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Towards sustainable wood–plastic composites: polymer types, properties, processing and future prospects

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The growing environmental awareness has led to the sustainable utilization of waste for the development of value-added products. In this regard, several analysts and researchers have attempted to utilise wood flour wastes as reinforcements or fillers for various recycled and virgin polymer matrices to generate materials called wood–plastic composites. These composites are fabricated *via* compression moulding, injection moulding, additive manufacturing, extrusion, and other processes. In this review, the properties of WPCs manufactured using five different thermoplastic polymers (polypropylene, high-density polyethylene, low-density polyethylene, polyvinyl chloride, and polystyrene) combined with wood flour are discussed in detail. Owing to their biodegradability, low density, relatively low cost, high stiffness, and strong mechanical properties, WPCs are widely adopted in infrastructure, packaging, household, automotive, construction and building applications. The findings of this study provide a thorough understanding of the influence of different matrix types and wood flour on the properties of WPCs, encouraging researchers to conduct more research for the development of advanced wood composites to fulfil the dual task of minimising waste and producing value-added products for high-end applications.

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Sustainability spotlight

There is an urgent need for sustainable wood waste management, and it has led to a strong innovation drive in wood–plastic composites (WPCs). These composites are emerging as a promising solution that can balance performance, affordability, and environmental responsibility. Manufacturers can efficiently meet the growing demand for WPCs by optimizing material selection and leveraging advanced production techniques such as extrusion and injection molding. Innovations such as pre-treatments, coupling agents, and nano-additives enhance mechanical and thermal properties, expanding applications across construction, automotive, and packaging industries. WPCs offer a sustainable alternative to conventional materials with biodegradability, lightweight composition, and cost-effectiveness. Their increasing adoption underscores their pivotal role in circular economy strategies, aligning with global sustainability goals and paving the way for a greener, resource-efficient future.

1. Introduction

Wood is a versatile, natural, and renewable raw material that plays a vital role in our everyday lives owing to its extraordinary structural and physical properties, such as variety, strength, low weight, functionality, appearance, cost, and accessibility.[1–7] A wide diversity of wood species possesses different compositions of chemical constituents and inorganic matter, along with physical, mechanical, thermal, and acoustic properties. The primary constituent of wood includes cellulose, hemicellulose and lignin, which are responsible for the complex structure of the cell walls of wood (Fig. 1).[8–13] Depending on the anatomical structure, geographical location and type, woods are classified as either hardwoods or softwoods (Fig. 2).[14–16] This botanical classification is unrelated to wood's actual hardness or weight. Softwoods come from gymnosperms such as conifers, while hardwoods are sourced from angiosperms (flowering plants). In temperate zones, needle-bearing evergreens such as pine and spruce are common softwoods, whereas hardwoods typically include broadleaf, deciduous trees such as oak, birch, and maple. Softwoods are anatomically simpler, composed mostly of tracheids, which serve dual roles in conduction and support. In contrast, hardwoods feature a more diverse cellular structure, including the presence of vessels (which are absent in softwoods), which enhances their functional complexity. Chemically, softwoods usually contain more lignin (26–34%) compared with hardwoods (23–30%), further distinguishing the two groups in terms of composition and behaviour.[17–19]

The consistent rise in population brings about greater demands for natural resources and their greater use.[21–28] New technologies have been developed to meet the needs of

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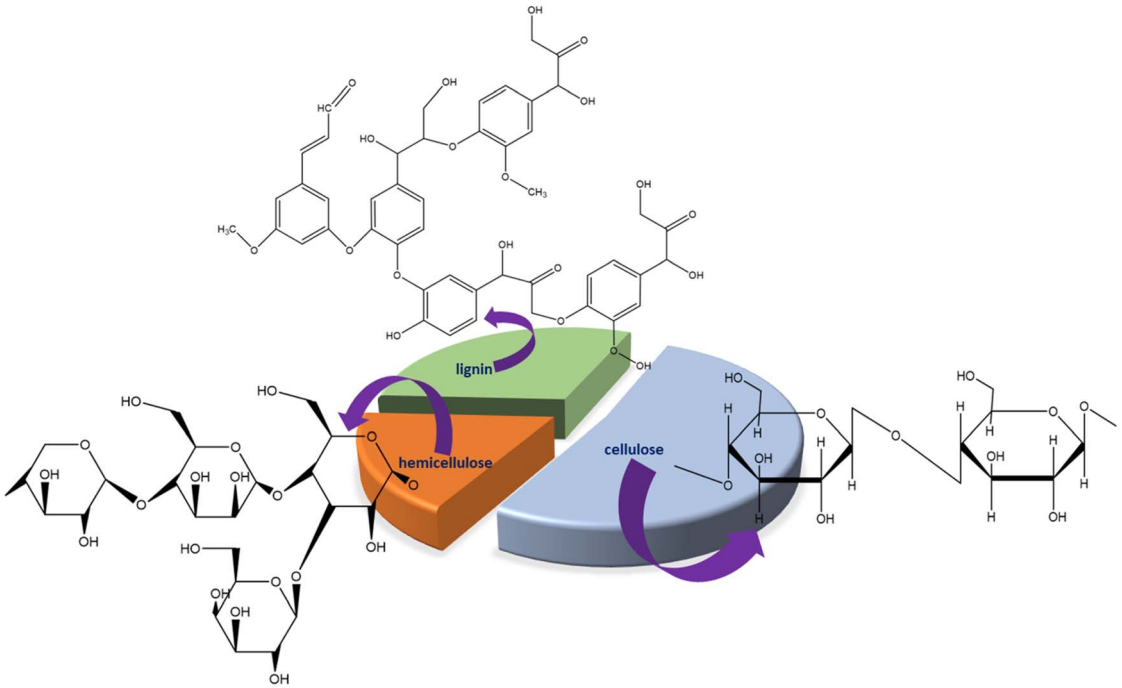

Fig. 1 Wood chemical constituents.

household, agricultural, and industrial sectors, generating various types of wastes as by-products.[21–23,25] Industrial operations such as grinding and cutting in wood-based industries, such as wood boards, particle and plywood panels, and sawmills, produce around 45–52% of wood waste as a major by-product.[29,30] The majority of these wastes end up in landfills, causing environmental, economic, and societal problems.[31–35] The best way to overcome such challenges is effective recycling and management of generated wood waste to make wood and other sectors more cost-effective and environmentally friendly as a result of sustainable design, proper resource usage, and reuse.[31,36–40]

