

## Recent development in thermoplastic/wood composites and nanocomposites: A review

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(Received 5 February 2016 • accepted 28 June 2016)

**Abstract**—Thermoplastic composites filled with wood-base fillers have gained increasing attention, because compared to virgin polymers they have many advantages of light weight, high strength and stiffness, low cost, biodegradability and renewability. These advantages let them find a large dispersal in many areas of technical applications. However, poor interfacial interaction between hydrophilic wood-base fillers and hydrophobic polymer matrices should be improved to get reasonable physical properties for their wide applications. The interfacial interaction could be improved by addition of coupling agents and chemical modifications of wood-base fillers. To improve physical properties of the thermoplastic/wood composites, further nanofillers can be incorporated. This review summarizes recent developments in thermoplastic/wood composites and deals with wood-base fillers for thermoplastics, various interface modification methods and various thermoplastic/wood composites as well as nanocomposites. This review can provide reasonable future perspectives in this research area and stimulate development of new innovative thermoplastic/wood composites as well as nanocomposites.

Keywords: Thermoplastics, Wood, Interface Modification, Composites, Nanocomposites

### INTRODUCTION

A thermoplastic/wood composite that is generally called WPC (wood/plastic composite) represents a new class of multicomponent material where a commodity polymer matrix like polyethylene (PE), polypropylene (PP) and poly(vinyl chloride) (PVC), each chemical structure is shown in Fig. 1, is reinforced with a wood-base filler. The WPC market has shown a great growth, averaging over 20% per year since 1998, due to the many advantageous properties that they present. The market was estimated to show promising growth (12.2%) in 2014 to 2019 [1,2]. WPCs have a wide range of applications, including different outdoor and indoor applications like fencing, decking, railing, docks, landscaping timbers, windows, doors and various parts of automobiles [3]. The main advantages of WPCs include high specific strength and stiffness, high filling levels, low cost, low thermal conductivity, biodegradability, recyclability and ease in processing with conventional plastic processing techniques such as extrusion, injection and compression molding [4-6]. Moreover, the surface appearance of WPCs

can be controlled by adding different wood species and colored pigments [7]. The manufacturing of WPCs is classified as a green technology because recycled plastics and waste wood-base fillers can be used.

However, the major problem of using wood as reinforcing filler is associated with the incompatibility of hydrophilic wood-base fillers with the hydrophobic polymer matrix [8-10]. Insufficient interfacial interaction between them results in poor dispersion and interfacial bonding of wood-base fillers in the polymer matrix, which in turn leads to the poor mechanical and water-resisting properties of the final product. The interfacial interaction between wood-base fillers and polymer matrices can be improved significantly by addition of coupling agents and various chemical modifications of wood-base fillers. Maleated polyolefins are the most commonly employed coupling agents [4,11-16]. The chemical modifications of wood-base fillers to make their surfaces hydrophobic include silylation, peroxide treatments, acetylation, hydrophobization by vegetable oils and benzylation [17-22].

Another problem in manufacturing WPCs resides with the thermal instability of wood-base fillers above 200 °C [23]. The majority of commodity thermoplastics like PE, PP and PVC that exhibit their melting points below 200 °C are quite safe from the thermal decomposition of wood-base fillers during thermal processing if optimized processing conditions are used in fabricating WPC products. However, thermoplastics like poly(ethylene terephthalate) (PET) and Nylon that have melting points above 200 °C are not safe from the thermal decomposition of wood-base fillers during thermal processing in fabricating WPC products.

To improve physical properties of the thermoplastic/wood composites further, nanofillers can be incorporated, and this makes the composites become thermoplastic/wood nanocomposites. Poly-

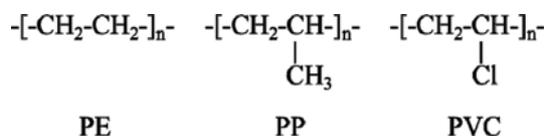


Fig. 1. Chemical structures of the thermoplastics widely used in the fabrication of WPCs.

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mer nanocomposites are a special class of composite materials with nanofillers that typically have 1-100 nanometers size in at least one dimension. In polymer nanocomposites, the interfacial interaction levels between the polymers and nanofillers are much higher than that in typical polymer composites with conventional fillers (typical size: 2-500  $\mu\text{m}$ ) at the same volume fraction due to very high specific areas and aspect ratios of the nanofillers involved. The interfacial region is responsible for communication between the polymer matrix and nanofiller and determines the physical properties different from the bulk matrix because of its proximity to the surfaces of the nanofillers. Typically, 3-5 wt% of nanofillers gives better reinforcement than 30 wt% of conventional micrometer-size fillers [24]. Nanofillers can be organic or inorganic with a wide range of material compositions and structures. Most commonly used inorganic nanofillers in thermoplastic/wood nanocomposites include layered silicates (nanoclay), carbon nanotubes, nanosilica and metal-oxide nanoparticles like  $\text{TiO}_2$  and  $\text{ZnO}$ . Organic nanofillers like cellulose nanofibers and nanowhiskers are also used in fabricating thermoplastic/wood nanocomposites.

During the last decade, many researches have been devoted to improvements of WPCs' properties through the optimization of ingredients and composition, processing conditions and interfacial interaction. This review deals with wood-base fillers for thermoplastics, various interface modification methods and various thermoplastic/wood composites as well as nanocomposites. By reviewing recent development and progress in thermoplastic/wood composites and nanocomposites and essential technologies related to WPCs, it is possible to provide reasonable future perspectives in this research area and stimulate development of new innovative thermoplastic/wood composites as well as nanocomposites.

### WOOD-BASE FILLERS

Based on their botanical differences, wood species are classified as hardwood and softwood. Hardwood trees have broad and flat leaves which fall off after maturity, while softwood trees have needle- or scale-like leaves and retain all over the year. Softwood is generally evergreen. The wood from conifers like pine is referred as softwood, and the wood from broad-leaved trees like oak, walnut, teak, maple and birch is referred as hardwood [25,26].

Wood is a lignocellulosic material composed of three major constituents (cellulose, hemicellulose and lignin) and minor constituents (ash and extractives). Cellulose, the main component of wood, is a polysaccharide consisting of a linear chain of several hundreds to many thousands of  $\beta(1\rightarrow4)$  linked D-glucose units (Fig. 2). Lignin, crosslinked phenol polymers that have basic con-

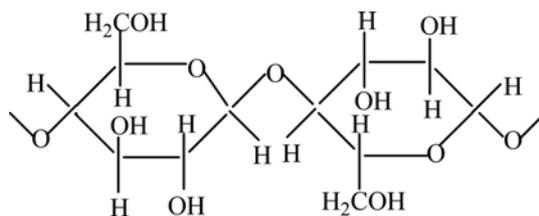


Fig. 2. A general structure of cellulose.

