

## POTENTIALS OF WOOD FIBRE REINFORCED POLYMERIC COMPOSITES: AN OVERVIEW

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### ABSTRACT

Wood has for quite some time been utilized by plastics industry as inexpensive reinforcement or filler to increase strength and stiffness of polymer composites and to decrease raw material expenses too. The shift from petroleum based fibres to plant fibres as reinforcements or fillers in thermosets or thermoplastics is due to relatively low cost, low density, eco-efficient, biodegradability and renewability. This paper provides an overview on the progress made in the area of wood fibre as a material for bio-composites, in terms of source, type, structure and composition. Consequently, this article discusses modification methods as well as most regular matrices utilized in wood fibre plastic composites from both petroleum based and bio-based sources. Properties such as mechanical behaviour, water absorption characteristics and thermal decomposition were reviewed. Hybridization of wood fibre reinforced composites and, processing technologies and application were also discussed. Finally, the review discusses current advances and future trends of wood fibre bio-composites as well as crucial issues that should be tended to.

**Keywords:** Wood fibre; Bio-composites; Mechanical properties; Water absorption; Thermal properties

### INTRODUCTION

In recent years, there is growing concern to utilize biofibres as reinforcements and/or fillers in plastics composites owing to the concern about environment and sustainability issues. It was reported that natural fibre reinforced composites have gotten the attention of researchers and scientists and have been extensively investigated [1]. Wood fibres such as kenaf, wood flour, jute, flax, sisal, bamboo and pineapple are currently being utilized as reinforcing materials in plastics, which offer low-cost, low density and possess good mechanical capability for structural applications [2].

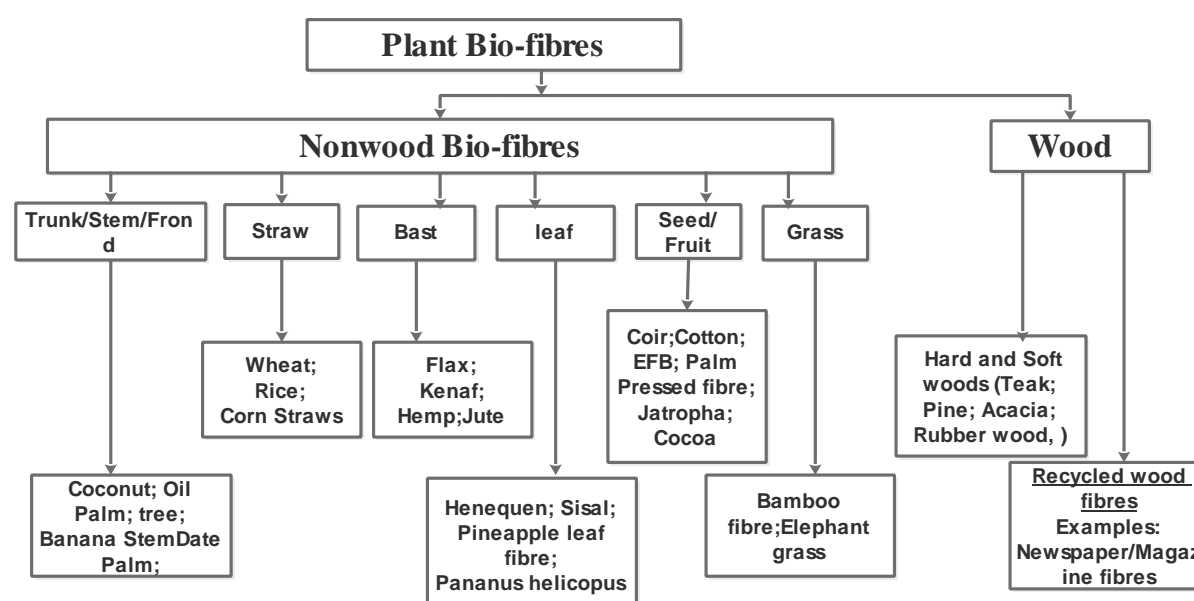
Other major advantages with the utilization of wood fibre composites as substitute to synthetic fibres in composites include recyclability and biodegradability, which implies it could be predisposed of upon the culmination of their life cycle by composting or by the retrieval of their calorific worth which is not conceivable with man-made fibre like glass fibre [3]. However, the major drawback of wood composites including sawdust/wood flour filled composites is that sawdust/wood flour are polar in nature which makes it to possess hydrophilic characteristics. These problems can be addressed by modification of the fibre surfaces through physical method such as corona treatment and cold plasma treatment [4], and chemical method such as dewaxing, alkali treatment, cyanoethylation and benzoylation [5].

Over the years, wood has been utilized by plastic industry as low-priced filler to enhance strength and stiffness of plastic materials because of its low cost, low density, readily available and bio-based nature. While waste disposal problems, environmental issues and high cost are the most grounded contentions for the substitution of synthetic fibres like carbon and glass fibres with wood fibres, wood fibres provide mechanical properties in composites that can measure up or if not better, reduces weight of product by about 15% and have extremely receptive surface structure. Glass fibre on the other hand causes skin and respiratory issues which can be reduced if not eliminated by the utilization of wood fibres [6]. Wood particles, for example chips, fibres, flakes and pulps [7] have been utilized as reinforcement materials in composites. Accordingly, wasted wood materials are currently being changed over into useful items, and this pattern will presumably progress quicker later on. In a similar vein, it has been observed that about 5-11% of total log of wood becomes wastage in form of sawdust of chips during the time of processing [8]. Currently, these wastes wood are either scorched or landfilled; these methods cause various ecological and environmental issues such as pollution, emission of greenhouse gases and occupation of valuable land. In addition, the biodegradable of wastes wood disposed in landfills emit methane, a greenhouse gas which has 72 times heating effect relative to that of CO<sub>2</sub> [9]. However, it has been pointed out that wastes wood incorporated into other materials present numerous advantages and utilities, turning into a focus of dynamic research area with new thoughts that are been conceived and afterward developed [10]. Wood filaments are relatively cheaper as substitute to synthetic fibres, for example, carbon and glass fibres. The cost of wood fibres sourced from hardwood and softwood is in the range of 0.44-0.55 US\$ as against carbon fibre and glass fibre which is 500 US\$ and 3.25 US\$ per kg respectively [2,11-12]. Similarly, wood flour is richly accessible in raw state [13]. The uniformity in properties and low prize of wood flour brands it exceptionally helpful for producing composites.

Wood Polymer Composites (WPCs) including wood flour polymeric composite products have risen as another class of materials that can be utilized as substitute option for solid wood and composites products made from synthetic based material for variety of applications, owing to its competitive mechanical performance, high durability properties, low maintenance, low thermal stability and less wear/abrasion resistances [13-15]. Wood flour has great potential as reinforcing filler owing to its easily availability, cost benefit, good strength, low density, and reasonable consistency (even properties) when compared to other lignocellulose fillers.