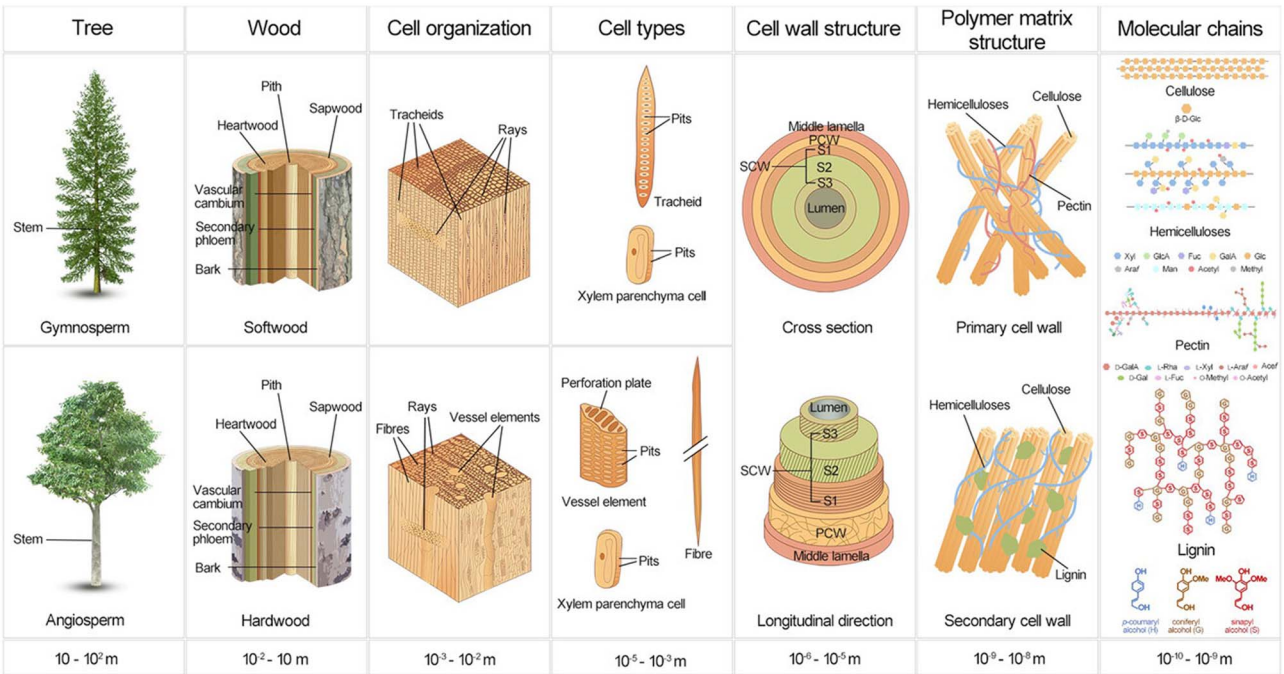

Fig. 2 Microstructure of softwood and hardwood. Reprinted with permission.[20] Copyright 2022, Wiley.

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In addition to wood waste, agricultural residues have emerged as a promising source of reinforcement for Wood–Plastic Composites (WPCs). Common agro-wastes such as rice husks, wheat straw, coconut shells, bagasse, and corn stalks are increasingly utilized due to their abundance, renewability, and biodegradability. Their incorporation into WPCs not only improves material performance but also plays a vital role in reducing environmental pollution by diverting waste from landfills and open burning. Moreover, the use of agro-waste in WPCs aligns with sustainable development goals by promoting resource efficiency, reducing dependence on virgin raw materials, and supporting the development of environmentally friendly composite materials.[41–47]

Attempts have been made by several analysts and researchers to utilise agro-wastes and WF as reinforcements or fillers for various recycled and virgin polymer matrices for the advancement of succeeding materials called WPCs.[48–58] The common manufacturing processes of WPCs include compression moulding, injection moulding, additive manufacturing, and extrusion (Fig. 3).[59–62] Due to its biodegradability, low density, relatively low price, higher stiffness, and strong mechanical properties, WPCs are widely adopted in infrastructure, packaging, household, automotive, construction and building applications (Fig. 4).[63,64]

The wood content and species, additives, compatibilizers, coupling agents, manufacturing techniques and types of matrixes all greatly influence the properties of WPCs. The scientific community is continuously working to develop WPCs with better characteristics and to figure out how to improve them more.[66–69] In order to improve the overall properties of WPCs, academicians and researchers have incorporated various pre-treatment methods of wood fibres since they are incompatible with hydrophobic polymers due to their high hydrophilicity, which results in weak interfacial adhesion and ultimately leads to a reduction in mechanical strength (Fig. 5). For the purpose of improving mechanical properties of WPCs, several approaches such as plasma treatment, corona treatment, esterification, silane treatment, acetylation, benzoylation, alkali treatment, heat treatment, addition of coupling agents (Fig. 6 and 7) and reinforcement of various mineral fillers such as quartz, clay and montmorillonite have been taken into consideration.[70–90] The introduction of some 2D materials such as MXenes can also enhance the mechanical and electrical properties of polymers.[91]

The mechanical properties of five thermoplastic polymers including polystyrene (PS), low-density polyethylene (LDPE), high-density polyethylene (HDPE), polyvinyl chloride (PVC), and polypropylene (PP) demonstrate clear differences in performance. PP shows the highest tensile strength, reaching up to 47.8 MPa, indicating its excellent ability to resist stretching forces. PVC follows, with tensile strength values as high as 42.5 MPa, reflecting its rigidity and strong intermolecular interactions. HDPE also performs well, with tensile strength ranging from 23 to 31.5 MPa, supported by its crystalline structure. In contrast, LDPE exhibits moderate tensile strength (16.25–30.2 MPa), which is expected due to its branched molecular chains that reduce chain alignment and cohesive strength. PS records the lowest tensile strength (12.58–29.9