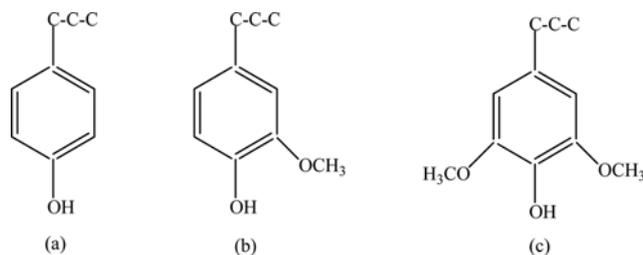


Fig. 3. Three important basic structures of lignin: (a) *p*-Hydroxyphenyl, (b) guaiacyl, (c) syringyl.

stituents of phenyl propane derivatives (Fig. 3), regulates the transference of fluid in the tree and also acts as a stiffener to give stems its resistance against gravity force and wind. Hemicellulose acts as an interfacial coupling agent between highly polar cellulose microfibrils and less polar lignin matrix [4,25,27]. The chemical composition of wood varies depending on the species and nature of wood. The variation in chemical composition may be observed from tree to tree or within different parts of the same tree. For example, lignin content in hardwood varies from 18% to 25%, whereas in softwood it's usually in the range of 25-35%.

Wood-base fillers are generally produced by milling waste wood parts or sawdust from sawmills. They are generally in the form of flour composed of very small particles with sizes ranging from several microns to hundreds of microns. The strength and stiffness of wood flour is important in selection of suitable wood flour for a specific WPC fabrication. The strength and stiffness of wood flour is provided by the hydrogen bonds and the fibrous crystalline cellulose parts. The properties of wood flour are governed by its strength, crystallinity, dimensions, defects and structures. The length of fibers present in the cellulose rich parts of wood varies within different parts of the same tree or tree to tree [28]. Generally, hard wood has fibers shorter (about 1 mm) than fibers that softwood has (about 3-8 mm) [29].

Wood flours are being used as green reinforcing materials for thermoplastics because they are abundantly available, low cost, light weight, biodegradable, have low abrasiveness and good mechanical properties. Wood flours also have some disadvantages, such as moisture absorption, quality variations, low thermal stability and poor compatibility with the hydrophobic polymer matrix [30,31]. However, these disadvantages as reinforcing fillers can be successfully overcome by attaining proper interfacial interaction between wood flours and the polymer matrices.

### THERMOPLASTIC/WOOD INTERFACE MODIFICATIONS

The poor interfacial adhesion between wood flour and a polymer matrix leads to poor physical properties of the final composite. To improve the interfacial adhesion between wood flours and polymers, various methods have been used. Addition of coupling agents during melt-mixing can improve the interfacial adhesion effectively. Maleated polyolefins are the most commonly employed coupling agents for polyolefin matrices [4,11-16]. Another method used is the chemical modification of the wood flour surface to give

it hydrophobicity. Among various chemical modification methods, silylation, peroxide treatments, acetylation, and hydrophobization by vegetable oils are most commonly adopted to modify wood-base fillers [17-22].

### 1. Addition of Coupling Agents

Addition of a coupling agent involves the simple physical addition of a monomeric or polymeric coupling agent to get a desired set of properties. Addition of a polymeric coupling agent includes block or graft copolymers which can be located at the interface and act as an emulsifying agent. Maleic anhydride grafted polyolefins were found to be very effective in modifying the wood flour/polyolefin interfaces. The hydrophobic polyolefin tail of a maleated polyolefin is compatible with the hydrophobic polymer matrix, and the anhydride group of the maleated polyolefin forms ester and hydrogen bonds with the hydroxyl groups of the wood flour sur-

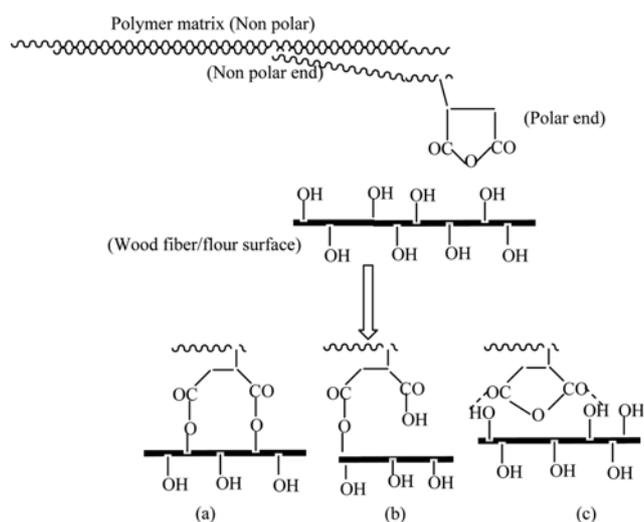


Fig. 4. Possible interaction of a maleated polyolefin with a polymer matrix and fillers: (a) and (b) covalent bonds, (c) hydrogen bond [4].

faces (Fig. 4). However, as can be expected, the maleated polyolefin was not so effective for a polar polymer matrix such as PVC [4].

### 2. Silylation of Wood

Silylation is the introduction of a substituted silyl group ( $R_3Si-$ ) to wood flour. Organosilicon compounds are highly hydrophobic. Chemical modification of wood flour with a low molecular weight organosilicon compound can enhance hydrophobicity of the wood flour. Silane coupling agents were found to be very effective in modifying the wood flour/polymer matrix interfaces by increasing the degree of crosslinking in the interface region [32].

Before silylation, the wood flour is generally treated with NaOH because the silane modification is more efficient for alkaline-treated wood flour than untreated one. The alkoxy groups of an organosilicon compound are hydrolyzed in the presence of moisture to form silanol groups. The silanol groups are then reacted with the hydroxyl groups of wood flour to form silyl ether groups, which are covalently bonded to the wood flour surfaces [33]. The hydrocarbon chains provided by the silane modification enhanced hydrophobicity of the wood flour and thus improved wettability towards the nonpolar polymer matrix [34].

In case of a polar polymer matrix like PVC, an aminosilane like N-2(aminoethyl)-3-aminopropyltrimethoxysilane can be effectively used to modify wood flour, and the mechanism of the interaction between the aminosilane and PVC can be described by Lewis acid-base theory (Fig. 5) [35]. The acid-base reaction between the amine group of the aminosilane and a PVC chain forms a covalent bond between the aminosilane and the polymer matrix. Consequently, the aminosilane can make the two covalent bonds at its both ends that connect the wood flour and the PVC chain. [4,32,35].

### 3. Peroxide Treatment

Upon heating, an organic peroxide ( $RO-OR$ ) undergoes homolytic cleavage of the O-O bond to form two free radicals ( $2RO\cdot$ ). These free radicals can abstract hydrogen atoms from wood flour as well as a polymer chain and generate new free radicals on the wood flour surface and the polymer chain, respectively. The possible reaction mechanisms for peroxide treatment of a PE/wood com-

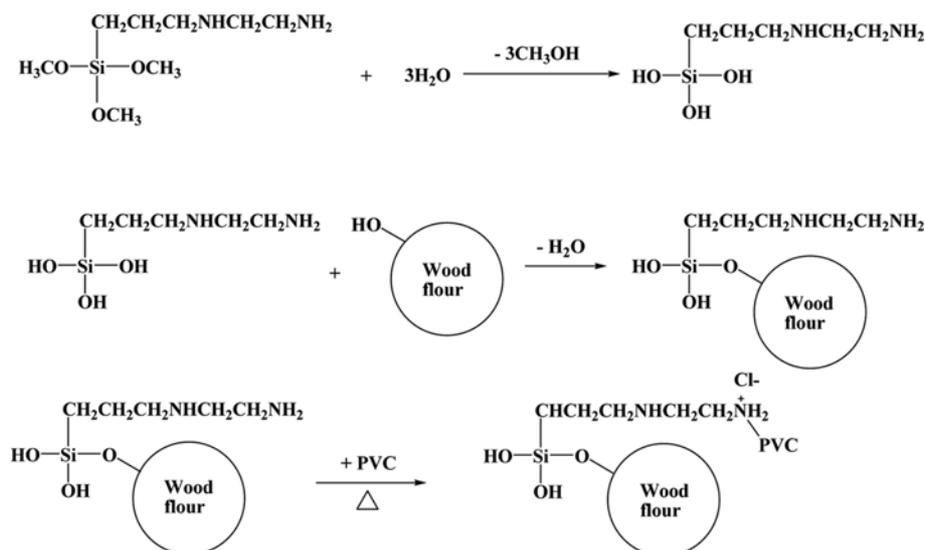


Fig. 5. Possible mechanisms of adhesion between PVC and aminosilane-treated wood flour [35].