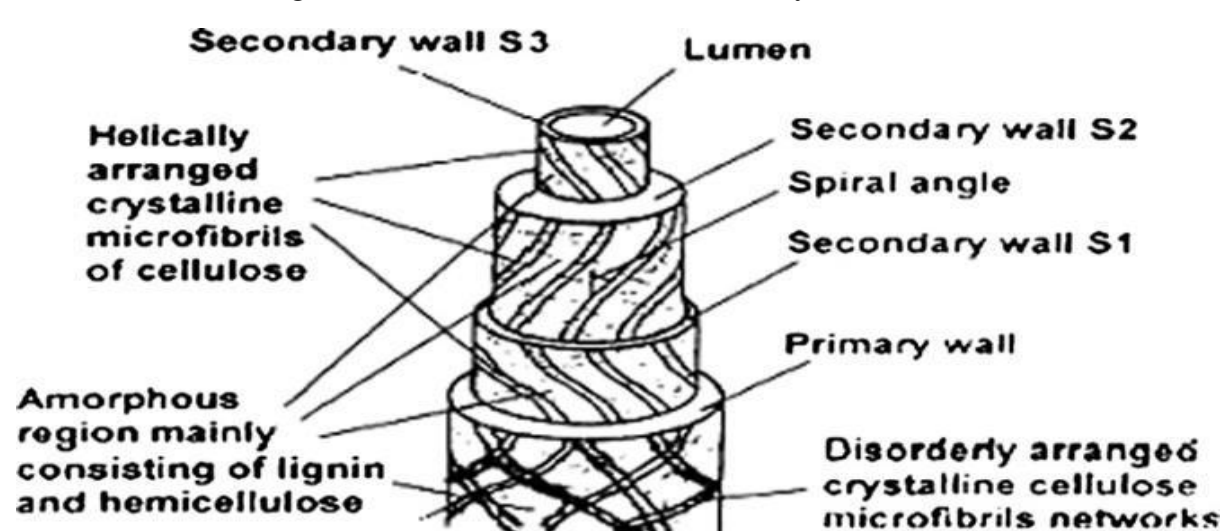
### PLANT FIBRE

Plant fibres are thought to be composites of hollow cellulose fibrils held together by lignin and hemicellulose framework [16]. A similar description of plant fibres was reported [17], which they labelled plant fibres as packs of stretched thick-walled of dead plant cells. A solitary or rudimentary plant fibre is a solitary cell commonly of a length from 1mm to 50mm and a diameter of around 10-50µm. Cellulose, hemicellulose, pectin, and lignin were identified as the main components of plant fibres. Similarly, plant fibres have been categorized into notable classes: stem; straw; bast; leaf; grass; wood and seed/fruit fibres, but a broader classification of plant fibres is represented in (Fig. 1) [19]. Cellulose remains the major constituent of most plant fibres excluding cotton. Natural fibres are made of cellulose, hemicellulose, lignin, pectic, waxes, and water soluble compounds. The reinforcing of lignocellulose plant fibres in a specified polymer matrix is mostly associated with the type of its crystallinity and cellulose quantity [21-23].



**Fig. 1** Schematic representation of reinforcing biofibres classification [20].

The cell wall in any filament of natural origin is described as a non-homogenous film as shown in (Fig. 2). Each fibril has a compound layered structure containing a thin essential wall called the primary wall stored amid cell development encompassing the secondary wall. Three layers and thick centre layer which govern the mechanical behavior and properties of the natural fibre made up the secondary wall. The middle of the road layer involves a grouping of helically circled cell microfibrils produced from broadened chain cellulose particles, the point in the midst of the fibre centre point and the microfibrils is known as the microfibrillar edge. The unmistakable incentive for this parameter varies starting with one characteristic fibre then onto the next. The structure, microfibrillar point, cell measurements, abandons and the concoction organization of fibres are the most noteworthy variable that decides the general properties of natural fibres, also the microfibrillar angle determines the stiffness and ductility of the fibres [24-25].



**Fig. 2** Structure of plant biofibres [25]

Wood from trees are classified into two broad groups: softwoods and hardwoods. These terms can be misleading since a few softwoods are harder than a few hardwoods, while a few hardwoods are gentler than a couple of softwoods, for example, softwoods such as douglas-fir, pine and longleaf are normally stiffer than the hardwoods such as aspen and basswood. Softwoods are accessible specifically from sawmill, retail yards and wholesale. Softwood lumber are being used in creating forms, profiles, scaffolding, sheathing, framing, flooring, panelling, cabinets, moulding, poles and piles, while hardwoods are being used for construction of architectural woodwork, flooring, interior and panelling, and are mostly accessible from lumber yards [26].

The content of cellulose found in wood is about 40% w/w. Table 1. shows the chemical composition of cellulose-wood containing materials from past researchers. Wood can be lessened to fibres, fillers, or pulp and be utilized without detachment of cellulose. Otherwise, for superiority and specified products, cellulose is required to be isolated from the other constituents such as hemicellulose, lignin, pectic and waxes. Cellulose fibres from tree are usually superior, though this depends on the tree part from which they are inferred [27-28]. Wood is an intricate substance which is made up of cellulose, hemicellulose, pectic, lignin and extract. The extent of these constituents differs from one type of tree to another and influences the properties and the behavior of wood. Thermal stability of wood filament can be ascertained by the amount of cellulose, hemicellulose, and lignin in that particular wood. The high and low thermal stability of wood fibre at high and low temperatures may be ascribed to the quantity of cellulose, hemicellulose, pectic and lignin as presented by [29]. Wood with high cellulose content likewise contains extra hydroxyl groups at wood surface, but the interfacial adhesion between such wood filament and the polymer matrix can be improved through the use of compatibilizer, which is usually graft copolymers of the polymeric matrix. A higher content of cellulose can badly influence the water sorption rate due to the rise amount of free hydroxyl groups. This factor is vital when considering mechanical properties, thermal stability and dimensional stability of wood polymer composite materials [30].

Wood fibres as reinforcement in composites offer competitive advantages compared to synthetic fibres. The essential characteristics which qualify fibres as reinforcement in composites are density, diameter, strength and stiffness. These properties, thus depend upon the structure and the specialized modifications, and the wood fibres variable are not controllable as far as such qualities. The distinctive values from softwood and hardwood are shown in Table 2. The frequently somewhat large values for strength and stiffness of lignocellulose fibres depend largely on the natural variation of plant type and source, growth circumstances, and harvest processes, and moderately early stage when make available for the industrial usage as reinforcement in composites [35].

Over the last two decades, numerous productions and applications of thermosetting and thermoplastic polymer composites have been on the increase with the combination of variety of reinforcing filler fibres, for example wood flour/sawdust [43]. Wood flour is a by-product of cutting, pounding, penetrating, sanding, or generally pummeling wood with a saw or other instrument; it is made out of fine particles of wood [44]. It is additionally the result of specific creatures, feathered creatures and creepy crawlies which live in wood, for example, the wood pecker and woodworker ant. In spite of the fact that, the utilization of wood-based fillers is not as prevalent as the utilization of organic fibres, yet wood-inferred fillers have a few points of interest over conventional fillers and reinforcing agents which includes low density, flexibility during processing with no harm to the equipment, acceptable specific strength properties and low cost per volume basis [45].

**Table 1** Composition of cellulose-wood containing materials by previous researchers

Wood fibre	Cellulose (%)	Hemi-cellulose (%)	Lignin (%)	Pectic (%)	Extract (%)	Xylan (%)	Others (%)	Reference(s)
Hardwood (teak)	43-47	25-35	16-24	-	2-8	-	-	[2]
Softwood (pine)	40-44	25-29	25-31	-	1-5	-	-	[2]
Hardwood (teak)	41.7	16.3	27.4	3.4	1.7	8.6	0.9	[31]
Softwood (pine)	41	2.3	22	2.3	3.2	27.8	1.4	[31]
Hardwood (southern red oak)	42	3	19	1	-	35	-	[32]
Softwood (incense cedar)	42	18	27	2	-	9	-	[32]
Hardwood (oak)	38.11	22.69	25.01	3.16	2.03	-	10	[33]
Softwood (pine)	31.84	23.23	22.13	2.35	3.45	-	17	[33]
Hardwood (red maple)	41	27	26	-	5	-	0.5	[34]
Softwood (ponderosa pine)	42	27	25	-	4	-	0.4	[34]
Softwood (pine)	40-45	30	26-34	0-1	2-5	-	1.3	[35]
Hardwood (oak)	40-50	23-39	20-30	0-1	2-4	-	0.9	[35]
Softwood Kraft pulp (pine)	77.5-78.5	19.2-19.4	7-11	0-0.5	0.1-0.5	-	-	[36]

**Table 2** Properties of wood fibres for composites from past researchers

Fibre type	Density (g/cm3)	Diameter (µm)	Length (mm)	Tensile Strength (MPa)	Young Modulus (GPa)	Strain at Break (%)	Reference(s)
Softwood (pine)	1.4	33	-	100-170	10-50	8.0-14.0	[35,37]
Hardwood (teak)	1.4	20	-	90-180	10-70	11.0-13.0	[35,37]
Softwood (pine)	0.3-0.59	30	1.0	45.5-110.7	3.6-14.3	4.4	[11]
Hardwood (teak)	0.3-0.88	16	3.3	51-120.7	5.2-15.6	-	[11]
Softwood Kraft pulp (pine)	1.5	-	-	1000	40	4.4	[38-39]
Softwood (douglas fir)	1.5	-	-	600-1020	18-40	-	[40-41]
Hardwood (birch kraft)	1.2	-	-	-	37.9	-	[42]

It was also demonstrated that wood flour was originally utilized for the purpose to dispose of a lot of wood wastes but are now preferably being used as reinforcing agents in polymer because of low prize, low density, environmental friendliness and in most cases, enhanced mechanical properties which are suitable for structural applications [46]. Some properties of wood and glass fibres are presented in Table 3.