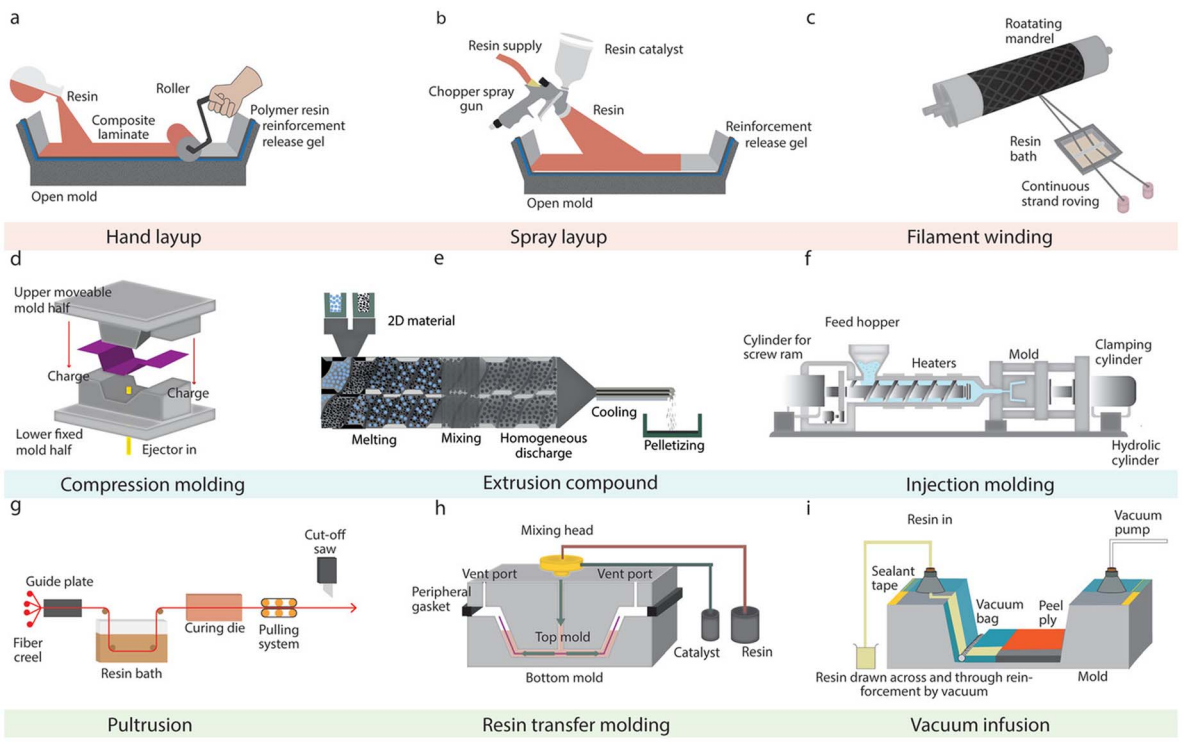

Fig. 3 Manufacturing techniques (a–i) of WPCs. Reprinted with permission.[65] Copyright 2024, Wiley.

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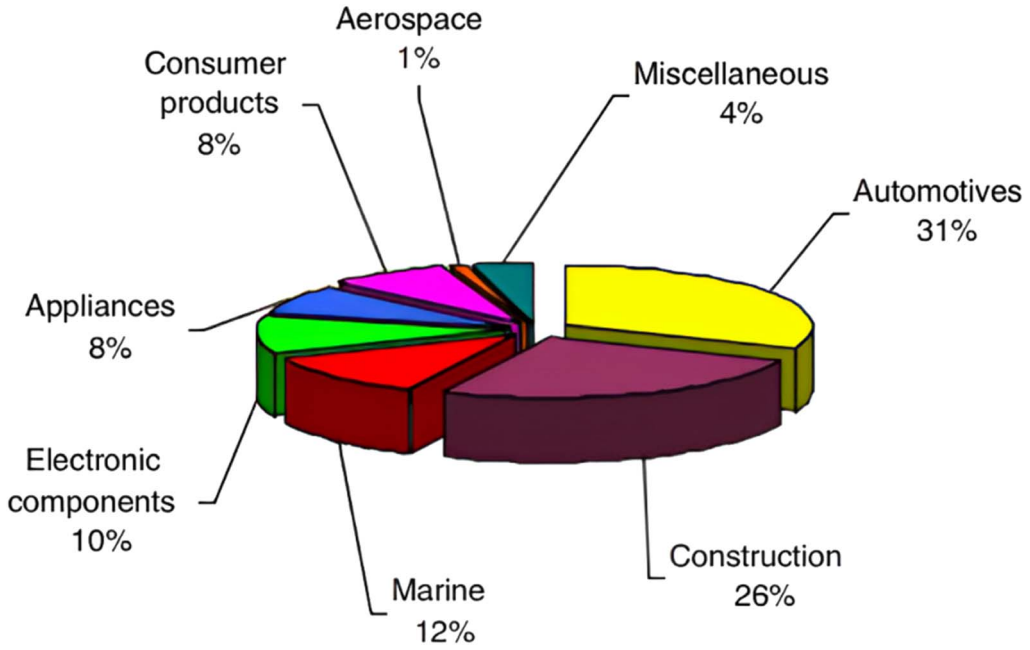

Fig. 4 Applications of WPCs. Reprinted with permission.[63] Copyright 2008, Elsevier.

MPa), consistent with its brittle and amorphous character. When comparing the tensile modulus, PP and HDPE display higher stiffness (up to 4.48 GPa and 3.63 GPa, respectively), while LDPE and PVC show more flexibility, with some values under 1 GPa. PS exhibits moderate modulus values, suggesting intermediate stiffness among the group. Regarding flexural strength, PVC and PP perform the best, with maximum values of 58.5 MPa and 54.6 MPa, respectively. HDPE follows closely with consistently high flexural strength, whereas LDPE shows significantly lower values, indicating less resistance to bending forces. For flexural modulus, PP and HDPE again dominate, showing higher stiffness under bending, while LDPE and PS remain at the lower end of the spectrum. Water absorption (WA) further differentiates the materials. PP and PS absorb the least water, suggesting good moisture resistance and dimensional stability. However, LDPE exhibits the highest water uptake, reaching up to 19.64%, which may compromise performance in humid environments. HDPE and PVC show moderate water absorption, and the dense structure of PVC generally limits moisture penetration. These variations in mechanical behaviour can be attributed to the molecular structure of polymers, including the degree of crystallinity, chain branching, and the

