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An Evaluation of the Physicochemical, Structural and Morphological Properties of Selected Tropical Wood Species for Possible Utilization in the Wood Industry

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Abstract

This work investigated and quantified the physicochemical, structural and morphological properties of four (4) tropical timbers as precursor raw materials for possible utilization in the wood plastic industry. The physicochemical properties of the wood samples such as the bulk and tapped density, moisture content, water absorption capacity at 25˚C, volatile content, fixed carbon, ash content, alpha cellulose, hemicellulose, lignin, and extractives contents were determined using standard methods like the European Committee for Standardization and (CEN/TS) and the American Society for Testing Materials (ASTM) standards. The structural and morphological properties of the samples were examined with Fourier Infrared Transform (FTIR) spectroscopy and scanning electron microscope (SEM). Results indicated that the bulk density values of the timbers ranged from 0.34 g/cm^3 in *Brachystegia eurycoma* (W_3) to 0.47 g/cm^3 in *Erythrophleum suaveolens* (W_2), with the other timbers, *Nuclea diderichii* (W_1) and *Prosopis africana* (W_4) having the same bulk density of 0.40 g/cm^3. With respect to their moisture content, W_2 had the highest value (8.38%) while *Nauclea diderrichii* had the lowest value (6.52%). The water absorption capacities of the woods studied correlated with the cellulose composition of wood in the order of: $W_3 > W_1 > W_4 > W_2$. The FTIR results showed that W_2 and W_3 presented a slightly more prominent and broader band than the other woods at 1731 cm^{-1}, in agreement with the higher holocellulose content of these species, while W_2 and W_4 presented the most prominent peaks indicating higher lignin content than W_1 and W_3. The SEM micrographs of the wood flour samples investigated indicated that the surfaces of the woods were rough and heterogeneous with irregular crystal and

brick shaped particles. A two-way analysis of variance (ANOVA) carried out with respect to the chemical composition of the wood samples indicated that there was no statistically significant variation in the wood chemical composition between species as the p-value (0.852) obtained was greater than the critical level of $\alpha = 0.05$.

Keywords

Wood Plastic Composites, Density, Water Absorption Capacity, Cellulose, Sustainability

1. Introduction

Wood-based wastes like sawdust from wood processing industries create environmental pollution unless reprocessed for different applications like particle-board pulp or any other useful wood-plastic composites (WPCs) [1]. Fortunately, wood from which sawdust is derived is a renewable, recyclable and biodegradable material and also has an added advantage that its higher strength and aspect ratio offer good reinforcing potential in the composite matrix when compared to other artificial fibers that can be combined with a plastic like Polyethylene Terephthalate (PET) into useful wood plastic composites (WPCs) [2]. Other favorable properties like low density, low cost, renewability, recyclability and desirable mechanical properties have engendered a phenomenal interest in WPCs [3].

However, some challenges among others with respect to the use of wood-based materials as fillers and reinforcements in the WPC industry include a high level of moisture absorption, relatively low degradation temperatures around 200˚C, and filler agglomeration because of the tendency of wood to form hydrogen bonds [4]. This is because wood is a hydrophilic substance that easily attaches to water molecules by means of the hydroxyl groups of its cell wall components [5] [6] [7]. Composite materials are known to degrade when subjected to humid conditions [8]. Research has shown that under the influence of water, a differential swelling in composite takes place [9], as wood flours distend in contrast to the thermoplastic matrix, resulting in cracks and failures in the material [10] [11] [12] [13]. These fractures allow for the faster penetration of water leading to undesirable impacts on the mechanical properties of composites [13]. For instance, that the absorption of 9% of water by WPCs leads to a loss of 39% and 29% of flexural and tensile modulus has been reported [14]. Furthermore, the difference between the surface energy of wood fiber (high) and plastic (low) complicates the bonding of the components of a composite with respect to their blending [5]. The high surface energy of wood fibers causes agglomeration and restrains the dispersion [5] [15].

These drawbacks, notwithstanding, wood plastic composites, being sustainable organic materials, still have great potential for the development of environmentally friendly products, thus effectively tackling to a significant extent, the challenges posed to the environment via pollution [16]. The phenomenal rise of

this industry to prominence has therefore given an impetus to the development of new applications in construction works and for building materials [17], thus making this relatively new generation of composite materials the most promising sector in the field of both composite and plastic industries [2]. But studies on the physical properties of tropical woods are aspects that are still limited [4]. These lacunae with respect to information and data on the physico-chemical, structural, and morphological properties of our local tropical timbers have also been reported as a factor militating against the growth of the WPC industry in the tropical regions of Africa [18]. Further investigation on these local timber species, as was carried out by this study, will provide useful information on new sources of raw material for the WPC industry and their effects on the products [19]. This work therefore investigated some of the physicochemical, structural and morphological properties of some selected tropical timbers as prospective raw materials for possible utilization in the wood plastic industry.