**Table 3** Comparison of properties of wood and glass fibres [47]

Type of fibre	Density (g/cm <sup>3</sup> )	Tensile Strength (MPa)	Modulus of Elasticity (GPa)	Specific strength (GPa cm <sup>3</sup> /g)	Specific modulus (GPa cm <sup>3</sup> /g)
Wood fibre	0.6-1.1	980-1770	10-80	1.63-2.95	17-133
E-glass fibre	2.6	3500	72	1.35	28

**Modification of Wood Fibre**

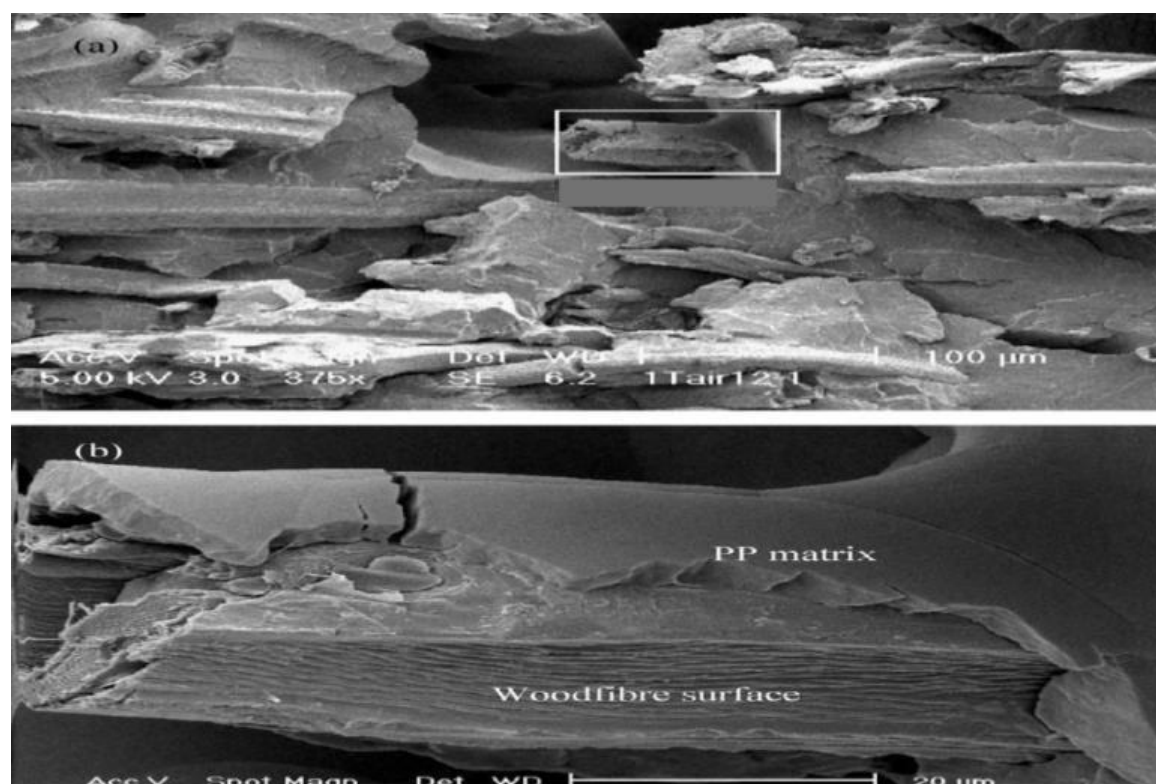
The utilization of wood fibre to produce cost effective and eco-efficient composite materials is a topic of huge significance. Nevertheless, certain drawbacks of wood fibres been extremely polar and hydrophilic in nature lead to poor compatibility with polymer matrix resulting to low mechanical behavior when exposed to atmospheric moisture sorption, but this issue can be solved by modification of the interfacial property [48]. Two main modification methods for reinforcing fillers or fibres are physical and chemical methods [49].

**Physical modification of wood fibre**

Physical modification has dependably been undertaken by the utilization of instruments to alter the surface and structural behaviour of the fibres, with the view of enhancing the mechanical properties of the fibres or fillers, and the interfacial compatibility between wood fibre and matrices. Physical modifications do not change extensively the chemical arrangement of the fibres/fillers, and thus the interface of fibre/filler is greatly improved by enhancing mechanical holding between the fibre and the matrix. One major attraction of this method is that chemicals are not used during the treatment process which makes the fibres/fillers very dry and clean with little or no environmental concerns. Good examples of physical treatment are corona, cold plasma and heat treatment [50]. Corona technique exploits the corona effect which involves the fibrillation of the fibre/filler surface through the development of high electromagnetic fields energy near to charged tiny lines or points thus ensuing ionization in within the closeness, at atmospheric pressure and comparatively moderate temperature. In the ionized area, thrilled species (ions, radicals, etc.) are found to be present, subsequently become active during the surface treatment, through the introduction functional groups containing oxygen. In addition, prolong time for treatment may give rise to fibre with noticeable rough surface [51]. Plasma treatment is another form of physical modification similar to the corona treatment which makes use of plasma property to modify the fibre or filler surface. At the course of the treatment, an ionized region is formed with its composition depending on the gas fed, including high energy electrons, photons and radicals [51]. While heat treatment encompasses heating the fibres/fillers or producing the composites at a high temperature near to which the constituents of lignocellulose fibres start to degrade. When cellulose is subjected to elevated temperature, it experiences both chemical and physical changes. Physical properties that are likely affected, for example, the weight, colour, strength, enthalpy and crystallinity. Chemical changes include creation of free radicals, formation of carbonyl and peroxide groups, and reduction of the degree of polymerization by bond scission [52].

The corona treatment on the cure characteristics, mechanical parameters and water desorption on wood flour composites resulted the wood filament into a semi active filler [55]. The authors concluded that the action of the treatment led to surface scratching that alters the geometric region of the wood fillers and the build-up of surface polarity of the wood fillers was attributed to the enhancement of the mechanical behavior noticed through the proper interfacial bonding between the wood filament-fillers and the matrix. The effect of plasma treatment in improving the performance of wood-flour-polypropylene (PP) composites has been reported [54]. Argon and air-plasma methods were utilized to treat the surface of wood flour. It was reported that tensile strength of wood-flour-polypropylene composites treated with plasma performed better over untreated wood-flour polypropylene composites, with air-plasma treatment recorded an increment of 20%, while argon plasma treatment had 12% increase when compared with the untreated wood-flour-polypropylene composites. Figure 3 showed the scanning electron microscopy (SEM) analyses of the crack surface of the air-plasma treated wood-flour-polypropylene composites. The examinations uncovered the upgraded morphologies of the break surfaces of the composites. The surface-sensitivity characterization through electron spectroscopy showed improvement in oxygen/carbon proportions of the wood fibres after the surface treatment.





**Fig. 3** Micrographs of the fracture surface of air-plasma treated wood fibre-PP composites (treatment time 30 s): (a) overall fracture surface; (b) the enlarged interpretation of the of improved morphology region [54].

Steam treatment of wood at elevated temperature results in numerous changes [55]. They went further to itemize some changes which include (i) deteriorate the hemicellulose in order to lower the hygroscopicity and equilibrium moisture content, (ii) produce furan monomers which could generate polymers for enhanced interior bond strength, (iii) thermoplastic laicize the lignin matrix and modify it to produce a new collapsed unstressed matrix, and (iv) offer ascent to composites with significantly enhanced dimensional stability. The effect of heat treatment on the mechanical behavior of wood-thermoplastic composites has been investigated, the wood-flour was subjected to different temperature (175, 190 and 250<sup>0</sup> C) for 45 minutes before incorporating into High-Density Polyethylene (HDPE) and MAPP coupling agent [56]. The authors reported that the effect of heat treatment temperature of wood-flour and the MAPP content on properties of composites with 25% fibre weight fraction was inconsequential, however at 50% fibre weight fraction, heat treatment was found to be a good way to build up performance of composites. The research concluded that heat treatment at 190 and 205°C brought about composites with the uppermost tensile strength and modulus as well as flexural strength and modulus.