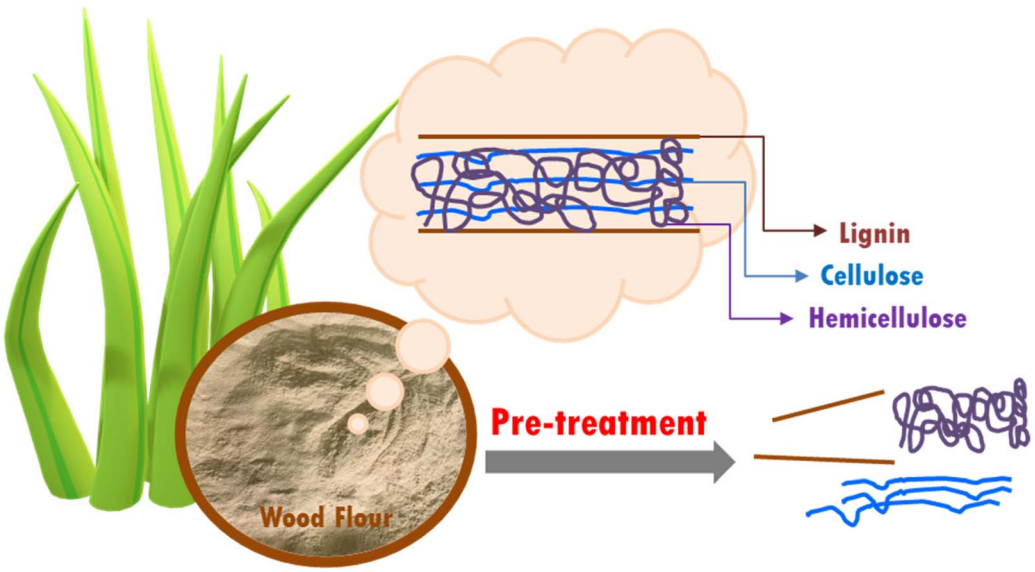

Fig. 5 Effect of pre-treatment on wood.

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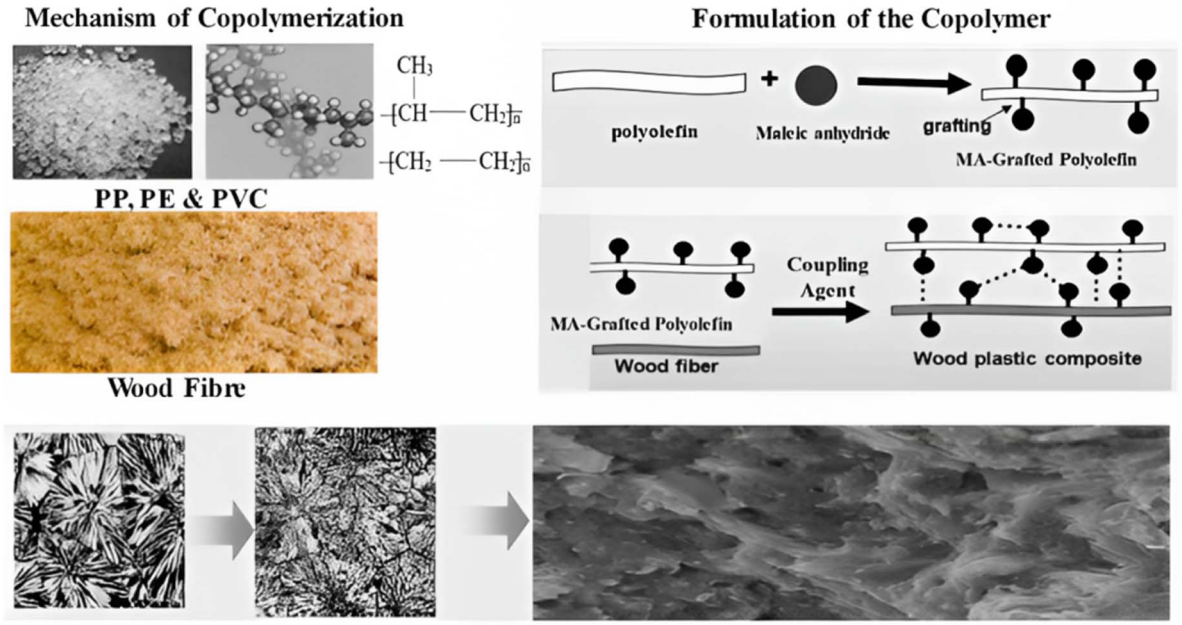

Fig. 6 Action of coupling agents with WPC constituents. Reprinted with permission.[84] Copyright 2021, MDPI.

presence of polar groups, which collectively influence strength, stiffness, and moisture sensitivity.

This study presents a comprehensive review of the literature on the physical and mechanical properties of WF/fibre-reinforced polymer composites with five different thermoplastics (HDPE, LDPE, PS, PVC, and PP). Based on previous studies, a comparison graph between the different mechanical and physical characteristics of WPCs with different matrixes has been created, and are discussed in Fig. 24–26. The study's findings are also summarised in this review.

2. Properties of WPCS

2.1 HDPE-based composites

HDPE is produced using catalysts such as chromium–silica, Ziegler–Natta, and metallocene. This polymer is primarily composed of a polyethylene $(CH_2)_n$ backbone with minimal side chains, facilitating better crystallization. With a density typically ranging between 0.941 and 0.967 kg m^{-3}, polyethylene with a density of 0.941 kg m^{-3} or higher is categorized as HDPE. The limited branching structure of HDPE leads to stronger intermolecular forces and higher tensile strength.[92] The performance of high-density polyethylene-based composites with varying WF content has been examined and discussed in Table 1, Fig. 11 and 12.

The recycling of waste artificial marble by utilising it as a reinforcing material for the development of WPCs was reported by Chen *et al.*[93] The results showed that flexural strength and flexural modulus both increased by 12.9% and 80.0%, respectively. The impact strength decreases greatly with the addition of waste artificial marble. However, after the addition of interfacial compatibilizer, *i.e.*, MAPE showed a remarkable increase in tensile and impact strength by 55.6% and 98.1%, respectively. The addition of MAPE also results in good interfacial adhesion between fillers and matrix. In another investigation, WPCs were prepared using chemo-thermo-mechanical pulp with three levels of length-to-diameter ratio classes (21.3, 13.0, and 8.3). The objective of their research was to investigate the effect of manufacturing conditions and the size of fibre on the structure and properties of WPCs, as reported by Migneault *et al.*[94] Micrographic images showed major dissimilarity between the orientation of fibres in composites prepared under two different processing conditions. According to the authors, this structural dissimilarity of composites prepared under two different processing conditions was a probable reason for differences in mechanical and physical properties. They reported an increase in the density of both injection and extruded composites with the addition of wood fibres. A significant effect of processing conditions on the water absorption behaviour of both injection and extruded composites was reported. Injection-moulded composites showed around 13% less water absorption than extrusion moulded samples. The mechanical properties of composites varied remarkably in processing conditions. Injection-moulded samples showed a higher tensile and flexural MOE by 17% and 31%, while 43% and 33% higher tensile and flexural MOR, respectively, as compared to the extruded samples. Around 170% higher toughness was observed for injection-moulded composites than for extrusion-moulded composites. The effect of esterification (propionate, benzoate, and acetate) of wood fibres on the properties of WPCs was studied by Wei *et al.*[95] They reported that esterified fibres were more hydrophobic than those without treatment, making them more compatible with the plastic matrix. Moreover, chemically treated fibres were more thermally stable than untreated fibres (Fig. 8).