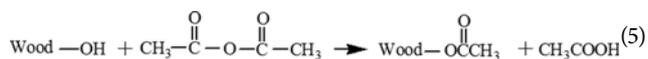
posite are shown below [36,37].



Generally, benzoyl peroxide (BPO) or dicumyl peroxide (DCP) is used for peroxide treatment of wood flour. Wood flours are generally immersed in the saturated solution of BPO or DCP in an organic solvent like acetone for a period of time, then the flours are washed many times with distilled water and dried in an oven [38,39]. Harnnarongchai et al. [40] reported that peroxide treated wood flour reinforced LDPE composites could withstand tensile stress to a higher strain level than the composite with untreated wood flour.

#### 4. Acetylation of Wood

In acetylation of wood flour, acetic anhydride is generally used. Acetic anhydride reacts with the hydroxyl groups on the wood flour surfaces to form ester groups, and this results in the introduction of acetyl functional groups on the wood flour surfaces. This process generates acetic acid as a by-product that must be removed from the wood flour by washing with distilled water. The acetylation of wood flour is shown below.



Prior to acetylation, the wood flours can be treated with dilute NaOH solution to activate the OH groups of the wood flours [41]. The attached acetyl groups cause plasticization of wood flour and are responsible for the decreased hydrophilic nature of the modified wood flour. Acetylation of the wood flour improved the wood flour/PE adhesion and mechanical properties of the composites [42].

#### 5. Hydrophobization of Wood by Vegetable Oils

Vegetable oils are composed of fatty acids esterified with glycerol. Wood-base materials like wood flours can be hydrophobized by vegetable oils via an acid-catalyzed or base-catalyzed transesterification reaction [12,43-47]. The commonly used vegetable oils for wood flour surface modifications are soybean oil and palm oil. The reaction between the OH groups of wood flour and the ester groups of soybean oil is shown in Fig. 6. Prior to surface modification, wood flours are generally washed with distilled water and

dried in an oven. The washed wood flours are suspended in a vegetable oil/organic solvent (usually ethanol) solution by rigorous stirring. After most of the solvent is removed from the suspension, the mixture without any catalyst is reacted in an oven at a high temperature over 100 °C for enough time to hydrophobize the wood flour. Jang et al. [48] reported that the hydrophobization of cellulose powder, which is very similar to wood flour, by soybean oil improved the interfacial interaction between cellulose powder and PP and resulted in significant improvements in the physical properties of the composite.

#### 6. Other Chemical Modifications

Paul et al. [36] and Zafeiropoulos [49] reported that treatment of wood-base fillers with a stearic acid/ethanol solution removed non-crystalline constituents of the wood-base fillers, resulting in surface topography changes of the fillers. Zafeiropoulos [49] also observed that the treated wood-base fillers had higher crystallinity than the untreated ones, and the treatment decreased the surface free energy of the fillers. Gregorova et al. [50] reported that stearic acid modification of wood flour improved the interfacial adhesion and mechanical properties of the wood flour filled poly(3-hydroxybutyrate) composites.

Sodium chlorite (NaClO<sub>2</sub>) is usually used in bleaching wood-base materials by removing lignin. This treatment can be used to modify the surface topography of wood-base fillers for the thermoplastic/wood composites.

Benzoylation is the introduction of benzoyl (C<sub>6</sub>H<sub>5</sub>C=O) groups onto wood-base fillers by surface treating with benzoyl chloride. The benzoyl functional groups could decrease hydrophilicity of the wood-base fillers [20]. Prior to benzoylation, the wood-base fillers are generally pretreated with an NaOH solution to activate the hydroxyl groups of the wood-base fillers.

### THERMOPLASTIC/WOOD COMPOSITES AND NANOCOMPOSITES

The preparation, characterization, properties and applications of thermoplastic/wood composites have been widely researched. Thermoplastic/wood composites are fabricated by dispersing wood flours into molten thermoplastics by various processing techniques such as extrusion, injection molding, compression and thermoforming [51,52]. Thermoplastic/wood nanocomposites are fabricated by dispersing nanofillers in thermoplastic/wood composites because nanofillers can further improve the physical properties of the composites.

The most commonly used thermoplastics in manufacturing ther-

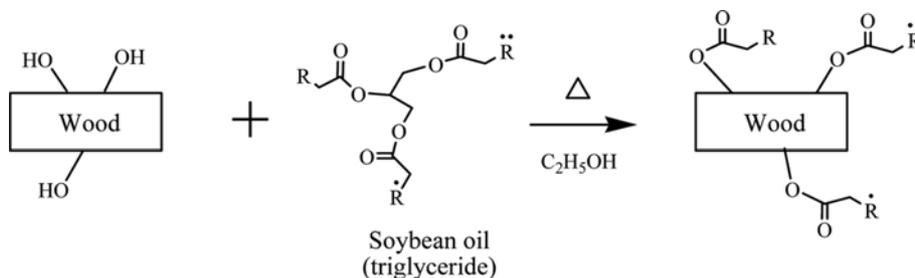


Fig. 6. A simple transesterification reaction procedure to hydrophobize wood flour by soybean oil [48].