#### Chemical modification of wood fibre

The weak compatibility between the highly hydrophilic wood fibres and the hydrophobic polymers is related with the poor mechanical behavior in wood polymer composites [57]. However, to enhance the interfacial attachment between the polymer matrix and wood flour, a chemical treatment of wood flour is a suitable arrangement. If two constituent materials are not compatible to each other, it is regularly conceivable to realize similarity by presenting a third material that has a middle of the road properties between the two material is introduced such as compatibilizer [50]. Compatibilizers are often called coupling agents. Different methods have been employed to modify the surface property of materials with chemical agents. Good examples of chemical treatments are mercerization, graft copolymerization, silane coupling agents and esterification-based treatments. Silane, isocyanate and titanite based compounds are the most important coupling agents, the chemical composition of these compounds allows them to react with fibre/filler surfaces which forms a bridge of chemical bonds between the fibre/filler and the matrix. In the case of cellulosic fibre/filler composites, isocyanates were found to be reliable. It is expected that the formation of a primary covalent bonds between cellulose and isocyanate, and secondary weak bond between matrix and isocyanate leads to enhancement of the mechanical behavior of wood fibre filled polymer composites. Modification of fibres by enclosed coating by means of silanes or isocyanates, grafting and esterification-based methods such as the used of carboxylic acid offer improved dispersion via plummeting the fibre-fibre interaction through the development of coating on the fibre surface [49].

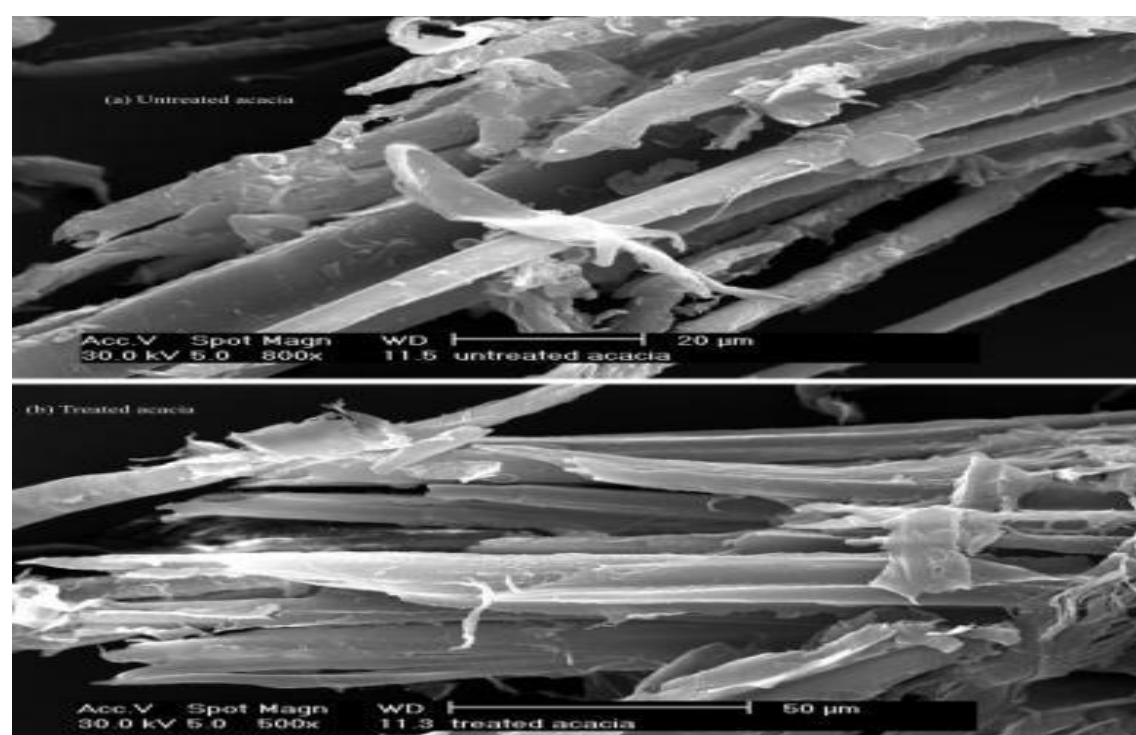
#### Mercerization of wood fibre

Mercerization or alkaline treatment is a standout amongst the most well-known methods of chemical treatment used for the treatment of wood fibres in composites either for thermoplastics or thermosets polymer. At the course of the treatment, the alkaline disrupts the hydrogen bonding in the system structure, thus surging surface roughness. This treatment effectively removed hemi-cellulose, lignin and certain amount of wax and oil on the fibre structure, thereby increasing the cellulose content in the fibre [58]. Therefore, alkaline treatment specifically impacts the cellulosic fibril and, likewise the level of polymerization and, the removal of lignin and hemicellulosic constituents [59]. The addition of aqueous sodium hydroxide (NaOH) to natural fibre according to [60] is expected to promote the ionization of the hydroxyl group to the alkoxide in the following reaction in equation 1.



Most researchers have varied sodium hydroxide concentration in the treatment of natural fibre/filler between 0.8-15wt% [61]. The authors further stated that higher concentration of alkaline up to 30wt% have likewise been attempted, however for composites fabrication, a lower level of alkaline is ideal. Surplus concentration of alkaline deteriorates the fibre strength severely. They affirmed that high level of alkaline is only suitable in areas, for example, extraction of Nano fibres, mercerization of textile apparels and so on. In a similar vein, it has been shown that alkali content increased to more than 10wt% led to tensile and flexural strengths decrease because of corrosive interactions between wood fibres in the composites caused by excessive alkaline that weakens the wood fibre surface [62-63]. The influence of alkaline treatment on the physical and mechanical properties of wood sawdust particles polymer composites has been studied [64]. Three diverse types of wood sawdust were modified with 10% of sodium hydroxide concentration differently. Both treated and untreated wood sawdust fillers were incorporated into polyester matrix and, the tensile strength and moisture sorption property were investigated. It was reported that the tensile strength of the composites significantly increases owing to the chemical modification of the sawdust particles, also noticeable is that the treatment of wood particles decreases the moisture sorption of the sawdust polyester composites. Other results revealed that the moisture uptake of the sawdust polyester composites rises with increment level of sawdust particles and weathering period. In a similar scenario, a study on the mechanical properties of composite materials produced using sawdust, cassava starch and natural latex was carried out [65]. The percentage of sodium hydroxide for the treatment of sawdust was varied from 1%, 3% and 5% w/v respectively. The results obtained from the various NaOH solution showed that the 5% NaOH concentration produced the best mechanical properties. The influence of alkaline treatment on the properties of sawdust/polyester composites was also investigated [66]. The sawdust filler was treated in a 10% solution of NaOH concentration for 3

hours at ambient temperature. The surface morphology of the treated and untreated wood particles was studied through SEM as shown in (Fig. 4). Fig. 4(a) according to the authors indicated a jagged and roughed surface for the untreated fillers, also exposed presence of oil, wax and some form of impurities on filler surfaces for the untreated fillers, while Fig. 4(b) displays that the substance on the surface of the filler was cleaned with the alkali treatment. Hereafter, produces an enhancement in wettability property. The both micrographs shown the fibrillation of the filler by the treatment. It is anticipated that the fibrillation led to an increase in the surface area of the filler and subsequently to an enhancement of the adhesion between the polymer matrix and the filler.