2. Materials and Methods

2.1. Sample Collection

Samples of the main trunks of four tropical timbers were obtained from various forests located in Ogwogo Nike in Enugu East of Enugu State, which is situated in the southeastern part of Nigeria. This was done with the aid of a well-trained government forestry official during the dry season. The selected timbers were: *Nauclea diderichii* (ubulu ani), *Erythrophleum suavolens* (inyi), *Brachystegia eurycoma* (achi), *Prosopis africana* (ugba). These timbers were pulverized using a sawing machine. They were milled and ground and passed through a sieve of 105 microns (mesh size) to remove impurities and then air dried for 48 hours.

2.2. Experimental Procedures

2.2.1. Determination of Moisture Content of Wood (Saw Dust) Samples [20]

A portion (2 g) of each of the raw materials was measured into a wash glass. The samples were placed in the oven for 24 hours at 105˚C. After 24 hours, the oven-dried samples were reweighed and the moisture content was determined with the formula:

$$M_c = \left[\left(W_o - W_1\right)/W_o\right] \times 100 \quad (1)$$

where M_c is the moisture content; W_1 is the new weight after drying; W_o is the initial weight of the dry samples.

2.2.2. Determination of Ash Content Wood (Saw Dust) Samples [21] [22]

Dry samples (2 g) were placed in a pre-weighed porcelain crucible and transferred into a preheated muffle furnace set at a temperature of 600˚C for 1 hour. The crucible and its contents were transferred to a desiccator and allowed to cool. The crucible and its contents were reweighed and the new weight was noted. The percentage ash content was calculated with the formula:

$$A_c(\%) = (W_a / W_o) \times 100 \quad (2)$$

where A_c is the ash content in percentage; W_a is the weight of ash after cooling and W_o is the original weight of dry samples.

2.2.3. Determination of Volatile Content of Wood (Saw Dust) Samples [21] [22]

2 g of each sample was heated to 300˚C for 10 minutes in a partially closed porcelain crucible placed in a muffle furnace. The crucible and its content were retrieved and cooled in a desiccator. The difference in weight was recorded and the volatile content was determined thus:

$$V_c = \left[(W_o - W_a) / W_o \right] \times 100 \quad (3)$$

where V_c is the volatile component in percentage; W_a is the weight of matter after cooling and W_o is the original weight of dry wood.

2.2.4. Determination of Fixed Carbon of Wood (Saw Dust) Samples

The Fixed carbon (F_c) content was determined using the formula:

$$F_c\% = 100 - V_c - A_c \quad (4)$$

where V_c, and A_c are the volatile and ash contents respectively.

2.2.5. Determination of Bulk and Tapped Densities of Wood (Saw Dust) Samples

The bulk density of the raw materials was carried out in the laboratory by the method described in the European Committee for Standardization (CEN/TS 15103, 2005) [23]. A known weight of sample was taken and packed into a 10 ml capacity cylinder of known weight, and carefully weighed. The Bulk density (BD) was calculated using and calculated with the formula:

$$\text{Bulk Density} = (\text{weight of sample}) / \text{volume} \quad (5)$$

For the tapped density, the bottom of the cylinder was tapped 100 times gently on the laboratory bench to contain more samples, weighed and density was also calculated using Equation (5).

2.2.6. Determination of the Water Absorption Capacity of Wood Samples [24]

2 g of sample (recorded as W_1) was carefully measured and dispersed in 20 ml of distilled water. The contents were mixed for 30 seconds every 10 minutes using a glass rod and after mixing five times, centrifuged at 4000 g for 20 minutes. The supernatant was carefully decanted and then the contents of the tube were allowed to drain at a 45˚ angle for 10 minutes and then weighed and recorded as W_2. The water absorption capacity was expressed as a percentage increase of the weight sample thus:

$$\text{Water absorption capacity}\{\%\} = W_2 - W_1 / W_1 \times 100 \quad (6)$$

2.2.7. Determination of Wood Chemical Structural Components

Wood chemical structural components to be determined by standard methods

[25] include extractives (E_c), lignin (L_n), alpha cellulose (A_{cell}) and hemicellulose (H_{cell}).