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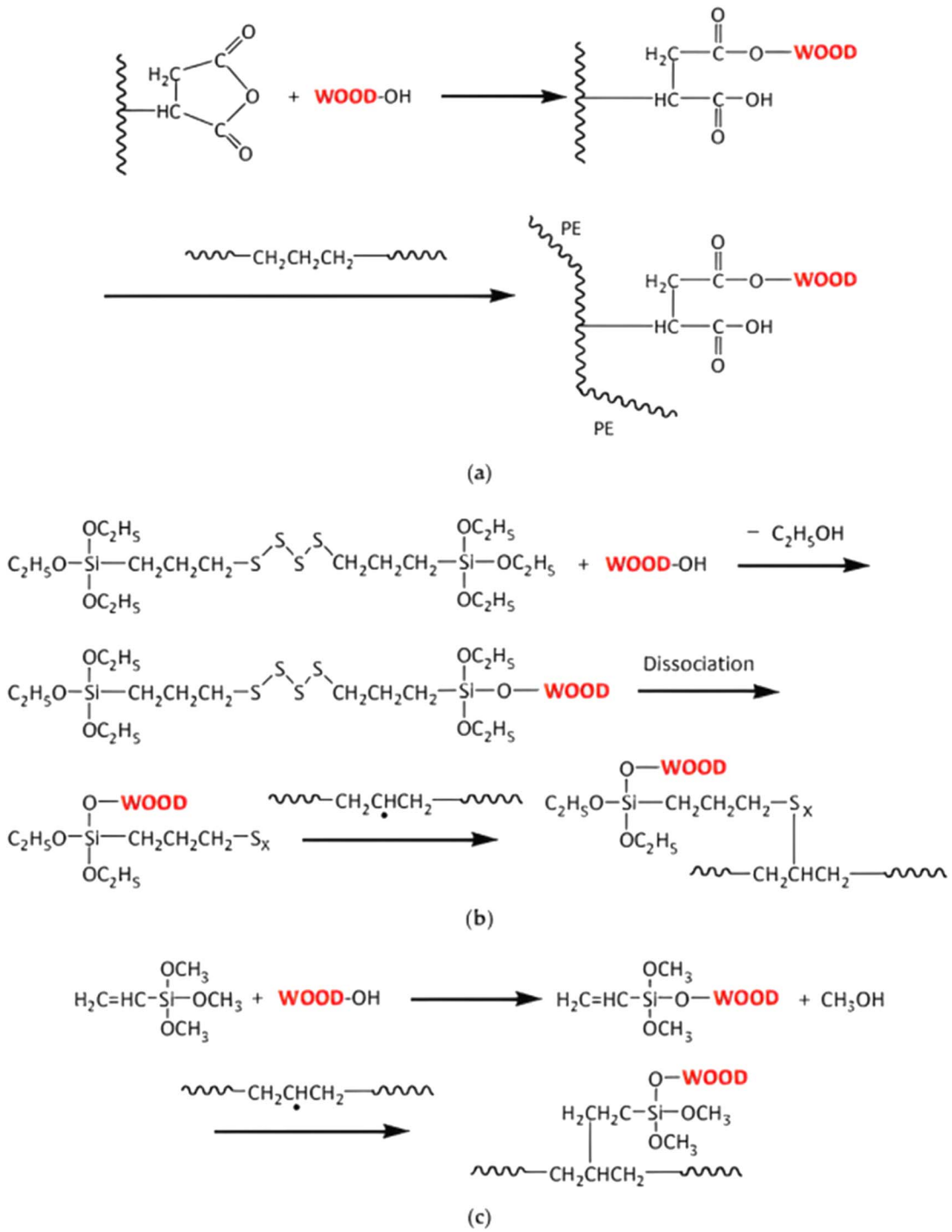

Fig. 7 Possible reactions of coupling agents: (a) MAPE, (b) Si69 and (c) VTMS with wood fibres. Reprinted with permission.[76] Copyright 2018, MDPI.

Due to the hydrophobicity and thermal stability of treated fibres, improvement in interfacial bonding was observed, which ultimately resulted in enhanced properties. The MOR of esterified fibre-based composites was around 20% higher than that of non-esterified fibre-based composites. However, about 10–15% lower flexural MOE of esterified fibre-based composites as compared to non-esterified fibre-based composites was reported. A significantly higher tensile strength was found for esterified fibre-based composites than for those composites prepared with non-treated fibres due to effective stress transfer, as treated fibres showed good dispersion within the matrix. Furthermore, the esterification of fibre also improved the toughness of WPCs. Apart from mechanical property improvement, esterification also results in improved resistance to

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Table 1 Mechanical and physical properties of WPCs reported by other researchers

S. no.	Type of polymer	Coupling agent/ catalyst	TS (MPa)	TM (GPa)	FS (MPa)	FM (GPa)	WA (%)	IS (kJ m^{-2})	Processing condition	References
1	High-density polyethylene (HDPE)	MAPE	28	—	42.8	2.7	—	5.03	Compression moulding, 160 °C, 3 minutes	93
2		MAPE	31.5	3.0	46.3	3.29	4.87	—	Injection-moulding, 180 °C	94
3		—	15.3	2.6	46.3	3.17	3.49	—	Twin-screw extruder assisted injection-moulding, 200 °C	95
4		—	13.3	3.18	18.8	3.15	0.53	2.9	Extrusion method, 200 °C	96
5		MAPE	—	—	47.4	4.42	11.4	0.002	Twin-screw extruder assisted injection-moulding, 175 °C	97
6		MAPP	19.3	2.35	24.9	1.81	1.24	—	Electrically heated platen presses at 200 °C, 4–5 minutes, pressure of 1–5 MPa	98
7		MAPE	23.0	2.7	43.0	2.9	—	—	Twin-screw extruder assisted compression moulding, 170 °C, 20 minutes	99
8		MAPE	25.80	2.54	31.20	1.35	—	0.055	Twin-screw extruder-assisted injection-moulding	100
9		MAPE	28.8	5.6	54.2	5.8	—	10.5	Extrusion method	101
10		MAPE	17.3	3.63	27.3	4.77	—	—	Extrusion method, 163 °C	102

fungal decay and dimensional stability. The weathering performance of esterified composites was also improved, as indicated by lowered surface lightness and total colour changes (Fig. 9).