**Fig. 4.** Photomicrographs of (a) untreated sawdust filler (x500) and (b) treated sawdust filler (x500) [66]

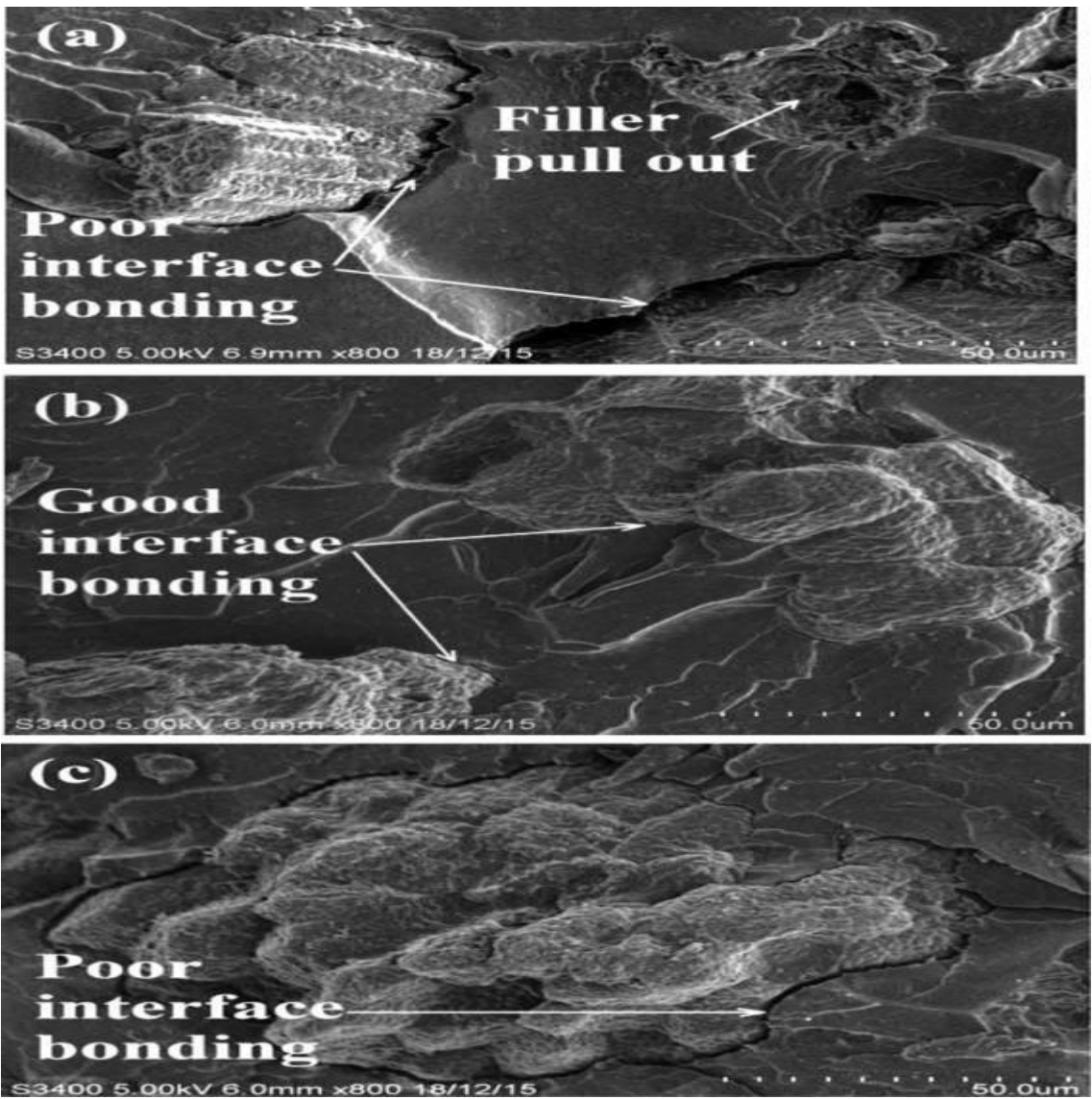
Mechanical and thermal properties of polymeric composite containing alkaline treated wood flour from palm oil biomass have been investigated by [67]. Hot alkali was varied at 1%, 7% and 9% respectively. It was reported that 7% NaOH displayed the best interfacial holding conduct when contrasted with 1% and 9% cases. The authors affirmed to the fact that their finding agrees with [68], where the increment in the mechanical properties was credited to the alkaline treatment of the fibre which resulted to improved mechanical interconnecting and increment of the fibre surface roughness together with an increased amount of cellulose been exposed on the fibre surface. Fig. 5 shows the SEM micrographs of the 1%, 7% and 9% alkali treated Oil Palm Shell (OPS) powder composites.

## MATRIX

Matrix is a material that gives body and holds the reinforcement of the composite together and is generally of lower strength than the reinforcement [69]. The plastic matrix has a low density but is not very strong or stiff, whereas the fibrous or particulate reinforcement can be very strong and stiff but requires a medium to protect the fibres or particles and help transfer loads among them. Matrix also performs the function of a binder which holds reinforcing agents together. Other than that, when a composites material is subjected to applied load, the matrix disintegrates and transfer the external load uniformly to the fibres or particles. Matrix likewise gives protection from break engendering and harm resistance attributable to the plastic stream at split tips. In a certain composite material, both matrix and reinforcement are discernible. To a large extent, each one of the materials keeps up its distinctive attributes, which enhances the behavior of the subsequent composite material. In general, mechanical and physicochemical properties of the composites are better than those of the matrix material [70]. Composites can be customized to show an extensive variety of wanted properties. Many composites materials offer valuable properties for example, high fatigue strength, low weight, corrosion resistance, and higher specific properties such as tensile strength, compressive strength, shear strength, flexural strength and impact resistance [71]. Additionally, the matrix function to protect the surface of particles or fibres from unfavourable environmental impacts and abrasion particularly during composites manufacturing [72].

### Synthetic Polymer Matrix Materials

In natural fibre reinforced composites, both thermoset and thermoplastic matrices are broadly being utilized. Thermosets are arranged polymers that are vigorously cross-connected to give a thick three-dimensional system. These connections avert the chains from sliding past each other bringing about a higher modulus and enhanced creep resistance. They are typically rigid. They can't be melted through heating and they deteriorate when subjected to high temperature. The name develops on the ground that it was fundamental to heat the principal polymers of this kind for the cross-connecting to occur. The term is by and by used to assign this kind of material notwithstanding when heat isn't required for the cross-connecting to occur. Thermosets, as a result of their three-dimensional cross-linked structure, have a tendency to have high dimensional steadiness, high-temperature resistance, and great protection from solvents. As of late, significant advance has been made in enhancing the toughness and most extreme working temperatures of thermosets. The most common types of thermosetting polymers are epoxies, polyester, vinyl ester and phenol formaldehyde [73]. Classical properties of these resins are given in Table 4. Thermosetting materials are most frequently used for high advanced composites as compared to thermoplastic polymer which consists of linear or branched molecules and they melt or soften when heated, so they can be moulded and remoulded by heating. Examples of thermoplastic matrices include Polyethylene, Polypropylene, Polystyrene, nylon, Polycarbonate, polyamide-imide, polyphenylene sulphide, Polyether-ether Ketone, polyacetals and polyether imide [74]. Also, typical properties of some common thermoplastic matrices are presented in Table 5.



**Fig. 5** Photomicrographs showing the influence of NaOH concentration on the quality of interfacial bonding in the 15 wt% OPS powder- polyester composites treated with hot alkaline at: (a) 1%, (b) 7%, and (c) 9% [67].

**Table 4** Properties of some common thermosetting matrix materials [75-76]

Properties	Polyester Resins	Vinyl ester Resins	Epoxy Resins	Phenolic Resins
Density (g/cm <sup>3</sup> )	1.2-1.5	1.2-1.4	1.1-1.4	-
Tensile Strength (MPa)	34-105	73-81	55-130	50-60
Tensile Modulus (GPa)	2.1-3.5	3-5.5	2.7-4.1	4-7
Flexural Strength (MPa)	70-110	130-140	110-150	80-135
Flexural Modulus (GPa)	2-4	3	3-4	2-4
Glass Transition Temperature (°C)	130-160	-	170-300	175
Specific Gravity	1.1-1.4	1.1-1.3	1.2-1.3	1.2-1.3
Moisture Uptake (wt.%)	0.5-2.5	-	2.5-6.0	-
Tensile elongation to break (%)	2	4-7	1-6	-
Cure Shrinkage (%)	5-12	5-10	1-5	2-4

**Table 5** Properties of some common thermoplastic matrix materials [10,38]

Polymer	Density (g/cm <sup>3</sup> )	Tensile Strength (MPa)	Young's modulus (GPa)	Elongation (%)
Polypropylene	0.9	35	0.83	200
Polyethylene (HDPE)	0.95	28	1.04	30
Polycarbonate	1.2	62	2.3	100
Polyetherimide	0	105	2.8	-
Polystyrene (high impact)	1.05	35	2076	15