1) Determination of the lignin content of wood samples

2 g of sample was measured into a 500 ml conical flask, and 15 ml of 72% sulphuric acid was then added. The mixture was stirred frequently for 2 hours 30 minutes at 25˚C. 200 ml of distilled water was then added. The mixture was boiled for 2 hours at 80˚C and cooled afterward. The mixture was kept for 24 hours, and was then transferred to a crucible and washed with hot water repeatedly until it was acid-free. It was then dried at 105˚C for 3 hours; cooled in a desiccator, and then weighed. The lignin content was collected with the equation:

$$\text{Lignin content } (\%) = \frac{\text{weight after drying}}{\text{weight of sample}} \times 100 \tag{7}$$

2) Determination of holocellulose content of wood samples

3 g of air-dried saw dust was weighed into a 500 ml conical flask. 160 ml of distilled water, 0.5 ml glacial acetic acid and 1.5 g sodium chloride were added successively. The mixture was then placed in a water bath and heated at 75˚C for one hour 0.5 ml glacial acetic acid and 1.5 g of sodium chloride was then added again repeatedly at 30 minutes intervals. An ice bath was then placed to cool below 10˚C. The mixture was then filtered and washed with acetone, ethanol and water respectively. The mixture was then dried in an oven at 105˚C, cooled in a desiccator and then weighed.

$$\%\ \text{Holocellulose } (H_{ocell}) = \frac{\text{weight after drying}}{\text{Weight of sample used}} \times 100 \tag{8}$$

3) Determination of alpha cellulose content of wood samples

2 g of the holocellulose was placed in a 500 ml beaker. 10 ml of 17.5% sodium hydroxide solution was then added. The mixture was stirred with a glass rod vigorously. 17.5% sodium hydroxide solution was then added to the mixture periodically (5 minutes intervals) for 30 minutes. The mixture was kept at 20˚C. 33 ml of water was then added to the breaker and kept for one hour. The mixture was filtered and transferred into a crucible. The mixture was then washed with 100 ml of 8.3% sodium hydroxide, 200 ml of water, and 15 ml of 10% acetic acid; water was added again; and the sample was dried and weighed. The alpha cellulose was calculated with this formula:

$$\text{Alpha-cellulose } (\%) = \frac{\text{weight after drying}}{\text{weight of holocellulose}} \times 100 \tag{9}$$

4) Determination of Hemicellulose content of wood samples

The percentage hemicellulose was determined with the equation:

$$\%\ \text{Hemicellulose} = \text{holocellulose} - \text{alpha cellulose} \tag{10}$$

2.2.8. Fourier Transformed Infrared (FTIR) Spectroscopy Experiment

The properties of the raw materials and composites were characterized using FTIR Shimadzu 8400s spectrometer in the range of 4000 - 400 cm^{-1}. Samples were run using the KBr pellet method and the spectra were obtained using 16

scans at a resolution of 4.000 cm^{-1}.

2.2.9. Scanning Electron Microscope

The morphological changes of the raw materials and composites were determined using a Phenom-Prox Electron Microscope. Samples were prepared by attaching individual fibres with carbon tape and coated with gold to be conductive.

3. Results and Discussion

3.1. Physicochemical Analysis of the Woods

3.1.1. Density

The density, moisture content and water absorption capacity of the studied timbers are presented in Table 1.

The results of the density measurements indicated that the bulk density values of the timbers ranged from 0.34 g/cm^3 in *Brachystegia eurycoma* to 0.47 g/cm^3 in *Erythrophleum suaveolens*, with the other timbers having the same bulk density of 0.40 g/cm^3. The trend in descending order of magnitude was: $W_2 > W_4 = W_1 > W_3$, implying that the bulk density of *Erythophleum suaveolens* (W_2) was the highest while that of *Brachystegia eurycoma* (W_3) was the lowest. This showed that W_2 flour had fewer voids than could be in other wood samples. The order of bulk density of wood was in the reverse order to the water absorption capacity as depicted in Table 1. Expectedly, the tapped density followed a similar order of magnitude with respect to the species investigated, that is, the tapped densities of Wood to Wood 3 ($W_{1\text{-}3}$) were greater than their respective bulk densities in the following sequence: $W_2 > W_4 > W_1 > W_3$. The positive correlation between their bulk and tapped density values could be attributed to a close packing of the same species arising from tapping as has been reported [26]. With the exception of W_3, (0.34 g·cm^{-3}), all the other woods were of the medium density extraction with respect to the bulk densities following the classification by the International Association of Wood Anatomists (IAWA) [27] thus:

1) Density low, ≤0.400 g/cm^3;
2) Density medium, 0.400 - 0.750 g/cm^3;
3) Density high, ≥0.750 g/cm^3.

In terms of their tapped densities, however, all of the sawdust derived from the selected timbers may be classified as medium density types by IAWA standards. The average tapped densities of the woods studied (0.5525 g/cm^3) in terms of expected ranges putting into consideration other variables like the anisotropic nature of wood, were in accordance with other studies in tropical forests of West and Central Africa [28] [29] [30].