The impact of the particle size distribution of WF particles on the properties of extruded WPCs was investigated by Chaudemanche *et al.*[96] They have converted the same type of wood chips into three types of WF of different sizes, *i.e.*, 200 μm, 500

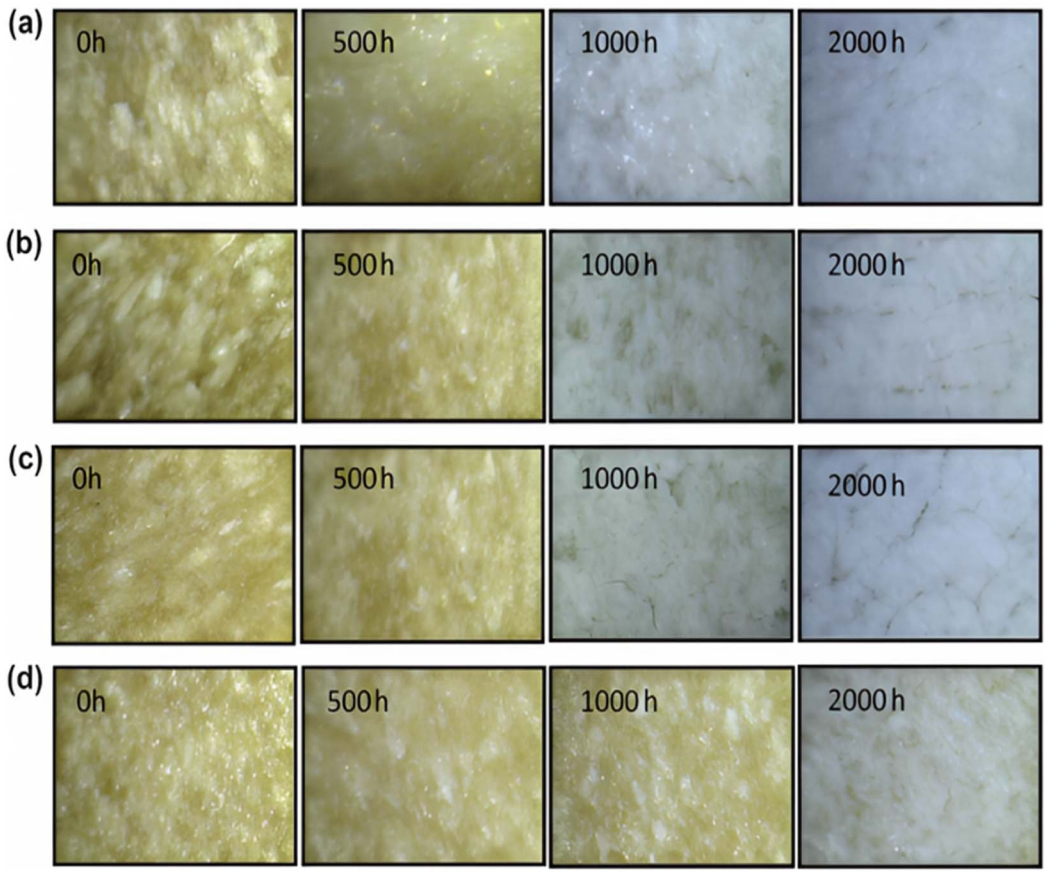

Fig. 8 Micrographs of modified and unmodified WPCs weathered for 0–2000 h (a–d). Reprinted with permission.[95] Copyright 2013, Elsevier.

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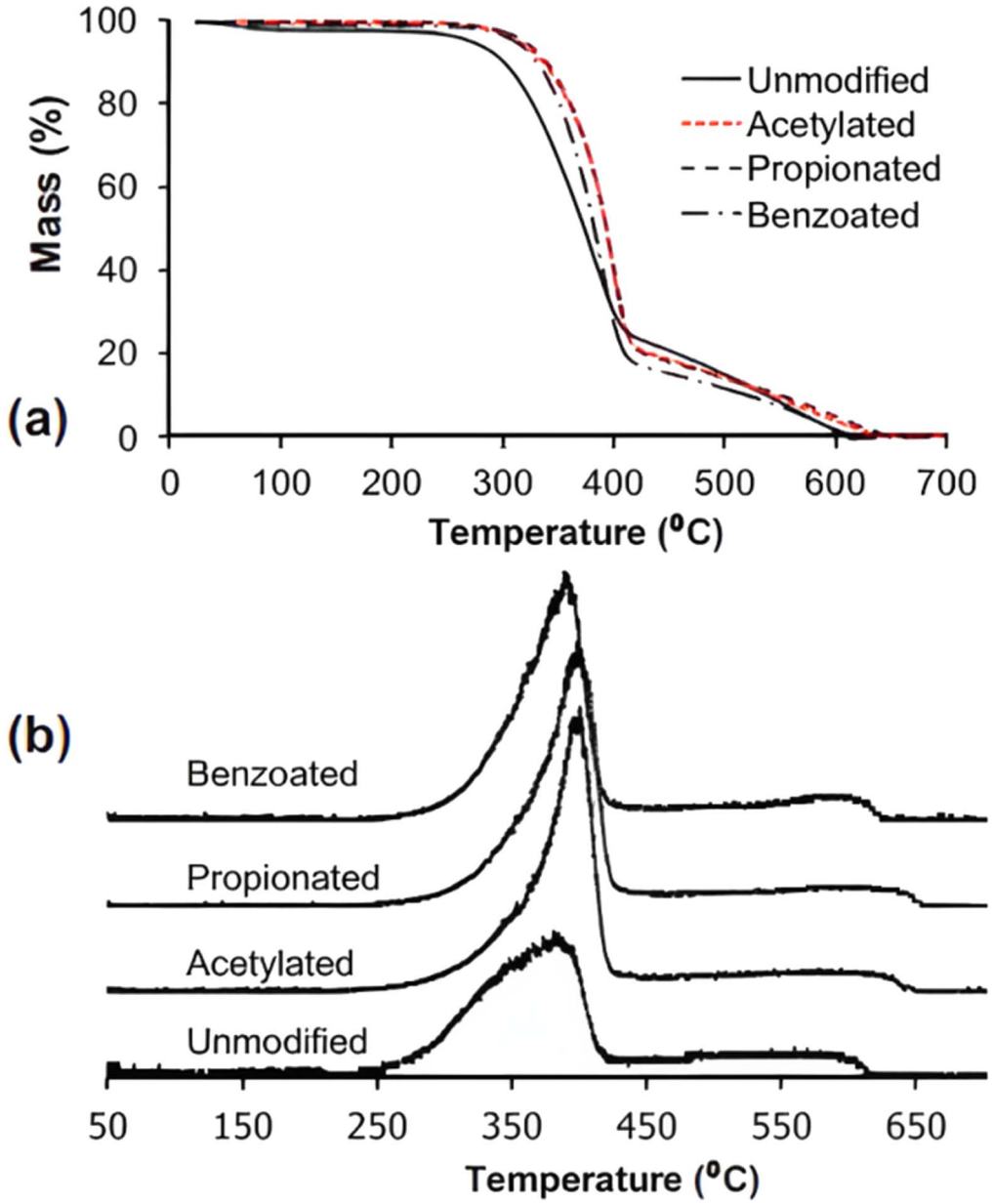