**Table 1. Representative recent researches on PE/wood flour composites**

Wood (particle size)	Surface modifier/ Coupling agent	Polymer matrix	Properties	Reference
Wood flour (10-150 $\mu\text{m}$ )	LLDPE-g-MA, HDPE-g-MA, PP-g-MA, HDPE-g-AA, SEBS-g-MA	HDPE	Improved tensile strength and modulus	14,15
Wood flour (70-80 mesh)	PE-g-MA, Oxidized PE	HDPE	Improved flexural and tensile strength and modulus	16
Wood flakes (1-4 mm length, 0.1-2 mm breadth)	Silane (Z6302 from Dow), HDPE-g-MA	HDPE	Improved tensile, flexural and impact strength	55
Sawdust (20-30, 30-60, 60-100 mesh)	Ethylene vinyl alcohol	LLDPE	Improved tensile strength and modulus, reduced strain at break	56
Sawdust (35-45 mesh)	PP-g-MA	HDPE, recycled HDPE	Improved tensile and flexural strength and modulus, improved dimensional stability	57
Poplar flour (0.76 mm length)	PE-g-MA	Recycled HDPE	Improved tensile and flexural strength and modulus, improved dimensional stability	58
Wood flour (<150 $\mu\text{m}$ )	Degraded LLDPE	LLDPE	Improved tensile strength and modulus	59
Wood flour (10-20, 20-40, 40-50, 50-100 mesh)	PP-g-MA	Recycled LDPE	Improved tensile and flexural strength and modulus	60
Paulownia elongata wood flour (<75 $\mu\text{m}$ )	PE-g-MA	HDPE	Improved tensile and flexural strength and modulus, improved dimensional stability	61
Teak wood flour (<180 $\mu\text{m}$ )	HDPE-g-MA	HDPE	Improved dynamic storage modulus	62
Wood flour (50-60 mesh)	Salicylic acid	Recycled HDPE	Improved tensile strength and modulus, reduced strain at break	63
Wood flour (200-400 $\mu\text{m}$ )	Vinyltrimethoxy-g-HDPE	HDPE	Improved tensile strength, reduced creep deformation	64
Palm wood flour (0.25-1 mm)	None	LDPE	Improved tensile and flexural strength and modulus	65
Palm wood flour (25-40 mesh)	None	LLDPE	Improved tensile and flexural strength and modulus	66
Wood flour (75-900 $\mu\text{m}$ )	NaOH treatment, silane, NaOH+silane, PP-g-MA	Recycled HDPE	Improved flexural strength and modulus, improved impact strength	67
Kymene modified wood flour (0.425 mm)	Stearic acid, stearic anhydride, PP-g-MA	HDPE	Improved modulus of rupture and modulus of elasticity	68
Wood flour (70-80 mesh)	PP-g-MA	HDPE, recycled HDPE	Improved tensile strength, modulus and impact strength	69
Sawdust (80-100 mesh)	None	LDPE	Improved modulus of rupture and modulus of elasticity, improved tensile strength	70
Wood flour (147 $\mu\text{m}$ )	Maleic anhydride	LLDPE	Improved tensile strength, creep resistance and ductility	71
Wood flour of aspen pulp (80-100 mesh)	Polymethylene, ethyl isocyanate, toluene-2-4-diisocyanate, 1-6 hexamethylene-diisocyanate,	LLDPE, HDPE	Improved tensile strength and modulus	72
Wood flour	MA, MMA and NA grafted copolymers of PE or PE wax, EVA-g-MA	Recycled PE	Improved tensile and flexural strength and modulus, improved water resistance	73

moplastic/wood composites and nanocomposites are polyethylene (PE), polypropylene (PP), poly(vinyl chloride) (PVC), and their recycled materials [53,54]. Other thermoplastics such as poly(ethylene terephthalate) (PET), Nylon, polystyrene (PS), poly(methyl methacrylate) (PMMA), poly(lactic acid) (PLA) are also used.

### 1. Polyethylene/Wood Composites

Polyethylene, which is one of the most widely used thermoplastics in the world, is generally divided into high-density polyethylene (HDPE), low-density polyethylene (LDPE), linear low-density polyethylene (LLDPE) and ultra-high molecular weight polyethylene (UHMWPE). As described above, there are many advantages for the use of wood flour as reinforcing fillers in PE. Virgin and recycled PE have been extensively used in wood plastic composites (WPCs) [4]. However, due to the poor interfacial adhesion between the hydrophobic PE matrix and hydrophilic wood flour, the filler does not transfer stress to the PE matrix effectively. In recent decades, much effort has been made to improve the interfacial interaction between the non polar PE matrix and polar wood-base fillers. Representative recent researches on polyethylene/wood composites are listed in Table 1 along with their improvements in physical properties.

Wang et al. [14] and Lai et al. [15] investigated the effects of various types of compatibilizers on the mechanical properties of HDPE/wood flour composites. Functionalized polyolefins, such as maleic anhydride grafted LLDPE (LLDPE-g-MA), maleic anhydride grafted HDPE (HDPE-g-MA), maleic anhydride grafted polypropylene (PP-g-MA), acrylic acid grafted HDPE (HDPE-g-AA) and maleic anhydride grafted styrene-ethylene/butylene-styrene copolymer (SEBS-g-MA), were incorporated to improve the interfacial interaction between the polymer matrix and wood filler. It was reported that HDPE-g-MA and LLDPE-g-MA provided higher tensile and impact strengths for the composites, probably due to their better compatibility with the HDPE matrix. Similar but less enhanced improvements in the mechanical properties were observed for SEBS-g-MA, which increased with increasing SEBS-g-MA loadings, whereas HDPE-g-AA and PP-g-MA slightly improved the tensile modulus and tensile strength depending on the loading. Liu et al. [16] also reported similar improvements in the interfacial adhesion as well as in the mechanical properties of the HDPE/wood composites with maleated polyolefins or oxidized polyolefins as compatibilizers.

Recently, Hong et al. [73] used multi-monomer graft copolymers of polyethylene (GPE) and polyethylene wax (GPW) to compatibilize the multi-scale interfaces of the recycled PE/wood flour composites. GPE with 10.5% graft degree was synthesized by grafting maleic anhydride (MA), methyl methacrylate (MMA) and butyl acrylate (BA) onto the PE initiated by benzoyl peroxide (BPO) at 120 °C, and GPW with 9.3% graft degree was synthesized by grafting MA, MMA and BA onto the PE wax initiated by BPO at 100 °C. High performance recycled PE/wood flour composites were prepared by the synergistic compatibilization of the GPE/GPW compounds. GPE imparted a strong interfacial interaction between recycled PE and wood flour, whereas GPW supplemented the interfacial interaction by permeating into the cavities and capillaries of wood flour. Significant improvements in mechanical properties as well as in water resistance were reported for the com-

posites compatibilized by the GPE/GPW compounds than the composite compatibilized by GPE or GPW only.

Li and He [74] investigated the mechanical properties, thermal stability and fire retardancy of LLDPE/wood composites. PE-g-MA was used as a compatibilizer, and ammonium polyphosphate (APP) and the mixtures of APP, melamine phosphate (MP) or pentaerythritol (PER) were used as flame retardants. They reported that the PE-g-MA improved tensile and impact strength of the LLDPE/wood composites. APP influenced impact strength of the LLDPE/wood composites, but it scarcely affected tensile strength. PER decreased the tensile and impact strength of the LLDPE/wood composites because it was involved in the esterification reactions between wood filler and MPE. APP was an effective flame retardant for the LLDPE/wood composites and improved the fire retardancy and thermal stability of the composites. Similar results were reported by Pan et al. [75] for HDPE/wood flour composites. Stark et al. [76] evaluated the effect of different types of fire retardants (decabromodiphenyl oxide, magnesium hydroxide, zinc borate and ammonium polyphosphate) on the fire retardancy of PE/wood flour composites. Magnesium hydroxide and ammonium polyphosphate improved the fire retardancy of the PE/wood flour composites the most, whereas the bromine-based fire retardant and zinc borate improved the fire retardancy the least.

Stark and Matuana [77] investigated the effects of hindered amine light stabilizer (HALS), ultraviolet absorber (hydroxyl benzotriazole) and colorant (zinc ferrite in a carrier wax) on the photo-stabilization of HDPE/wood flour composites. They reported that both the colorant and ultraviolet absorber were more effective photo-stabilizers for the HDPE/wood flour composites than the hindered amine light stabilizer. Stark et al. [78] reported that the durability of HDPE/wood flour composites was greatly influenced by manufacturing method.

Kuan et al. [79] used water crosslinking technique to improve the mechanical properties and thermal stability of LLDPE/wood flour composites. A coupling agent, vinyltrimethoxysilane, was added to the LLDPE/wood flour mixture during processing and then moisture-crosslinked in the presence of hot water. They reported that the water-crosslinking treated LLDPE/wood flour composite exhibited better mechanical properties and thermal stability than the non-crosslinked one because of the improved chemical bonding between the wood filler and the polymer matrix.