Epoxies, polyesters and vinyl esters account for roughly 90% for all thermosetting materials are utilized in composites manufacturing [2]. While epoxy resins have been extensively utilized as a model matrix for many researches on lignocellulose fibre composites, they are probably not going to see far reaching usage in commercial lignocellulose fibre composites due to their comparatively high cost. Cheaper resins, for example, polyester and vinyl ester are more frequently utilized. Orthophthalic polyester polymer resin is the standard cost-effective resin commonly used and it gives great rigid composites with low heat resistance and it is also becoming the preferred material in marine applications owing to its superior water resistance [2]. Phenolic resins have good fire resistance but are more difficult to process. Many research works have been done with wood flour/sawdust thermoset reinforced composites as well as wood flour/sawdust thermoplastic reinforced composites. The influence of filler content on the curing behavior and, mechanical and thermal behavior of Oil Palm Shell (OPS) flour filled thermoset reinforced composites has been investigated [77]. The composites were fabricated using unsaturated polyester, vinyl ester or epoxy with OPS flour. The authors reported that the OPS flour was noticed to have better compatibility with the polyester resin than the vinyl ester and epoxy, with the epoxy having the least compatibility. Wood dust reinforced epoxy composites were fabricated with seven different percent of filler weights [78]. It was observed that the mechanical behavior rises up to specific percent of filler content and subsequently, the mechanical properties slowly decreased. A research on the properties of sawdust-polyester resin composites in light of reused Polyethylene Terephthalate (PET) has been carried out, and reported



that the results from the research showed both tensile modulus and flexural modulus increased with higher percent of filler content whereas the tensile strength and flexural strength declined [79]. However, the researchers concluded that this trend was overwhelmed by the treatment of sawdust filler with 10% NaOH arrangement. The tensile strength, flexural strength, water sorption and hardness tests reviewed that the alkaline treatment has improved the bonding between the sawdust and the matrix.

Wood flour-polypropylene composites treated with maleated polypropylene showed slight increment in tensile strength and modulus [80]. In a similar vein, [30] reported higher tensile strength of wood flour-polypropylene composites with coupling agent over composites without coupling agent. The properties of sawdust reinforced polypropylene composites and reported that the values of the mechanical properties of the treated sawdust-polypropylene composites were observed to be altogether higher than those of the untreated ones [81]. The influence of Melamine Polyphosphate (MPP) and Aluminium Hypophosphite (AHP) on the mechanical properties, flame retardancy and thermal degradation of high-density polyethylene/wood flour composites was investigated [82]. The research revealed that incorporation of MPP and AHP enhanced the mechanical and thermal properties of the polyethylene/wood flour composites.

**Bio-based Polymer Matrix Materials**

Bio-based or biodegradable polymers which can be sourced from sustainable agricultural materials are currently been used as potential substitutes for existing petroleum-based synthetic polymers due to their easily available, cost effective and good biodegradability characteristics. Little works have been carried out to study composites with matrices derived from natural resources as compared to petroleum-based synthetic polymers [83-85]. They attributed the low patronage of bio-based matrices to poor commercial availability, poor processability, poor impact strength, low heat distortion temperature, low toughness and low moisture stability. Polymers from renewable materials that are commonly used in composites are cellulose esters, polylactic acid, poly hydroxyl butyrate's, lignin-based plastics and starch [85]. A standout amongst the most promising bio-based polymers is the Polylactic acid (PLA). PLA is sourced from renewable resources such as corn starch, tapioca starch or sugarcane. PLA is in a class of crystalline natural thermoplastic polymer with moderately melting point and brilliant mechanical properties. Polylactic acid has become popular owing to its commercially available from renewable resources [86-88]. Properties of PLA is showed in Table 6.

**Table 6** Properties of Polylactic acid resin matrix [89]

Density (g/cm <sup>3</sup> )	Tensile strength (MPa)	Tensile modulus (GPa)	Flexural strength (MPa)	Flexural modulus (GPa)
1.2	32.5	3.8	71.5	4.9

Cashew nut shell liquid resin to reinforce teak wood sawdust was studied [90]. Three set of samples were fabricated by varying the amount of resin, and also keeping the quantity of teak wood sawdust at constant, for the purpose of investigating the mechanical behaviour of the composites. The authors concluded that the composites can be utilized adequately for taken a cost viability where high quality and firmness is not the real concern. The thermal and mechanical properties of wood flour/talc-filled polylactic acid composites have been investigated [91]. The authors reported that the use of wood flour, talc and silane in the composites causes progressively bigger decline in the composites crystallinity. The incorporation of talc and silane to PLA/wood flour composites enhanced the tensile modulus. The tensile strength of the composites diminishes marginally with the incorporation of talc, yet it extensively enhances with the utilization of 1wt % of silane coupling agent. In a similar manner, [92] studied the surface modification of spruce wood flour and its effects on the dynamic fragility of PLA/wood flour composites. The authors reported that with the incorporation of 40% un-treated spruce wood flour in PLA, the PLA/wood flour composites recorded an increment of tensile modulus with decreased tensile strength, while the composites containing silane-treated spruce wood flour induced a tensile strength increment with higher tensile modulus.

**PROPERTIES OF WOOD -POLYMER COMPOSITES**

Most properties of wood polymer composites to a great extent rely upon various factors, for example, volume fraction and aspect ratio of wood fibre, wood fibre orientation, dispersion level, fibre-polymer adhesion, mixing time and processing temperature. Past researchers have identified some properties of wood polymer composites, the performance of wood polymer composites is a function of fibre content, various treatments of the fibres/fillers and the use of external coupling agents [93].

**Mechanical Properties**

The mechanical behaviour of wood polymer composite, such as strength properties, stiffness, impact resistance and hardness play a vital role in determining the suitability of wood polymer composites for numerous applications, and largely depended on several factors such as collaboration between wood filler and matrix, including matrix attributes, characteristic of wood filler and also processing conditions [94-95]. Several research works have been conducted on wood polymer composites to fully characterize the effect of wood fibre/filler in polymer composites [30,44,77,92]. Table 7 showed mechanical properties of wood polymer composites from previous researchers.

**Moisture Properties / Water Absorption Characteristics**

Since moisture can behave like a dispersant when absorbed into composites, thus it can affect both the mechanical behaviour and dimensional stability of the composites. The dynamics of water uptake in composites encompasses diffusion via the matrix, capillarity through wood fibres or movement through porosities in the matrix or the fibre-matrix interface. Water uptake in composites does not only depend on the hydrophilic nature of the filler and the matrix, but also on the fibre-matrix interphase and the morphology of the composites. Composites morphology can take in form of processing conditions while interphase morphology is influenced by voids, fibrillation and diffusion of additives to the fibre-matrix interface [104]. Water uptake in composites can be measured at different relative humidity or during water immersion. The percentage weight of water uptake can be calculated from equation 2 [105].

$$M\% = \frac{M_t - M_0}{M_0} \times 100 \tag{2}$$

Where  $M_0$  is the dry initial weight, and  $M_t$  is the weight of the specimen during the exposure. [106] investigated the effect of water sorption on the mechanical behaviour of wood flour- Polypropylene composites. The composites were loaded with 20% or 40% wood flour by weight and sited in different environment. The condition of exposures were 30%, 65% and 90% relative humidity (RH). It was reported that the composites filled with 20% wood flour absorbed moisture in all the environmental exposures, but no significant degradation of property was noticed, however it was observed that the 40% wood flour composites assimilated more water than the 20% wood flour composites. The same study gave results of water sorption of composite samples containing 20% wood flour immersed in water as little above 1.4% of composite moisture uptake when equilibrium was achieved, while 40% wood flour composite samples retained roughly 9.0% moisture at equilibrium. Equilibrium time in the water was achieved at roughly 1500 hours for 20% wood flour samples and 1200 hours for 40% wood flour samples. Fig. 6 and 7 show moisture uptake for both 20% and 40% wood flour composites as a function of exposure time. Similarly, [107] carried out a research on water absorption behaviour of wheat flour and wood sawdust reinforced-PP composites. The research revealed that polypropylene is extremely hydrophobic, and its water uptake ability is increased

by the incorporation of sawdust and wheat flour. Water absorption is higher in PP-sawdust composites when compared to PP- wheat flour. This phenomenon was attributed to the finer particle size of sawdust which provided higher surface area.