3.1.2. Moisture Content (M_c)

The results of the moisture content (Table 1) indicated that W_2 had the highest value (8.38%) while W_1 had the lowest (6.52%). Since the more the moisture content of the wood sample, the more susceptible it could be to microbial attack

Table 1. Physical properties of wood sample of species investigated.

Wood species	Bulk density (g/cm^3)	Tapped density (g/cm^3)	Moisture content (%)	Water absorption capacity at 25˚C (%)
Nauclea diderrichii (W_1)	0.40	0.54	6.52	5.29
Erythophleum suaveolens (W_2)	0.47	0.62	8.38	4.29
Brachystegia eurycoma (W_3)	0.34	0.47	7.69	5.66
Prosopis africana (W_4)	0.40	0.58	6.80	5.31

Note: W_1 = Wood One, W_2 = Wood Two; W_3 = Wood Three; W_4 = Wood Four.

in service [31], it follows then that W_1 could be the least susceptible to microbial attack while W_2, the most. Nevertheless, it was observed that the four woods investigated were all within the safe margins for industrial use, since their M_c values were less than 20% [32]. Also, the moisture content of wood represents the free and the bound water in wood samples and can directly affect the drying temperature of wood species [33]. It therefore follows that W_1 and W_4 could be easier to be dried than W_2 and W_3.

3.1.3. Water Absorption Capacity (WAC) at 25˚C

The results of the water absorption at 25˚C (Table 1) of the timbers investigated followed the trend $W_2 < W_1 = W_4 < W_3$. The inverse correlation between the moisture content and the water absorption capacity observed was in line with earlier works reported [34] that indicated that the close packing of the same species affects WAC, since water absorption can be linked with porosity [26] [34]. Interestingly, W_3 had the lowest bulk density (0.34 g/cm^3) while W_2 had the highest bulk density (0.47 g/cm^3). W_3 had the highest water absorption capacity at 25˚C while W_2 was the least, implying that W_3 was more porous than other wood species. The tendency of wood species to absorb water can result in intermittent shrinking and swelling under service conditions thus resulting in a decrease in performance [35]. It was also observed that the water absorption capacity of wood correlated with the cellulose composition of the wood in the order of: $W_3 > W_1 > W_4 > W_2$. This may be attributed to the possible interaction between the hydroxyl group of α-cellulose and water [36].

3.1.4. Proximate Analysis of Wood Samples

The properties of wood play an important role in its effective utilization in the wood industry [37]. Proximate analysis constitutes moisture content (M_c), volatile matter (V_c), fixed carbon (F_c) and ash content (A_c). These categorizations also have implications for energy-related properties of biomass and therefore for the environment with regard to sustainability. Wood's four characteristics (M_c, V_c and A_c) could be determined by the parent source of the biomass, resulting in a wide variety of fuel properties. Depending on these fuel properties, a wood material, for instance could be excluded as an option in production processes for technical or environmental reasons [38]. The results of the moisture content of

the selected timbers studied have been discussed in section 3.1.2., where it was noted that all the selected timbers had values below the 20% threshold for production processes. The Volatile Matter (V_c), Fixed Carbon (F_c), and Ash Content (A_c) of the wood samples studied are shown in Table 2.

Wood plastic composites being a combination of both wood and plastic will *ipso facto,* inherit as it were, the shortcomings of these materials material too (McCoyMart, 2023) [38]. This highlights the importance of doing this analysis which a quest for more insight with regard to their V_c, F_c and A_c.

1) Volatile Matter (V_c)

The V_c is the measure of volatile constituents of wood species. It was observed that W_1 had the highest volatile component (68.55%) while W_4 had the least (50.75%). This would have an implication for the flammability of wood during service since the volatile matter content of the wood component may affect the level of the WPC's resistance to thermal degradation with respect to resistance to high temperature [39]. The observed trend with respect to the V_c of the woods investigated was: $W_4 < W_2 < W_3 < W_1$. The implication with respect to this trend is that *Nauclea diderichii* (W_1) was the least stable with regard to flammability and resistance to heat while *Prosopis africana* would be the most stable with respect to the selected timbers.

2) Fixed Carbon (F_c)

The F_c represents the carbon content after the removal of volatile matter and ash content. From Table 2 W_4 had the highest F_c (43.31%) while W_1 had the least (28.59%). The observed trend for the F_c of the selected timbers considered was: $W_1 < W_3 < W_2 < W_4$. This trend was a reversal of the sequence in the case of the Vc of the woods implying that the V_c was inversely proportional to F_c as reported in literature [40].

3) Ash Content (A_c)

Ash content (A_c) of wood species represents the incombustible inorganic part left after the complete combustion of wood species. The ash content is a vital parameter that affects directly the heating value; insoluble compounds can behave as heat sink in the same way as moisture, lowering combustion efficiency [41]. It has been noted that a biomass with high mineral contents will have a negative impact on the heat content by lowering it [42]. The observed trend with respect to the woods studied was: $W_3 < W_1 < W_2 < W_4$. The implication was that W_3 had less heat sink and as such more heating value than W_4.