Fig. 9 TGA thermogram (a) and first derivative (b) of treated and untreated fibres. Reprinted with permission.[95] Copyright 2013, Elsevier.

μm, and 800 μm. The substantial effect of the particle size distribution of WF particles on flexural properties was observed. The reported increment in flexural strength was around 14%, while elongation at break and Young's modulus increased by 35% and 9%, respectively. Tensile properties showed the effect of the distribution and orientation of wood particulates within the matrix. A decrease of around 20% in tensile strength and 12% in modulus in the transverse direction was observed. They reported improvement in mechanical properties with larger and machine-direction-orientated wood particles, while fine particles and transverse direction both provide better resistance, and hence, show fewer mechanical properties. Similar results were obtained for impact properties, where the impact strength increases with the WF size in both directions. SEM analysis suggests that the finest particles are more oriented in the transverse direction (Fig. 10). The water absorption of WPCs at room temperature increases with particle size due to poor porosity and the lowest packaging of particles with a higher aspect ratio. However, with the increase in temperature (about 60 °C), finest particle-based composites showed maximum water absorption due to thermal expansion.

The effect of wood preservative treatments on the properties of WPCs prepared using a co-rotating twin screw extruder followed by injection moulding at 175 °C was studied by Behzad *et al.*[97] All composites showed improved mechanical properties with the addition of WF compared to neat HDPE. They used two types of fungicide agents, namely IPBC and Irgaguard, as wood

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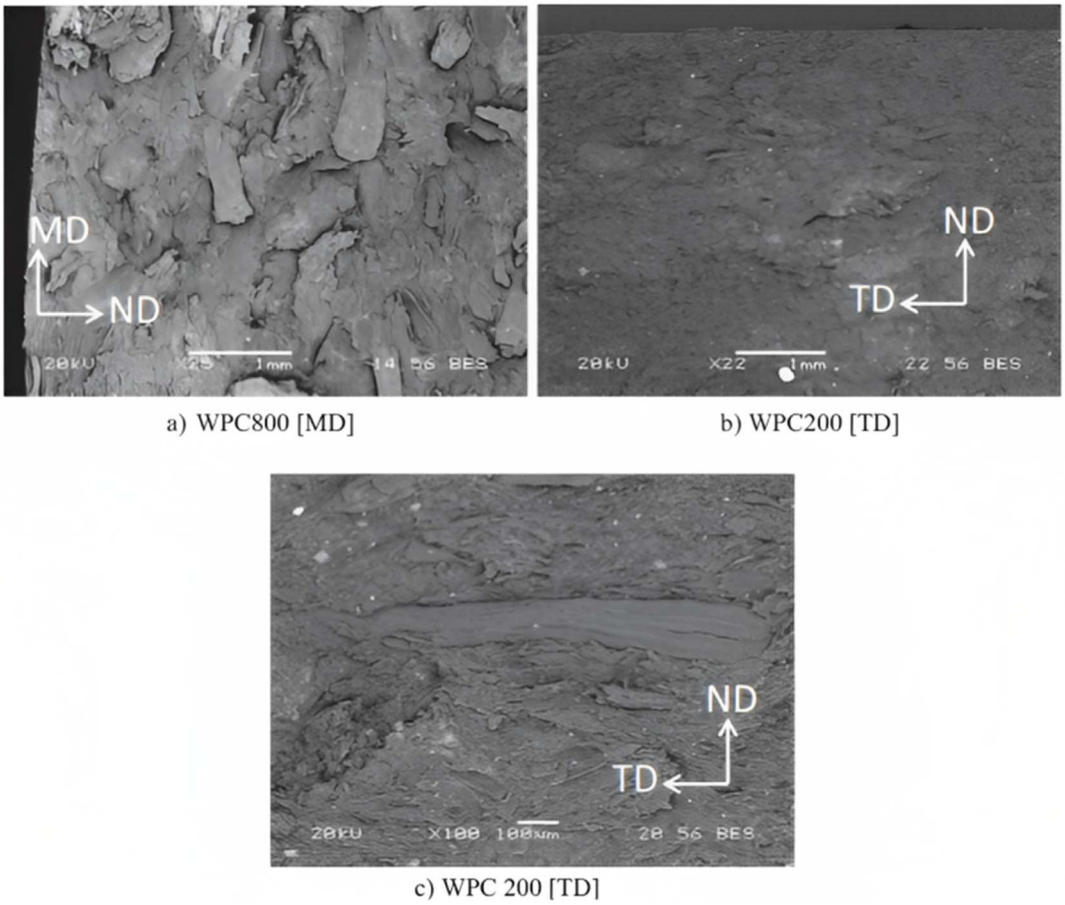

Fig. 10 SEM images (a–c) showing the directions of fibres (TD: transverse direction; MD: machine direction). Reprinted with permission.[96] Copyright 2018, Elsevier.

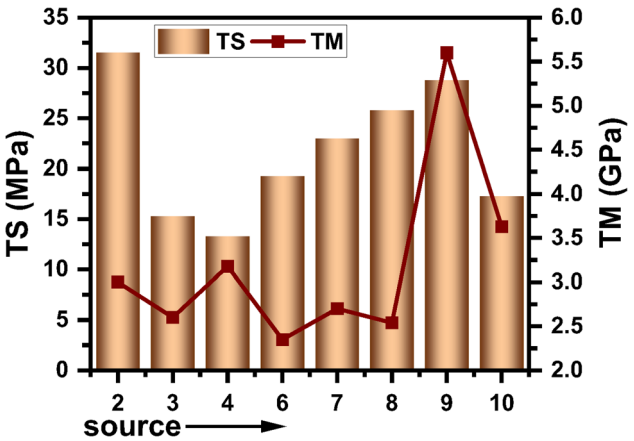

Fig. 11 Tensile properties of HDPE-based WPCs.

preservatives at concentrations of 0.3, 0.6, and 0.9% along with WF, HDPE, and coupling agents for the development of WPCs.

