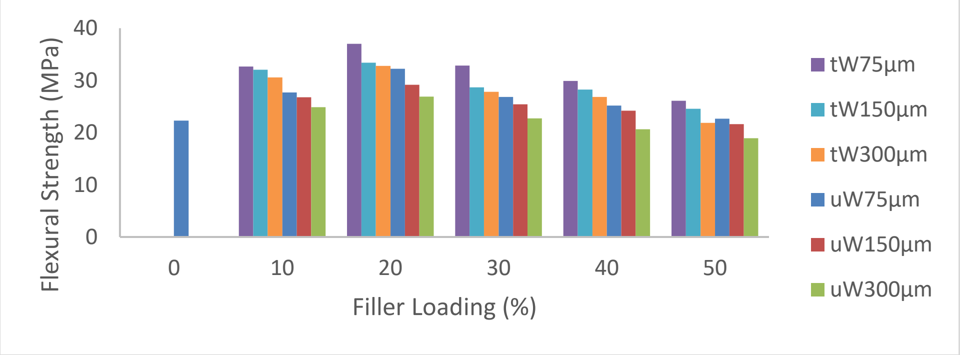

Figure 5: Effect of filler loading and Particle size on Flexural Strength for treated and untreated composites.

As depicted in Figure 5, flexural strength follows the same trend as tensile strength, with treated samples showing greater flexural strength than the untreated samples and an initial increase in flexural strength up to 20 wt % filler loading, but at higher filler loading (30, 40, 50 %), decreased flexural strength was observed. Such an increase in flexural strength at lower filler loading relative to higher filler loading has previously been reported by Onuoha et al. (2017). A phenomenon attributed to the even distribution and wettability of wood particles in the matrix, which creates better interfacial bonding and subsequently resists bending processes to produce higher flexural strength, but lower flexural strength at higher filler loading occurs due to poor interfacial bonding caused by poor dispersion of fillers in the matrix. It was observed that an increase in particle size decreased flexural strength due to a smaller surface area provided by the larger particle size (300 µm), which creates gaps between filler/matrix, unlike closed particles reported in the smaller particle size (75 µm), leading to a poor interfacial bonding between the Deleb wood particles filler and the rPP matrix. Lawal *et al. (2023) observed that the smaller particle size of date seed has a* higher flexural strength of the date seed particles/waste polypropylene composites. They attributed this character to better filler dispersion, adding that filler-matrix interactions may be the main reason for the observed trend.

Elongation at Break

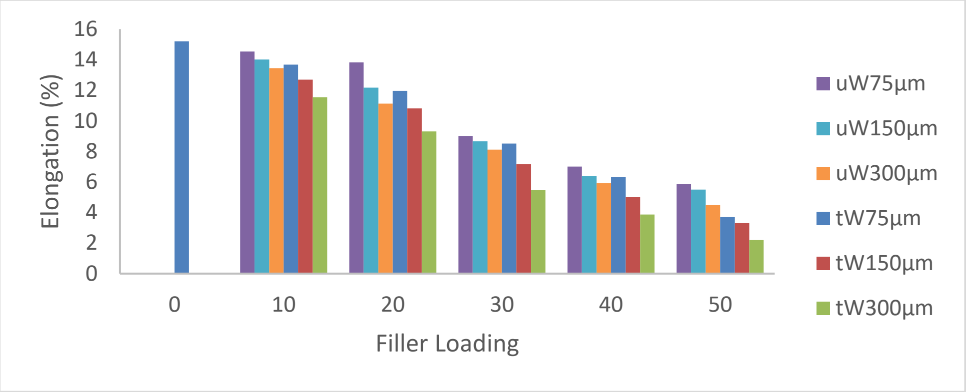

Figure 6: Effect of filler loading and Particle Size on Elongation at Break for treated and untreated composites.

Figure 6 shows that the control sample (100 % rPP) has the highest value of elongation at break (15.21%), this is closely followed by the untreated composites with the values of (14.54, 14, and 13.45%) and the treated (13.67, 12.69 and 11.54%) composites both at 75, 150, and 300µm, respectively. The lower values for treated composites may be attributed to HWT reducing the hydroxyl groups on the fibre surface and improving the Deleb wood–rPP matrix bond adhesion, which may have facilitated better stress transfer. Furthermore, hot-water-treated particles become more crystalline, stiffer, and less hygroscopic in the composite, resulting in low elongation at break. This verdict is supported by Chien *et al*. (2024), who reported that hot water treatment of wood typically reduces elongation at break. Also, elongation at break was observed to decrease with an increase in filler loading and particle size of Deled wood. At any chosen particle size, elongation at break decreases progressively, as shown in Figure 6. Generally, fillers in the matrix reduce the mobility of the polymer chains, thereby reducing ductility and increasing stiffness in the composites. When filler content increases because of a smaller particle size, weaker interfacial regions between filler and matrix are formed, leading to cracking. The crack travels more easily through the weaker interfacial regions, thus decreasing the elongation at break. This reduction scenario was also reported by Lawal *et al.* (2023).