3.1.5. Wood Chemical Structural Components

The chemical structure of the wood plays a role in the resulting properties of the species and that is why the knowledge of the chemical properties of wood is very crucial for a proper understanding of the various principles and techniques involved in the employment of wood materials in the wood industry [37]. The wood chemical structural components, viz Extractives (E_c), Lignin (L_n), alpha cellulose (A_{cell}) and hemicellulose (H_{cell}) of the selected woods studied are presented in Table 2.

Table 2. Chemical composition of wood sample of species investigated.

Wood species	V_c (%)	F_c (%)	A_c (%)	E_c %	L_n (%)	A_{cell} (%)	H_{cell} %	H_{ocell} (%)
N. diderrichii (W_1)	68.55	28.59	2.86	1.90	42.32	41.09	11.83	52.92
E. suaveolens (W_2)	58.97	36.78	4.25	9.48	24.06	32.37	29.84	62.21
B. eurycoma (W_3)	64.85	32.83	2.32	2.06	27.01	42.91	25.70	68.61
P. africana (W_4)	50.75	43.30	5.95	5.08	45.57	39.82	3.58	43.40

1) Wood Extractives (E_c)

Wood extractives (E_c) are natural products such as aromatic phenolic compounds, aliphatic compounds (fats and waxes), and terpenes and terpenoids, present within a cell wall, but are not chemically attached to it. Their aliphatic components can act as surfactants limiting fungal adhesion on wood surface, while their phenolics have a more direct effect on fungal physiology [43]. The trend observed with regard to the E_c of the woods investigated was: $W_1 < W_3 < W_4 < W_2$. It follows then that W_2 could be the most protected from termite and microbial attacks in comparison to other wood types in service conditions [44].

2) Lignin (L_n)

Lignin acts like glue, holding the carbohydrate (holocellulose) fraction of the wood together. The precursor of lignin is phenylalanine, and it accounts for some of the nitrogen content of the wood, since nitrogen stimulates its synthesis [45]. From the investigation of the selected timbers, the observed trend was $W_2 < W_4 < W_1 < W_3$. The implication then is that the nitrogen content of W_4 was the highest while that of W_2 was the least.

3) Alpha Cellulose (A_{cell})

The Alpha cellulose (A_{cell}) is the base extractable part of wood and the observed trend was: $W_2 < W_4 < W_1 < W_3$. This trend indicated that A_{cell} correlated positively with the water absorption capacity (WAC) of the woods studied and this may be attributed to hydroxyl groups within the species as has been noted [36].

4) Hemicelluloses (H_{cell})

Hemi cellulose represents the difference between the holocellulose (H_{ocell}) and the alpha cellulose (A_{cell}) content of wood. The observed trend with respect to selected woods studied was: $W_4 < W_1 < W_3 < W_2$. This implied that W_2 had the highest hemicelluloses content, while W_4 had the least. The trend observed in the case of the H_{cell} was $W_4 < W_1 < W_2 < W_3$. It was observed that both the A_{cell} and H_{cell} contributed to the moisture content of wood species, hence W_1 and W_4 had lower water contents compared to W_3 and W_2.

3.2. Structural Properties of the Woods—FTIR Results

The FTIR spectra of the selected wood flour samples analyzed are shown in **Figure 1** and **Figure 2**. The spectra of the wood samples were separated into two regions because of their complexity, namely: the OH and CH stretching vibrations in the 3800 - 2700 cm^{-1} region (**Figure 1**), and the fingerprint region which

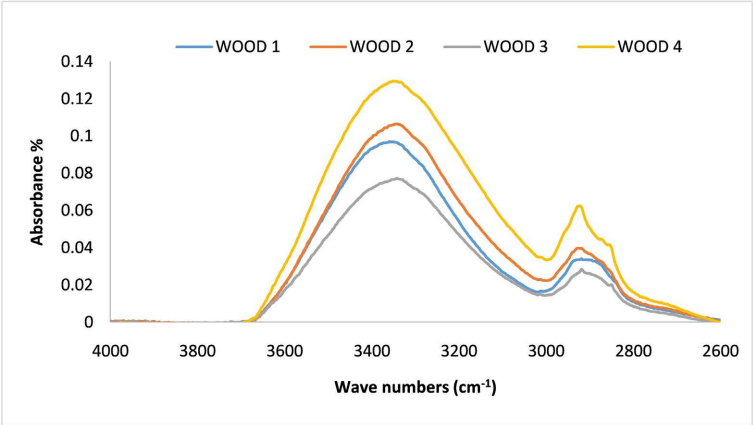

Figure 1. FTIR spectra (Functional group region) of the four wood species studied. Note: WOOD 1 = W_1; WOOD 2 = W_2; Wood 3 = W_3; WOOD 4 = W_4.