Yuan et al. [80] prepared PE/wood flour composites with high modulus and high impact strength by combining low melt viscosity PE and wood flour. They reported that the low melt viscosity PE molecules penetrated into the vessels and cracks of the wood filler, which decreased the number of voids and produced a higher density composite with improved mechanical properties. The low melt viscosity PE molecules reduced the overall viscosity of the system.

### 2. Polypropylene Wood Composites

Polypropylene (PP), another widely used thermoplastic, has outstanding properties such as the lowest density among commercial thermoplastics, good surface hardness, scratch and abrasion resistance, high chemical resistance, excellent stress-crack resistance, exceptional flex life, steam sterilizability, and excellent electrical insulation properties [81]. However, like PE, PP is also hydropho-

**Table 2. Representative recent researches on PP/wood flour composites**

Wood (particle size)	Surface modifier/ Coupling agent	Polymer matrix	Properties	Reference
Wood flour (50-60 $\mu\text{m}$ )	Various organosilanes, PP-g-MA	PP	Improved tensile and flexural strength	81
Oil palm wood flour (63, 124, 180 and 250 $\mu\text{m}$ )	None	PP	Improved tensile and flexural strength, improved impact strength	82
Red pine wood flour (200 $\mu\text{m}$ )	PP-g-MA	PP	Improved tensile strength and modulus, reduced impact toughness	83
Hard and soft wood flour (150-500 $\mu\text{m}$ ), wood chips	PP-g-MA	PP	Improved tensile and flexural strength, improved impact strength	84
Wood flour (147 $\mu\text{m}$ )	PP-g-MA	PP	Improved tensile and flexural modulus	86
Wood flour (20 and 40 mesh)	Alkali treatment, PP-g-MA Vinil-tris-(2-metoxietoxi) silane	PP	Improved tensile strength and modulus	89
Eucalyptus wood fiber (0.7 mm length)	<i>m</i> -Isopropyl- $\alpha,\alpha$ - dimethylbenzyl- isocyanate-g-PP	PP	Improved tensile and flexural strength, decreased impact strength	90
Wood flour (0.125-0.210 mm)	PP-g-MA, Vinyltriethoxysilane-g-PP	PP	Improved tensile strength and modulus, reduced water absorption	91
Wood flour (210 $\mu\text{m}$ )	Benzylation	PP block copolymer (ethylene 8-11%)	Improved processability, reduced water absorption	92
Wood flour (210 $\mu\text{m}$ )	PP-g-MA	PP	Improved tensile and flexural strength and modulus, improved dimensional stability	93
Red pine wood flour (400 $\mu\text{m}$ )	Vinyltriethoxysilane-g-PP	PP	Improved tensile strength and modulus	94
wood flour (70-150 $\mu\text{m}$ )	3-Aminopropyltriethoxysilane, Triethoxyvinylsilane, NaOH treatment, Benzylation	PP	Improved tensile strength and modulus	95
Poplar wood flour (75 $\mu\text{m}$ )	Amino-/alkyl-functional, siloxane co-oligomer	PP	Improved tensile and dynamic storage modulus, reduced water absorption	96
Wood flour (53-105 $\mu\text{m}$ )	Hexanoic, octanoic, decanoic and dodecanoic acids	Recycled PP	Improved interfacial adhesion and thermal stability	97
Vinyl acetate modified wood flour (40 mesh)	PP-g-MA	PP	Improved tensile strength and modulus, reduced water absorption and thickness swelling	98
Rubber wood flour (80 mesh)	PP-g-MA	Recycled PP	Improved tensile strength and modulus and hardness	99
Wood flour (210 $\mu\text{m}$ )	PP-g-MA, stearic acid, cellulose palmitate, benzylation	PP	Improved flexural strength and modulus	103
Rubber wood flour (250-300 $\mu\text{m}$ )	Gamma irradiation, PP-g-MA	PP	Improved tensile and flexural modulus	104

bic and incompatible with hydrophilic wood fillers. Representative recent researches on polypropylene/wood composites are listed in Table 2 along with their improvements in physical properties.

Coutinho et al. [81] fabricated PP/wood composites at three different temperatures of 170 °C, 180 °C, and 190 °C, respectively. Wood fillers were surface modified with various organosilanes

(vinyl-tris (2-methoxy ethoxy) silane, *g*-methacryloxy propyltriethoxy silane, and *g*-aminopropyl triethoxy silane). PP-*g*-MA was used as a compatibilizer. They reported that 180 °C and vinyl-tris (2-methoxy ethoxy) silane resulted in the best mechanical properties of the PP/wood composites.

Zaini et al. [82] investigated the effect of wood flour size and loadings on the mechanical properties of PP/oil palm wood flour composites. Wood flour of different sizes (63, 124, 180 and 250 μm) and different loadings (20, 30, 40 and 50 wt%) was used to prepare various composites. The maximum improvements in tensile and impact properties were achieved when the composite had 250 μm wood flour 50 wt%.

Perez et al. [83] studied the effect of wood flour content (10, 20 and 30 wt%) and PP-*g*-MA on the tensile and fracture behavior of PP/red pine wood flour composites. In unmodified composites, tensile modulus was reported to increase with increasing wood flour content, whereas tensile strength, strain at break and fracture toughness were decreased with increasing filler content. Addition of PP-*g*-MA enhanced the tensile strength and ductility of the composites, but had no significant effect on fracture toughness.

Bledzki and Faruk [84] studied the effect of wood filler geometry on the physico-mechanical properties of PP/wood composites. Standard hardwood flour (Lignocel HBS 150-500) and softwood flour (Lignocel BK 40-90) with particle size of 150-500 μm, long wood fillers with particle size of 4-25 mm and wood chips were used to prepare the composites. PP-*g*-MA was used as a compatibilizer. They reported that PP/wood chips composites showed better tensile and flexural strength than other PP/wood filler composites. The hardwood flour reinforced PP composites showed better impact strength than other PP/wood filler composites. Thumm and Dickson [85] investigated the effect of wood filler length and damage on the mechanical properties of PP/pine wood flour composites. They reported that filler length only had an influence when it dropped below a critical length. The critical length for the pine wood filler was reported to be 0.8 μm. However, wood filler damage like dislocation and nodes only had a minor impact on the mechanical properties of the composites.

Nunez et al. [86] studied the effect of a coupling agent on the mechanical properties of PP/wood flour composites. Wood flour was incorporated into the PP matrix after surface modification (esterification) with maleic anhydride. It was reported that tensile modulus and flexural modulus of the composites increased after the surface modification with maleic anhydride. Sombatsompop et al. [87] investigated the effects of different types and content of PP-*g*-MA on the mechanical properties of PP/wood sawdust composites. Three different PP-*g*-MAs were used. Optimum mechanical properties were observed for the PP-*g*-MA with low melt flow index at 2 wt% loading. Similar results were also observed by Correa et al. [88].

Ichazo et al. [89] studied the effects of alkali treatment and silane modification of wood flour on the physical properties of PP/wood flour composites. 18% aqueous NaOH solution and 10% aqueous solution of vinyl-tri-(2-methoxyethoxy) silane were used, respectively, to modify the wood flour surface. Two PP-*g*-MAs were used as compatibilizers. The PP-*g*-MA and the silane modification improved PP/wood adhesion and dispersion of the wood particles,

while the alkali treatment only improved the dispersion. Though the alkali and silane modifications enhanced the tensile strength and modulus of the composites, the silane modification was more effective.