**Table 7** Mechanical properties of wood fibre reinforced polymer composites from previous research

Filler type	Matrix	Treatment	Filler Content (%)	Particle Size (µm)	Tensile Strength (MPa)	Tensile Modulus (GPa)	Flexural Strength (MPa)	Flexural Modulus (GPa)	Elongation at break (%)	References
Wood flour	PP	3% MAPP	40	212	25.7	3.61	42.6	3.15	2.27	[96]
Wood Flour	PP	3% MAPP	40	212	25.5	3.80	43.99	3.20	-	[97]
Wood flour	PE	1.2-1.8 % MAPP	40	150-355	26.0	-	34.89	-	-	[98]
Wood flour	PE	-	55	500	13.9	3.24	20.5	3.12	-	[99]
OPS flour	Polyester	7%NaOH	13	75-150	42.6	2.41	77.8	4.06	-	[100]
OPS flour	Vinyl Ester	7%NaOH	13	75-150	40.8	1.95	60.2	3.10	-	[100]
OPS flour	Epoxy	7%NaOH	13	75-150	44.7	1.87	61.8	2.45	-	[100]
Wood flour	Epoxy	-	10	2	28.29	1.19	47.65	1.34	-	[78]
Wood flour	PP	18% NaOH	40	250	38	3.21	-	-	-	[45]
Wood flour	PP	5.7% NaOH	40	75-150	42.28	-	71.33	-	-	[91]
Wood Saw dust	Polyester	10% NaOH	5	250-500	34	-	-	-	-	[64]
Saw dust	PP	5%NaOH + Benzene diazonium salt	15	180	28.5	1.2	51.5	1.75	-	[81]
Wood flour	Polyester	10%NaOH	40	57	-	-	45.05	5.02	-	[101]
Wood flour	PP	3% MAPP	70	180-250	23.24	4.14	-	-	-	[102]
CSP flour	Epoxy	-	20	100	37.31	0.7	-	-	-	[103]