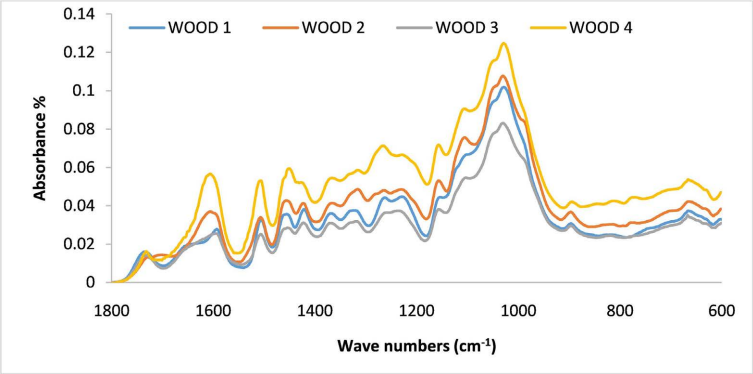

Figure 2. FTIR spectra (Fingerprint region) of the four wood species studied.

is assigned to stretching vibrations ascribed to different groups of wood components at 1800 - 800 cm^{-1} (Figure 2).

In the infrared spectrum presented in Figure 1, it was observed that there was a strong absorption band at 3400 cm^{-1} which could be assigned to different OH stretching modes and another band at 2850 cm^{-1} relating to the asymmetric and symmetric methyl and methylene stretching groups. However, these two bands were more prominent and broader in W_2 and W_4. This might be attributed to the higher extractive contents in these woods, since some compounds like fatty acid methyl esters and phenolic acid methyl esters which contain methyl and methylene groups are present in organic extractives [46] [47].

The fingerprint region contained several bands and peaks assigned to the main components of the wood as presented in Figure 2. The bands at 1592, 1505 and 1228 cm^{-1} are signals assigned to C=C, C-O stretching and bending vibrations of different groups present in lignin. The bands at 1480, 1410, 1300, 1228 and 1120 cm^{-1} were signals characteristics of C-H, C-O deformation, bending or stretching vibrations of different groups for lignin and carbohydrates. The bands at 1731, 1350, and 1029 cm^{-1} were signals characteristics of C=O, C-H, C-O-C, C-O deformation or stretching vibrations of different groups from carbohydrate [48] [49].

However, in the different types of wood, the positions of absorption and intensities of absorption were different. The absorption signal at 1731 cm^{-1} was assigned to C=O stretching vibrations of the carbonyl and acetyl groups in hemicelluloses. Higher holocellulose content and density are indicated by a broad band at 1731 cm^{-1} [50]. W_2 and W_3 presented a slightly more prominent and broader band than the other woods at 1731cm^{-1}, in agreement with the higher holocellulose content. The signal at 1505 cm^{-1} arising from the aromatic skeletal vibrations C=C of the benzene ring is characteristic of lignin [49] [50]. W_2 and W_4 presented the most prominent peak indicating a higher lignin content than W_1 and W_3. However, the results presented in **Table 2** showed that W_2 contained the lowest quantity of lignin. The anomaly observed in W_2 could be due to the very high extractive content, which contains compounds that show absorptions at 1510 cm^{-1} [51]. Poletto *et al.* (2012) [4] revealed that benzoic acid present in wood tannins and extractives, contain aromatic rings in their structure which show absorption at 1510 cm^{-1} and could influence the intensity of this band, therefore making it very difficult to use the peak at 1510 cm^{-1} to compare different lignin contents and lignin/carbohydrate ratios in wood species with higher extractive content. The signal at 1421 - 1430 cm^{-1} is related to aromatic skeletal vibrations associated with C-H in plane deformation of cellulose. The bands at 1368 cm^{-1} and 1097 cm^{-1} are signals associated with carbohydrates. The signal at 1368 cm^{-1} is assigned to CH bending in cellulose and hemicelluloses while the absorption signal at 1097 - 1106 cm^{-1} is assigned to C-O-C asymmetric stretching vibrations in cellulose and hemicelluloses [52]. The signal at 825 - 810 cm^{-1} is assigned to CH deformation in cellulose [51].

The band at 1420 - 1430 cm^{-1} is associated with the amount of crystalline structure of the cellulose while the band at 898 cm^{-1} is associated with the amorphous region in cellulose [52]. The ratios between the two bands are defined as the empirical crystallinity index and presented as the lateral order index (LOI). Also, the signal at 1372 cm^{-1} and 2900 cm^{-1} was also presented as total crystallinity index (TCI) [53]. The ratio between the absorption bands at 3400 and 1320 cm^{-1} was used to study the hydrogen bonding index (HBI) which presents the relationship between the crystal systems and the degree of intermolecular regularity, relating to crystallinity and amount of bound water [54]. The TCI, LOI and HBI of the woods investigated are presented in **Table 3**.