Impact Energy

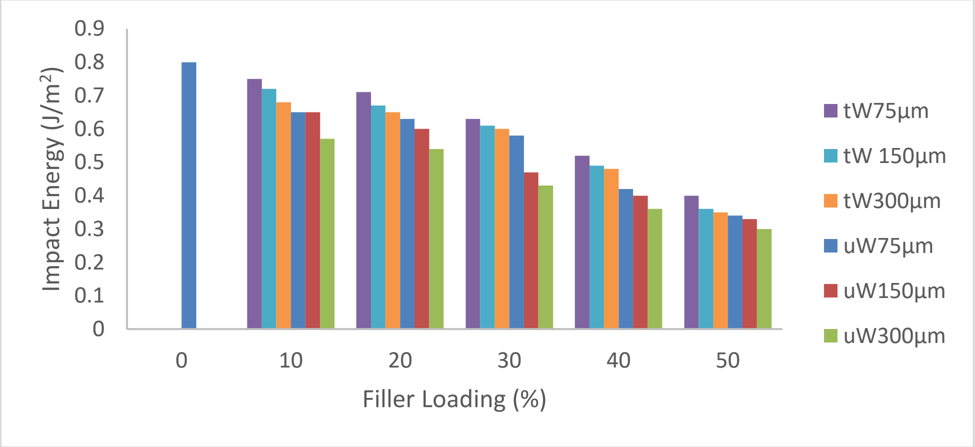

Figure 7: Effect of filler loading and Particle Size on Impact Energy for treated and untreated composites.

The impact energy is the measurement of toughness of a material, i.e., the determination of resistance to fracture of a material that is subjected to a sudden and intense blow or mechanical shock. As depicted in Figure 7, impact energy decreases with increased filler loading and particle size. This could be attributed to the irregular orientation of large particles, which resulted in less interaction within the composite's composition. This observed decrease may also be due to large wood particles and agglomeration of excessive fillers oriented in layers, which are incapable of transmitting stress from the polymer matrix to the filler. This observation was also reported by Lawal *et al.* (2023). The hot-water-treated wood composite samples had higher impact energy values than the untreated wood composite samples. The impact energy range values obtained for untreated composites were 0.67-0.38, 0.65-0.34, and 0.52-0.31 J/m2, and for treated composites, the range was 0.72-0.41, 0.69-0.37, and 0.64-0.34 J/m2 at 75, 150, and 300 µm, respectively. This is because the hot water treated wood particles were more compatible with the hydrophobic nature of the polymer matrix, HWT may have depleted some OH-moiety along with hemicellulose removal that tends to improve the interfacial bond between the filler/matrix, hence increased the values of the HWT samples over the untreated samples as also observed in other tests (Tensile, flexural and hardness).

Hardness Test

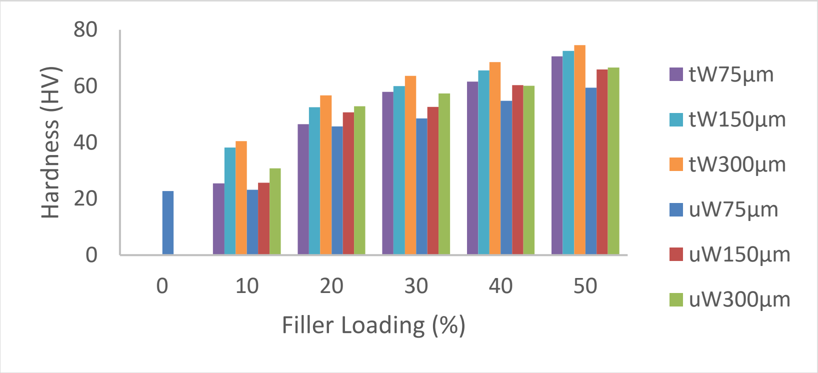

Figure 8: Effect of filler loading and Particle Size on the hardness test for treated and untreated composites

Figure 8 depicts the hardness test conducted on the composites in this study. The HWT composites have higher values than untreated WPCs because of their close compatibility with the matrix, which promotes the interfacial bond between the filler/matrix. The Vickers hardness (HV) of the control sample (100% rPP) was 22.8 HV. At the same time, the reinforced Deleb/rPP composites at 75, 150, and 300 µm have the range values of 23.21-59.43, 25.67-65.91, and 30.85-66.62 HV, respectively, for untreated composites and 28.53-70.6, 38.27-72.5, and 40.43-74.62 HV, respectively, for treated composites. The Vickers hardness increased with increasing filler loading. Also, it increased with increasing particle size, with the highest value obtained being 74.62 HV at a particle size of 300 µm (50% filler loading) on the treated composite, and the lowest value was 23.21 HV at a particle size of 75 µm (10% filler loading) on the untreated composite. This is attributed to the fact that wood particles reinforced the polymer matrix, thereby enhancing the material's stiffness (Mohd *et al.,* 2018). The higher the percentage of fillers incorporated into the polymer matrix, the harder and more rigid the material becomes. Furthermore, large particle sizes in composite materials tend to be arranged near the surface; this arrangement contributes significantly to the increased hardness observed for larger particle sizes compared with smaller ones. This attribute of higher particle size increasing hardness was equally reported by Lawal *et al.* (2019).

Conclusion

Based on the series of tests conducted on composite samples, the hot water treatment was effective in reducing the hydrophilicity of Deleb wood for use as a reinforcement in WPCs with rPP as the matrix. The mechanical properties of the hot water-treated wood composites exhibited higher values than the untreated wood composites with the same wood filler/matrix composition. The tensile strength increases with increasing filler loading, and the composite of particle size 75 µm at 20 wt % filler loading has the highest tensile strength. Also, the hardness of the composite samples increased with increasing filler loading. Therefore, the samples should be suitable for products that require hard-surface materials, and hot water treatment can be adopted for wood treatment because it is cost-effective and environmentally friendly.

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