**Note:**

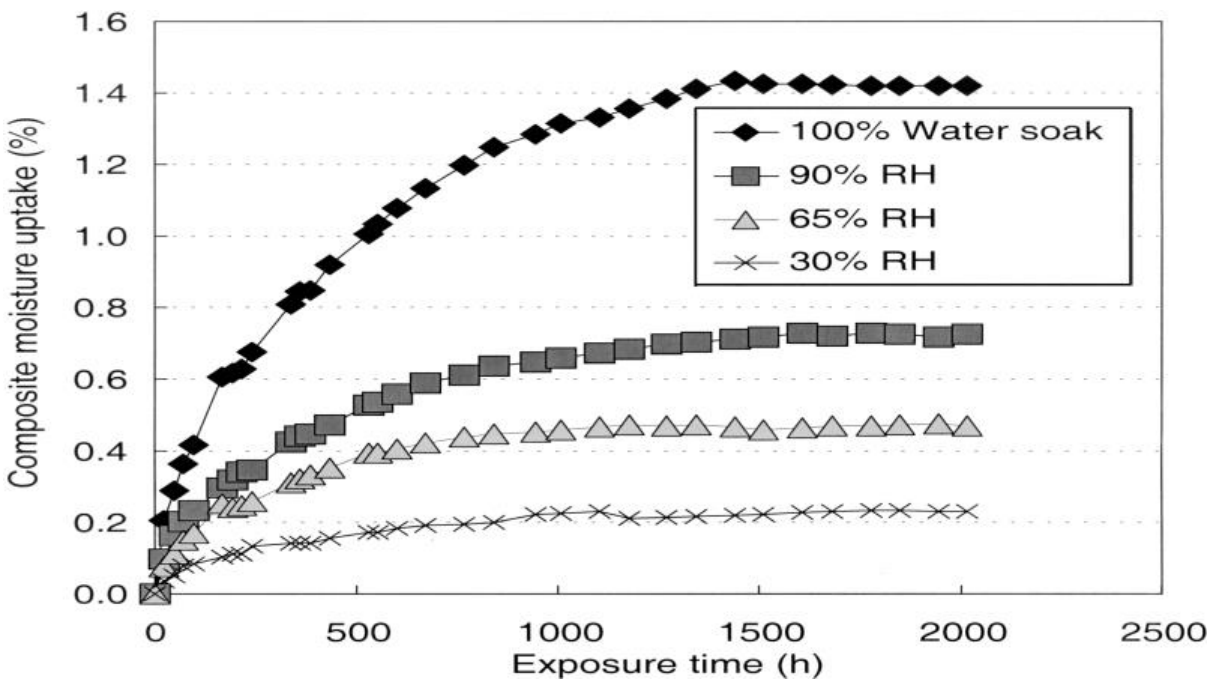
PP- Polypropylene

PE- Polyethylene

MAPP- Maleic anhydride grafted polypropylene

OPS- Oil palm shell

CSP- Coconut shell particle

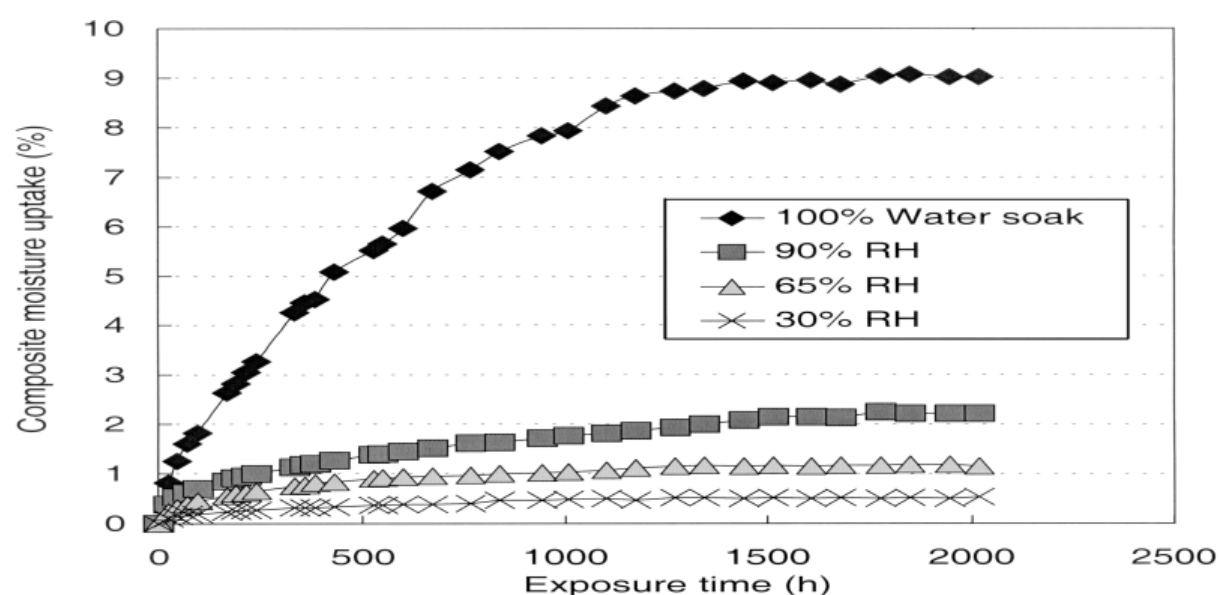


**Fig. 6** Moisture absorption of 20% wood flour composites as a function of exposure time [103]

**Thermal Properties**

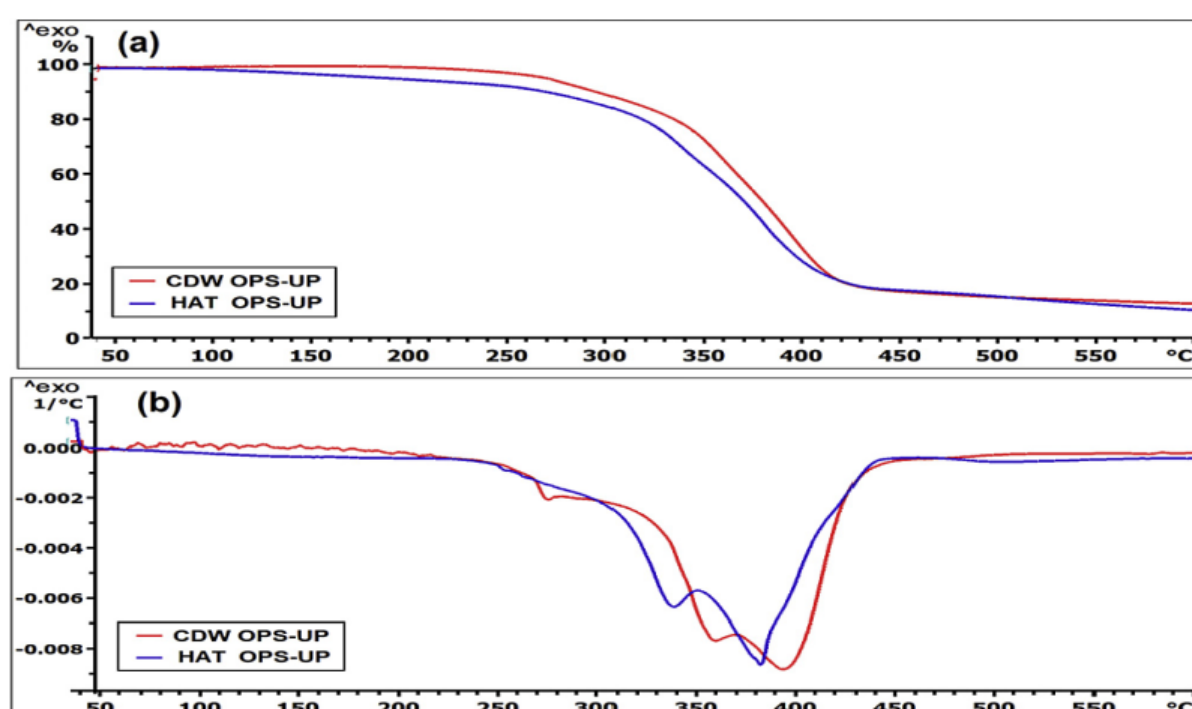
Thermal examination of bio-composites materials avails us the necessary information concerning thermal stability of these materials [108]. [109] pointed out that the thermal behaviour of wood fibres and wood fibre reinforced composites can be studied through Dynamic Mechanical Analysis (DMA), Thermo-gravimetric Analysis (TGA) and Differential Scanning Calorimetric (DSC). Since wood fibres are hydrophilic in nature, the water absorption peak level is usually observed around 100<sup>0</sup>C. The measure of assimilated water relies upon the ambient humidity. No polymer decomposition takes place below 160<sup>0</sup>C according to [110]. The temperature at which noteworthy weight reduction begins is taken as a premise to measure up the thermal stabilities of the specific fibres or composites. Thermal decomposition characteristics of polypropylene carbonate-poplar wood flour was examined by [111] through the means of TGA and DTA.





**Fig. 7** Moisture absorption of 40% wood flour composites as a function of exposure time [103]

Composites with wood fibre fraction from 20 – 50wt% and in addition the neat samples were studied. The authors observed reduction in mass of lesser temperature allocated to the normal thermal decomposition of the polypropylene carbonate-poplar wood flour composites. The general rate of disintegration at a given temperature declines with increasing wood filler content. The main decomposition behaviour does not change however, with the incorporation of wood, the curves moved to upward temperatures with increment in wood filler content. [77] studied the influence of filler loading on the curing behaviour and thermal properties of wood flour filled polymeric composites. It was observed that the thermal decomposition and the linear shrinkage of wood flour filled composites was found to decrease with an increase in filler load. The authors further pointed out that the phase separation was influenced to some degree by the modification of the plant filler flour with two-fundamental peak in the DTG curve getting thinner as could be seen in (Figure 8) also with the low peak being removed as a result of the treatment. Also, the key peak position at 349.25 and 403.40°C were moved to lower values of 336.7 and 362.17°C also as the result of the of 7% hot alkali treatment (HAT). The NaOH treatment composites demonstrated a lesser mass residue of 8.37% when compared to the oil palm shell (OPS) – unsaturated polyester (UP) composite with filler immersed in distilled water (CDW) at 25°C which has a value of 10.44% as shown in Fig 8(a). It was concluded by the researchers that the results may be because of the way which alkaline treatment can clean certain impurities from the lignocellulose fibre cell such as oil, waxes, and some constituents of lignin and hemicellulose that constitute a considerable extent of residue and deterioration during elevated temperature. The treated composites undergo a lesser measure of residue with deterioration starting and concluding at lesser temperatures after comparison was made with the untreated OPS composites.



**Fig. 8** Effect of treated and untreated OPS powder- polyester composites at 28 wt% on the thermal study of (a) TGA and (b) DTG [77]

### WOOD FIBRE IN HYBRID COMPOSITES

The incorporation of two or more different types of fibres in a single matrix is classified as hybrid composites. The behaviour of these composites is a measured entirety of the individual constituents in which there is a more favourable balance between the inherent merits and demerits, also the merits of one type of fibre might complement with what are deficient in the other, for situation that two or more types of fibre are incorporated into the composites, thus a balance in cost and mechanical performance could be realized via appropriate material design [112]. Hybrid composites using wood flour/kenaf fibre have been investigated by [113]. It was reported that hybridization can improve the mechanical properties of natural fibre polymer composites. Both tensile strength and tensile modulus were enhanced when kenaf fibres were incorporated to wood-flour/polypropylene composites. [114] have investigated hybrid glass fibre/wood flour thermoplastic composites. The authors observed that the incorporation of wood filler and recycled glass fibres considerably increased the flexural modulus but decreased the flexural strength. However, the incorporation of recycled glass fibres in hybrid composites gave an enhanced water absorption behaviour when compared with the WPCs with equal amount of filler. [115] also studied the mechanical properties of wood-polymer composites reinforced with continuous and non-continuous glass fibre. Three diverse lengths, 5, 15, and 25mm of glass fibres were embedded to the wood polymer composite materials through extrusion process. Furthermore, continuous glass fibres were also incorporated to the extruded reinforced WPC containing 70wt% wood fraction using a special tool in extrusion. The mechanical properties according to the authors showed that applying non-continuous glass fibres slightly improved the mechanical strengths. Thus, continuous fibres relatively enhanced the ultimate properties of the manufactured composites. The non-continuous glass fibre dimension was measured after extrusion, and it was noticed that extreme fibre breakages happened amid the process, which might have been responsible for the ineffective of non-continuous fibres. The flexural strength, tensile strength, and impact resistance were enhanced up to 14%, 50%, and seven times respectively in the continuously glass fibres reinforced-WPC when compared to non-continuously glass fibres reinforced-WPC.

## WOOD POLYMER COMPOSITES MANUFACTURING AND APPLICATION

The fabrication methods of composites depend upon matrix materials, productivity, shape and size of product etc. The traditional fabrication techniques according to [116-117] that are applied to wood plastics composites with thermoplastic and thermosets include hand lay-up method, Resin transfer moulding, Vacuum bagging, Compression moulding, Injection moulding, Extrusion etc. [118] demonstrates that fabrication technique regularly prompts fibre bundles instead of individual fibres, and for that reason the density, particle size distribution and moisture content are observed for consistency during processing. Generally, wood floor (20-120 mesh) is less demanding to deal with during manufacturing than long wood fibres, which have a tendency to agglomerate and causes dispersion issues during mixing [118]. In a similar manner, [96] demonstrated that composites with finer particles (70 mesh and higher) had better tensile strength and modulus than their counter parts with coarser particles (35 mesh), and the same trend was observed with the flexural properties. Wood polymer composites is now being utilized widely in automotive, construction, furniture, and other variety of end user applications. Presently, wood polymer composites applications involve flooring, decking, doors and windows, lineal, railing, tables and benches, landscape, timber, fencing, roofing, pergolas and gazebos, play park equipment and auto parts [119].

## CONCLUSION

The incorporation of wood wastes or fibres into polymer composites can enhance sustainable and eco-efficient construction, and improved sustainability of automotive parts. Wood polymer composites are becoming attractive and are preferred to synthetic-based composites manufactured from aramid, carbon and glass fibres owing to significant cost savings, low density and eco-friendly. However, more research work is required to tackle obstacles such as water sorption, increase in long term durability, construction of very large panels and structural design. Other area of interest is that fibres provides mechanical advantages over flour and particles, however, an effective coupling agent must be used to attain the benefits. Finally, end material structure has large influence on the material properties. Continuous research is required in the area between processing methods, materials structure, and properties.

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