The TCI is proportional to the degree of crystallinity of cellulose in woods and the LOI is correlated to the overall degree of order in cellulose [4]. There is no regular trend for these results of TCI and LOI as presented in **Table 3**. The

Table 3. FTIR crystallinity ratio and hydrogen bond intensity for the wood samples.

	TCI	LOI	HBI
Nauclea diderrichii (Wood 1)	1.072	1.104	2.476
Erythrophleum suaveolens (Wood 2)	1.109	1.060	2.054
Brachistigia eurycoma (Wood 3)	1.185	0.983	2.251
Prosopis africana (Wood 4)	1.067	1.241	2.105

irregularity in the trends may be a result of the complex nature of woods as has been reported elesewhere, the same results were reported elsewhere [4]. However, W_2 had the lowest HBI value. These results may be associated with the lesser amount of absorbed water in W_2, since the HBI value presents the amount of water absorbed [4]. This could be attributed to the higher degree of non-polar aromatic rings from extractives earlier suggested for the higher value for W_2 at 1505 cm^{-1}.

3.3. Morphological Properties of Woods—SEM

The SEM analysis results (SEM micrographs) of the wood flour samples investigated are shown in **Figures 3-6**. It was observed that the surfaces of the woods were rough and heterogeneous with irregular crystal and brick shaped particles. It also contained waxy and fiber shaped materials. These fibrillations may serve as binding materials. Cracks and damages were not observed in all the woods indicating an ordered cellulose structure. It was observed that the SEM micrographs correlated with the tapped densities of the woods studied, for instance the

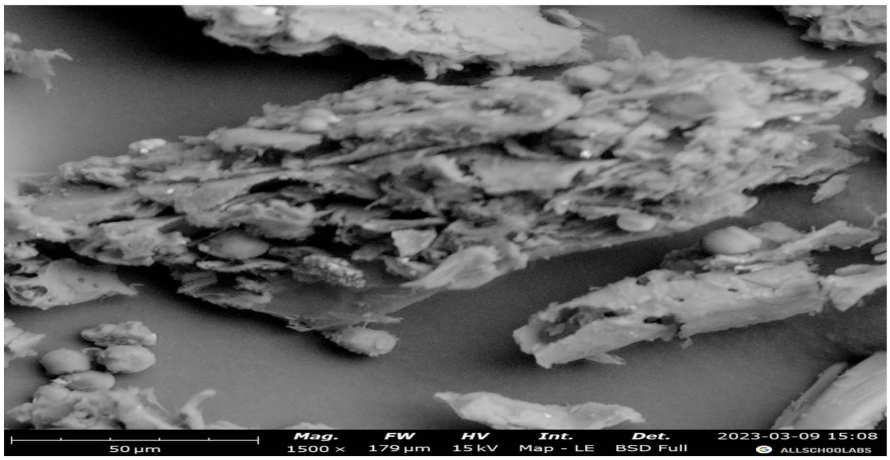

Figure 3. SEM micrograh of *Nuclea diderrichii* (wood one).

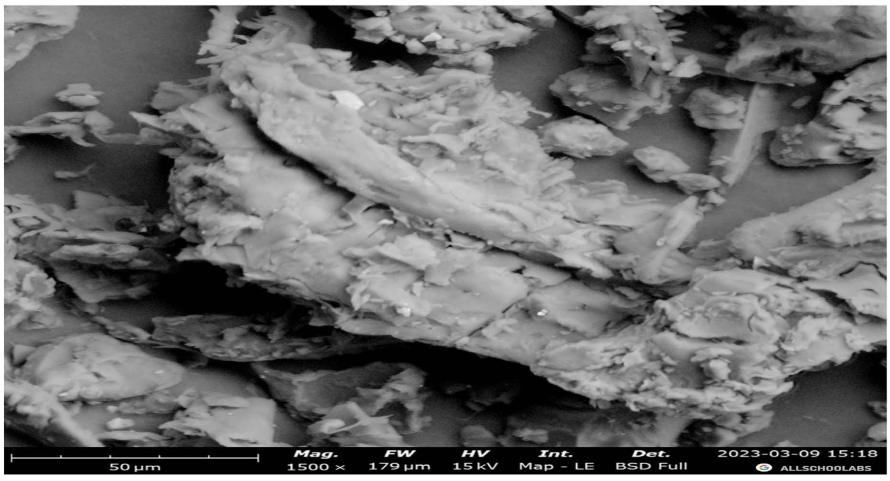

Figure 4. SEM micrograph of *Erythrophleum suaveolens* (wood two).