The effects of grafting level of maleic anhydride (0.5, 1 and 1.5 wt%) in PP-*g*-MA on the mechanical properties, fracture and deformation mechanisms of PP/wood flour composites were studied by Horistov et al. [100]. The maximum improvements in tensile strength, strain at break and impact strength were observed when the grafting level of MA in PP-*g*-MA was 1 wt%. At low grafting levels of maleic anhydride (0.5 wt%), thin and irregular interfacial polymer layers were formed. However, at high grafting level of maleic anhydride (1.5 wt%), stronger interfacial interaction between the PP matrix and the wood flour was obtained. They also studied the synergistic effect of a compatibilizer (PP-*g*-MA) and an impact modifier (styrene butadiene rubber (SBR)) on the impact fracture behavior of PP/wood flour composites. Addition of the SBR increased the impact strength without sacrificing tensile modulus and strength [101,102].

Danyadi et al. [103] compared four different surface modification methods to improve interfacial interaction in PP/wood flour composites. PP-*g*-MA, two surfactants (stearic acid and cellulose palmitate) and wood flour surface-modified by benzylation were used to prepare the composites. They reported that the addition of PP-*g*-MA enhanced the interfacial adhesion as well as tensile and flexural properties of the composites. However, the surface modifications with the surfactants led to moderate decreases of interfacial adhesion, and benzylation decreased interfacial adhesion significantly resulted in inferior mechanical properties.

Stark [105] investigated the effect of moisture absorption on the mechanical properties of PP/wood flour composites. The composites were placed in three different humidity rooms (30%, 65%, and 90% relative humidity at 26.7 °C) as well as in a water bath at room temperature. The composite immersed in the water bath and the one exposed to 90% relative humidity showed more decrease in mechanical properties than other composites. Lin et al. [106] reported that the degree of moisture absorption was increased with increasing immersion temperature, and wood flour content, resulted in a decrease in mechanical properties of the composites. Bledzki and Faruk [107], and Mishra and Verma [108] reported that addition of PP-*g*-MA decreased the moisture absorption as well as water swelling of the PP/wood composites.

Borysiak et al. [109] reported that the melt flow index (MFI) of PP had a great influence on the flammability of PP/pine wood flour composites. PPs with various MFIs from 2.8 g/10 min to 50 g/10 min were used to prepare the composites. The composites had shorter time to ignition values than their neat PP. The composites with higher MFI PP had longer time to ignition, lower heat release rate and longer total burning time. Borysiak [110] further reported that chemical modifications of wood flour had a significant effect on the oxidative induction time (OIT) of the PP/wood composites. They observed that the PP/wood composites with mercerized wood fillers had shorter OIT than that of the composite with unmodified wood flour. However, surface modification with maleic anhydride led to much longer OIT than that of the unmodified PP/wood composite.

**Table 3. Representative recent researches on PVC/wood flour composites**

Wood (particle size)	Surface modifier/ Coupling agent	Polymer matrix	Properties	Reference
Wood flour (0.25-0.5, 0.5-1, 1-2 and 2-4 mm)	None	PVC	Improved tensile and flexural strength and modulus, improved impact strength	118,119
Wood flour (40 mesh)	Chitin, chitosan	PVC	Improved tensile strength and modulus	120
Wood flour (150-180 $\mu\text{m}$ )	Chitosan	PVC	Improved tensile and flexural strength, heat resistance	121
Wood flour (50-150 $\mu\text{m}$ )	Ethanolamine	PVC	Improved tensile strength and modulus; reduced heat resistance	122
Wood flour (50-150 $\mu\text{m}$ )	Aminosilane, melamine, acetic anhydride	PVC	Improved tensile strength, strain at break and impact strength, improved resistance to fungi, reduced moisture absorption	123,124,125
Wood flour (40 mesh)	Poly(MAA-BA-MMA) ter-polymer	PVC	Improved tensile and flexural strength and modulus, improved processability, reduced moisture absorption	126
Wood flour (<100 $\mu\text{m}$ )	Polyurethane prepolymer from poly-1,4-butylene adipate diol (PBA)	PVC	Improved tensile and flexural strength and modulus	127
Poplar wood flour (50-80 mesh)	None	PVC	Improved thermal stability	130
Pine wood flour (60 mesh)	Acetone extracted	PVC	Improved outside weather and xenon arch resistance	132

Arao et al. [111] introduced various fire retardants such as ammonium polyphosphate (APP), melamine polyphosphate (MPP) and aluminum hydroxide to improve the fire retardancy of PP/wood composites. They reported that the PP/wood composites with 10 wt% APP showed self-extinguishing properties with a flammability class of V-0. APP interacted with wood flour during combustion and formed a thick char layer which acted as a thermal and gas barrier. However, the fire retardants decreased the tensile strength and modulus of the composites. Guan et al. [112] designed a new flame retardant, poly(N4-bis(ethylenediamino)-phenyl phosphonic-N2,N6-bis(ethylenediamino)-1,3,5-triazine-N-phenyl phosphonate), to improve the flame retardancy of PP/wood composites. The newly designed flame retardant showed a positive effect on the mechanical properties of the composites, whereas it just moderately improved the flame retardancy.

### 3. Poly(vinyl chloride)/Wood Composites

After PE and PP, PVC is the most widely used thermoplastic to manufacture WPCs. PVC/wood composites are widely used as building construction materials like window/door profiles, decking, railing and siding because they offer acceptable mechanical properties, rot-proof ability, chemical and water resistance, stain and paint-ability, a long lifetime and easy maintenance. Furthermore, PVC/wood composites can be cut, sawed, screwed and nailed by the conventional wood working equipment [113]. Several researchers [114-117] have worked on PVC/wood flour composites and found that adding wood flour only to PVC led to poorer

mechanical properties due to poor interfacial interaction between the wood flour and the PVC. Kociszewski et al. [118,119] reported that the tensile and flexural properties as well as the impact strength of the unmodified PVC/wood composites increased with increasing particle size. Representative recent researches on poly(vinyl chloride)/wood composites are listed in Table 3 along with their improvements in physical properties.

Shah and Matuana [120] used chitin or chitosan as coupling agents to improve the interfacial strength of PVC/wood flour composites. They reported that the addition of chitin or chitosan increased the flexural properties of the composites. Xu et al. [121] also investigated the effect of chitosan on the thermal properties of PVC/wood flour (60/40) composites. Chitosan samples of various particle sizes (80-100, 100-140, 140-180 and 180-220  $\mu\text{m}$ ) at various concentrations (10, 20, 30 and 40 phr) were used to prepare the composites. The addition of the chitosan sample with particle size (180-220  $\mu\text{m}$ ) 30 phr improved the glass transition temperature as well as thermal stability of the composites. Muller et al. [122] reported that the ethanolamine treatment of wood flour improved tensile properties but reduced the thermal stability of the PVC/wood flour composites.