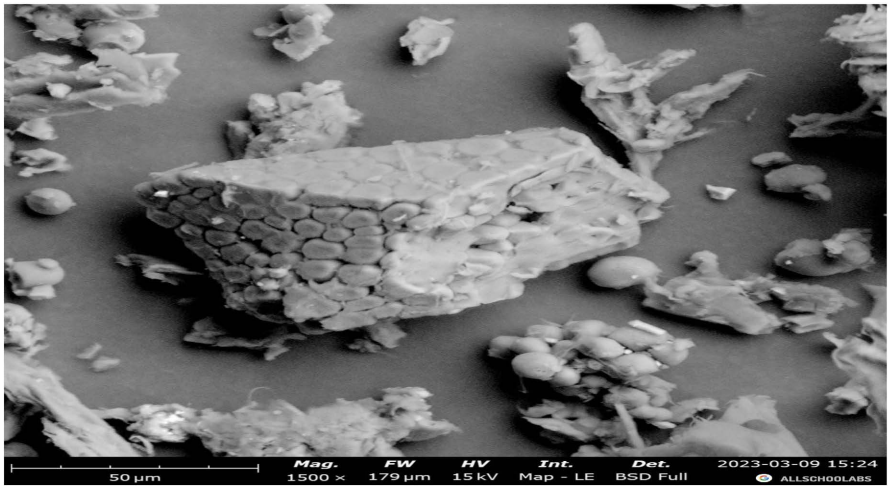

Figure 5. SEM micrograph of *Brachystegia eurycoma* (wood three).

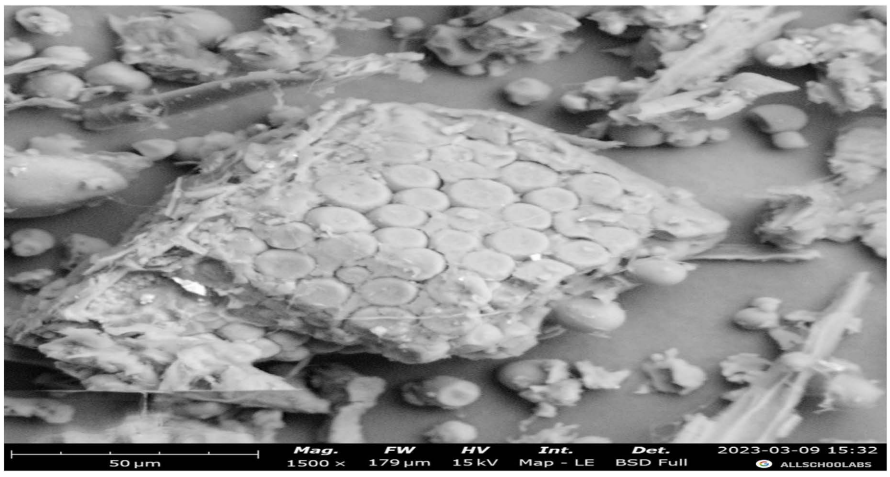

Figure 6. SEM micrograph of *Prosopis africana* (wood four).

SEM micrograph of *Erythopleum suaveolens* (Plate II) correlated with the close packing indicated by its tapped density value which was the highest (0.62 g·cm^{-3}). However, it should be noted that wood particles are generally irregularly shaped and can be classified as non-spherical, but it is not easy to focus on a single feature because of the polymorphic nature of wood [55].

4. Conclusion

This study investigated the physicochemical, structural and morphological properties of four (4) tropical timbers as precursor raw materials for possible utilization in the wood plastic industry. Results showed that there were correlations between the physicochemical, structural and morphological properties of the woods investigated within and between the species. It was observed that water absorption capacity of wood correlated with cellulose composition of wood and this could be attributed to the possible interaction between the hydroxyl group of alpha cellulose and water. The results of the moisture content indicated that

Erythophleum suaveolens had the highest value (8.38%) and would therefore be the least susceptible to microbial attack. The order of the fixed carbon content of the wood was: $W_1 < W_3 < W_2 < W_4$ and this could be correlated with the possibility of predicting the would-be composite that could contribute least with respect to C footprint to the environment. *Nuclea diderichii* (W_1) which had the lowest value of F_c (28.59%) would probably be more desirable for use in the Wood industry. All of the sawdust derived from the selected timbers may be classified as medium density types by IAWA standards and their M_c values, being less than 20% were well within the safe margins for industrial use. These findings, therefore suggest that sawdust waste from these tropical timbers that litter our environment could be credible sources for raw materials needed in the WPC industry in Nigeria for building and construction purposes in a sustainable manner.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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