Muller et al. [123,124] investigated the effect of the modification of wood flour by aminosilane, melamine or acetic anhydride on the water absorption and mechanical properties of PVC/wood flour composites. All the chemically modified wood flour/PVC composites showed decreased equilibrium moisture content and

reduced water absorption rates than the composite with unmodified wood flour. The aminosilane treated wood flour significantly improved the tensile strength, strain at break and impact strength of the composites compared to the melamine or acetic anhydride treated wood flour. Muller et al. [125] also investigated the effect of the modification of wood flour by aminosilane, melamine or acetic anhydride on the fungi resistance of the PVC/wood composites. The melamine or acetic anhydride treated wood flour filled composite showed higher resistance to the fungi than the aminosilane treated wood flour filled composite.

Zhu et al. [126] studied the effect of poly(methyl acrylate-co-butyl acrylate-co-methyl methacrylate) ter-polymer on the mechanical properties of PVC/wood flour composites. The ter-polymers with different inherent viscosities (41.85, 33.87, and 39.07 mL/g) were used. The addition of the ter-polymers improved the water-resistance, mechanical properties and processing properties of the composites, and increased density. The highest improvement in mechanical properties was obtained when the ter-polymer with inherent viscosity of 33.87 mL/g was used.

Zhang et al. [127] used polyurethane prepolymer derived from poly-1,4-butylene adipate diol as a compatibilizer for PVC/wood flour composites. A multifunctional layer was in-situ formed by the prepolymer during melt mixing between PVC and wood flour. One side of the layer consisted of urethane linkages between wood flour and the prepolymer, and the other side of the layer was compatible to the PVC matrix because the diol segment behaved as a plasticizer for PVC. This resulted in improvement in the mechanical properties of the composites.

Valle et al. [128] and Jiang et al. [129] reported that the increasing addition of wood flour to PVC resulted in a small but progressive increase in the decomposition temperature of the composites. The glass transition temperature slightly increased by the addition of untreated or ethanolamine treated wood flour.

Pilarski and Matuana [131] studied the effect of accelerated freeze-thaw actions on the durability of PVC/wood flour composites. The density and dimensional stability of the composites were negligibly affected by freeze-thaw cycling, but the stiffness was significantly reduced after only two freeze-thaw cycles.

Chaochanchaikul et al. [133] reported that the addition of a UV stabilizer (Tinuvin P, 2 phr) improved the photo-stability of PVC/wood flour composites both in natural as well as accelerated weathering conditions.

Kositchaiyong et al. [134] studied the anti-algal performances of PVC/wood flour composites with a urea- or a triazine-based algacide. The addition of the urea-based algacide tended to considerably change the surface color of the composites, but the addition of the triazine-based algacide resulted in higher anti-algal performance. They further studied the anti-fungal performance of PVC/wood flour composites using 3-iodopropinyl-N-butylcarbamate (IPBC) as a fungicide. They reported that the composites were more susceptible to fungal attack after UV aging and soil-burial [135].

#### 4. Other Thermoplastic/Wood Composites

Besides PE, PP and PVC, other commercially available thermoplastics such as polystyrene (PS), poly lactic acid (PLA), ethylene vinyl acetate (EVA) and polyethylene terephthalate (PET) can be also used to prepare WPCs.

Maldas and coworkers [136-140] published a series of papers on PS/wood sawdust composites. They examined the effects of wood sawdust particle size (20 and 60 mesh), filler loading (10 to 40%) and four different wood-modification methods (silane, isocyanate, phthalic anhydride and maleic anhydride) on the mechanical properties of the PS/wood sawdust composites. The addition of modified wood sawdust enhanced the tensile strength and modulus. The smaller wood sawdust (60 mesh) showed better enhancement in mechanical properties than the larger one (20 mesh). The isocyanate-treated wood sawdust showed better improvement in tensile strength and modulus than other treated wood sawdust. The mechanical properties of the composite were further enhanced by adding both isocyanate and maleic anhydride together. Poletto et al. [141,142] and Lisperguer et al. [143] reported that the addition of wood flour up to 20% did not decrease the flexural strength and modulus of the composites with recycled PS. The addition of maleic anhydride or styrene-co-maleic anhydride as a coupling agent improved the interfacial adhesion between the PS matrix and wood flour, and increased the flexural and impact strengths of the composites.

Huda et al. [144] prepared PLA/wood composites using a micro-compounding molding system and compared them with PP/wood composites processed under similar conditions. The flexural modulus (8.9 GPa) of the PLA/wood composite (30 wt% wood) was quite higher than that of the PP/wood composites (3.4 GPa). The addition of wood flour significantly enhanced the storage modulus of the PLA/wood composite. Takatani et al. [145] synthesized cellulose esters of several carboxylic acids, RCOO-cellulose (R=CH<sub>3</sub>, C<sub>2</sub>H<sub>5</sub>, C<sub>3</sub>H<sub>7</sub>, C<sub>4</sub>H<sub>9</sub>, C<sub>5</sub>H<sub>11</sub>, C<sub>11</sub>H<sub>23</sub>), to improve the interfacial interaction of PLA/wood composites. The mechanical properties of the composites were improved by adding a small amount of cellulose esters, especially cellulose butyrate or cellulose valerate. Petinakis et al. [146] reported that the addition of methylene diphenyl-diisocyanate improved the tensile strength and modulus of the PLA/wood composites, 10% and 135%, respectively, indicating enhanced PLA/wood interfacial adhesion.

Dikobe and Lyut [147] studied the effects of wood content, particle size and a coupling agent, poly(ethylene-co-glycidyl methacrylate) (EGMA) on the mechanical properties of EVA/wood flour composites. The tensile strength decreased with increasing wood flour content for uncompatibilized composites, while for compatibilized composites, the tensile strength initially decreased, but increased after 5% loading. The composite with smaller size wood particles (<150 μm) showed higher tensile strength than the one with larger wood particles (301-600 μm). The presence of EGMA improved the interfacial interaction between EVA and wood flour by reaction between EGMA and wood flour.

Rahman et al. [148] investigated the mechanical properties of recycled PET/wood sawdust composites at various sawdust loadings. Modulus of elasticity and modulus of rupture reached to maxima (2008.34 and 27.08 N/mm<sup>2</sup>, respectively) when the wood sawdust content was 40%. The results indicated that the fabrication of WPCs using PET would be technically feasible.

#### 5. Thermoplastic/Wood/Nanofiller Nanocomposites

As discussed above, the low thermal stability and low compatibility of wood-base fillers greatly reduce the overall performance

**Table 4. Representative recent researches on thermoplastic/wood nanocomposites**

Nanofiller	Wood (particle size)	Surface modifier/ Coupling agent	Polymer matrix	Properties	Reference
Cloisite 20A	Wood flour (70-150 $\mu\text{m}$ )	PE-g-MA	HDPE	Improved tensile and flexural strength, improved dimensional stability	11
Cloisite 30B	Wood flour (70-150 $\mu\text{m}$ )	N-2(aminoethyl)-3-aminopropyl-trimethoxysilane	PVC	Improved flexural strength, impact strength, tensile strength and modulus, reduced water absorption	35
Nanomer	Wood flour (60 mesh)	PE-co-GMA	HDPE, LDPE, PP, PVC	Improved mechanical properties, UV resistance and chemical resistance	151
Cloisite 20A	Wood flour (80 mesh)	PP-g-MA	PP	Improved tensile strength and modulus, impact strength, water resistance	152
MMT	Coir fiber/Wood fiber (16-22 mm)	NaOH-treated	PP	Improved tensile strength and modulus, reduced water absorption	153
Cloisite 10A	Wood flour (40 mesh)	PP-g-MA	PP	Improved flexural strength, modulus and impact strength	154
Nanomer	Maple wood flour (177 $\mu\text{m}$ )	PP-g-MA	PP	Improved mechanical properties, reduced water absorption	155
Cloisite 20A	Wood flour (75-125 $\mu\text{m}$ )	PE-g-MA	HDPE	Improved tensile and flexural modulus, improved flame retardancy	156
Cloisite 20A	Wood flour (60-80 mesh)	PE-g-MA	PE	Low water absorption and thickness swelling	157
Cloisite15A	Wood flour (40-60 mesh)	PP-g-MA	PP	Low water absorption and thickness swelling	158
Cloisite 20A	Wood flour (75-125 $\mu\text{m}$ )	PE-g-MA	HDPE foam	Improved cell density in the composite foams	159
Cloisite 10A, 15A, 20A, 25A, 30B	Wood flour (40 mesh)	PE-g-MA	HDPE	Improved tensile and flexural strength and modulus	160
MWNT	Wood flour (40-60 mesh)	None	PVC	Improved tensile and flexural strength and modulus	161
MWNT MWNT-OH	Wood flour (60-100 mesh)	PP-g-MA	PP	Improved tensile strength and thermal stability, reduced flammability	162
SWNT	Wood flour (80 mesh)	PE-g-MA	LDPE	Improved flexural strength and modulus, improved impact strength	163
Nano-SiO <sub>2</sub>	Wall nut shell flour (60-100 mesh)	PE-g-MA	HDPE	Improved tensile and flexural strength and modulus, improved hardness	164
Nano-SiO <sub>2</sub>	Wood flour (70-150 mesh)	SEBS-g-MA, PP-g-MA	PP	Improved tensile strength, improved flame retardancy	165
Nano-SiO <sub>2</sub> , nano-TiO <sub>2</sub> , nano-ZnO, Nanomer	Wood flour (60 mesh)	PE-co-GMA	HDPE, LDPE, PP, PVC	Improved tensile strength and modulus, improved thermal stability and flame retardancy	166,167, 168

of WPCs. For successful applications of WPCs, physical properties such as mechanical properties, thermal stability, barrier resistance and fire resistance have to be improved to meet specific end-use requirements. Many efforts have been made to improve the essential properties of WPCs. Recently, the uses of nanofillers such as nanoclay, carbon nanotubes and silica nanoparticles to improve the essential properties of typical WPCs have been intensively explored. Representative recent researches on thermoplastic/wood nanocomposites are listed in Table 4 along with their improvements in physical properties.

Kord et al. [149] studied the effect of organically modified montmorillonite (OMMT) on the morphology and properties of PP/wood flour (50/50) composites. PP-g-MA was used as a coupling agent. The flexural and tensile properties and impact strength increased when OMMT loading was 3 wt%, but decreased when OMMT loading was 6 wt%. At 3 wt% loading, MMT platelets were well dispersed through the nanocomposites and both intercalated and exfoliated morphology were observed. However, at 6 wt% loading, MMT platelets aggregated and decreased the mechanical properties. Zhao et al. [150] also observed similar results for PVC/wood flour/OMMT nanocomposites. They reported that the addition of 0.5% OMMT increased the tensile strength and impact strength of the nanocomposites. The impact strength decreased when the OMMT concentration exceeded 0.5%, while the tensile strength increased up to 1.5% OMMT concentration.

Faruk and Matuaana [161] improved the flexural properties of PVC/wood flour composites by the incorporation of multi-walled carbon nanotubes (MWNTs, 5%). Fu et al. [162] studied the effects of pristine carbon nanotubes (CNTs) and hydroxylated CNTs (CNT-OHs) on the thermal stability and flammability of PP/wood flour composites. PP-g-MA was used as a compatibilizer. The addition of CNTs or CNT-OHs could significantly increase the tensile strength, thermal stability and flame retardancy of the PP/wood composites. However, CNT-OHs conferred better tensile strength, thermal stability and flame retardancy to the composites than CNTs, due to the improved interfacial interaction between CNT-OHs and wood flour as well as the PP matrix.

Kordkheili et al. [163] investigated the effects of single-walled carbon nanotubes (SWNTs, 1-3%) and PE-g-MA (as a coupling agent, 3%) on the physical properties of LDPE/wood flour (50/50) composites. The addition of the SWNTs and PE-g-MA significantly enhanced the flexural strength and modulus of the composites caused by the high aspect ratio, large surface area as well as improved interfacial interaction between the SWNTs and the LDPE matrix conferred by PE-g-MA. The nanocomposite having 2% SWCNTs exhibited the highest impact strength.

Tabar et al. [164] investigated the effect of nano-SiO<sub>2</sub> particles (0, 2 and 5 wt%) on the physical properties of HDPE/wall nut shell flour composites. PE-g-MA was used as a compatibilizer to strengthen the interfacial bonding between the nano-SiO<sub>2</sub> particles and the wood flour as well as the HDPE matrix. The addition of the nano-SiO<sub>2</sub> particles improved the tensile, flexural and hardness properties of the nanocomposites. Zang et al. [165] reported that nano-SiO<sub>2</sub> particles showed a flame retardant synergistic effect with ammonium polyphosphate (APP) in PP/wood composites. A small amount of nano-SiO<sub>2</sub> particles enhanced the tensile

strength of the nanocomposite.

Deka and Maji [166-168] studied the synergistic effects of nanoclay (Nanomer) with nano-SiO<sub>2</sub>, nano-TiO<sub>2</sub> and nano-ZnO particles on the wood flour/polymer (HDPE, LDPE, PP and PVC) composites. The addition of the nanoclay and metal oxide nanoparticles each 3 wt% improved the mechanical properties, thermal stability and flame retardancy of the composites. Water uptake was decreased by the incorporation of the nanoclay and metal oxide nanoparticles.

## CONCLUSIONS AND FUTURE PERSPECTIVES

The addition of wood-base fillers to a thermoplastic polymer matrix produces renewable and environmentally friendly composites. Various chemical modifications of wood-base fillers were proved to improve the interfacial interaction between wood-base fillers and the polymer matrices. Due to the improved interfacial interaction, the mechanical properties of the WPCs greatly improved. However, the chemical modifications of wood-base fillers had less effect on the thermal stability, barrier resistance, fire resistance and water repellency of the WPCs. Addition of nanofillers such as nanoclay, carbon nanotubes, and other nanoparticles (SiO<sub>2</sub>, TiO<sub>2</sub> and ZnO) to the typical WPC systems resulted in thermoplastic/wood nanocomposites with significantly improved mechanical properties, thermal stability, fire resistance, barrier properties, chemical resistance and photo-resistance when uniform dispersions of the nanoparticles were achieved. Future researches on WPCs would focus on improving further the interfacial interaction between wood-base fillers and thermoplastic polymer matrices by modifying the wood-base fillers more effectively and incorporating more effective coupling agents and nanofillers. Researches to elucidate the effects of incorporating special additives like stabilizers and biocides to a typical WPC on the performance of the composite would be necessary for a specific application of the WPC.

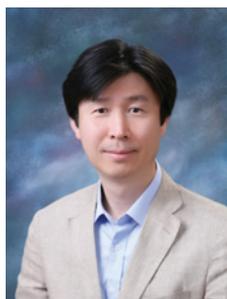
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