It was observed that samples treated with 0.3% IPBC showed maximum values in terms of MOR and MOE. In addition, increasing the IPBC and Irgaguard content beyond 0.3% significantly results in a reduction in mechanical properties due to weak interfacial adhesion between wood particles and the polymer matrix in the presence of wood preservatives. Moreover, a DMSO solvent was used to dissolve the fungicide agent, which might have a destructive effect on WF. The impact strength decreases substantially with the addition of WF and fungicide agents due to increased stress sites and crack initiation. Water absorption of composites with WF increases compared to neat HDPE due to the hydrophilic nature of WF and the presence of micro gaps and voids at the interface. In addition, with the increase in the content of Irgaguard, water absorption and thickness swelling increase significantly. In another study, waste WF and HDPE were utilised by Adhikary *et al.*[98] for the development of WPCs. They investigated the impact of different WF incorporations and coupling agents on mechanical properties and dimensional stability. The microstructure of composites was also studied. The authors reported that the water absorption of composites made with recycled HDPE was lower than that of composites made with virgin HDPE. The addition of WF results in higher water absorption due to increased water retention sites, while the addition of a coupling agent results in reduced water absorption. The thickness swelling of composites also showed a similar trend. The tensile strength of composites decreases with loadings.

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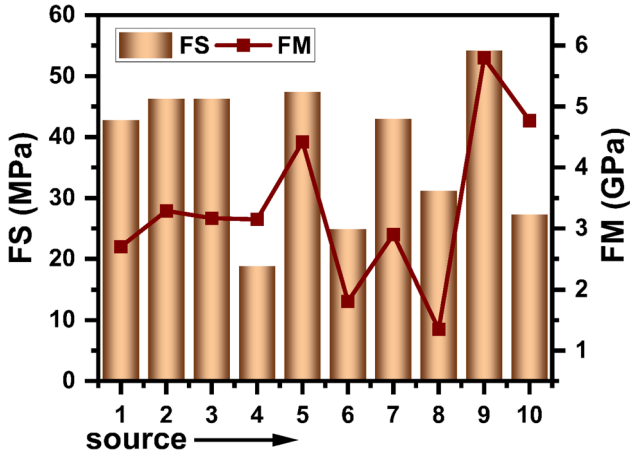

Fig. 12 Flexural properties of HDPE-based WPCs.

Recycled HDPE-based composites showed better tensile strength than virgin HDPE-based composites. Impurities present in recycled HDPE might interfere with the improvement of interfacial adhesion and thus be responsible for the better strength. The tensile modulus of recycled plastic composites was almost similar to or higher than that of virgin plastic composites. The incorporation of a coupling agent results in the improvement of both tensile strength and modulus. It was observed that the addition of 3 wt% MAPP in recycled HDPE and 50 wt% WF results in around 60% higher tensile strength than the composites without MAPP, with the same formulations of WF and polymer. Improvement in tensile strength and modulus with the incorporation of a coupling agent indicates improved interfacial adhesion between the filler and the matrix. Similarly, the flexural strength of recycled HDPE-based composites was a little higher than that of virgin HDPE-based composites. The addition of WF resulted in a drop in flexural strength, while flexural modulus increased. Coupling agent incorporation has been found to induce improvement in flexural properties. The microstructure of composites without a coupling agent showed cracks, fibre pull-outs and numerous cavities, probably responsible for poor interfacial bonding, while composites with a coupling agent showed good interfacial bonding and hence showed better properties.

The enhancement of wood–plastic composites (WPCs) through reinforcement with fabrics has been explored in several studies, notably Deng *et al.*,[99] utilized both treated and untreated glass and sisal fabrics as reinforcements in the matrix. Reinforced and unreinforced composites have similar physical appearances, but reinforced composites showed better properties. The incorporation of treated and untreated sisal fabric into WPC panels did not show any impressive improvement in tensile results, except for increased moduli as compared to the unreinforced WPC. An increase in the layers of sisal fabric and the addition of coupling agents also did not show much effect on tensile properties. The probable reason for such type of results is weak interfacial bonding due to improper mixing of polymers and sisal fibre bundles in sisal fabric and the presence of small hollow sub-fibrils. The reinforcement of untreated sisal fabric, even with increased layers, did not have much effect on flexural properties. However, the reinforcement of two layers of treated sisal fabric improved flexural properties, particularly in the presence of coupling agents. The reinforcement of glass fibre substantially improved the mechanical performance of composites. In particular, the incorporation of two layers of treated glass fibres showed much higher strengths and modulus than the unreinforced composites. However, similar to sisal fabric reinforced composites, a single layer of glass fabric also did not show much improvement in the overall performance of the composites. In a separate analysis, the effect of reprocessing on the thermal and mechanical properties of WPCs was studied by Bhattacharjee *et al.*[100] Fibre length was found to be decreased with the increase in reprocessing cycles, and ranges from 433.66 μm to 348.26 μm from cycle 0 to cycle 6. The molecular weight of the polymer also decreased from cycle 0 to cycle 6: the weight averaged molecular weight (M_w) decreased from 116 113 to 110 360, and the number average molecular weight (M_n) decreased from 110 602 to 102 198. A significant effect of reprocessing on the mechanical properties of composites was observed. Tensile, flexural and impact properties were found to be decreasing with reprocessing cycles. The tensile strength of the composite with 30% WF decreased by 10.45%, while flexural strength and modulus decreased by 15.67% and 25.94%, respectively, from cycle 0 to cycle 6. The flexural modulus of the composite with 50% WF decreased by 24.08%. The reduction in these properties was probably due to the sensitivity of WF and HDPE towards higher temperature and stress, which was therefore responsible for their degradation during repetitive extrusion. Moreover, successive reprocessing cycles lower interfacial adhesion between the polymer and WF due to reduced fibre length, pores and agglomeration of small fibres. Reprocessing cycles increase the thermal stability of composites, probably due to the decreased molecular weight of the polymer, stabilization of WF and reduced amount of volatile matter in composites due to repetitive extrusion.

The comprehensive findings provide valuable insights into how fibre length variations can influence the overall strength and durability of WPCs, contributing to more tailored and efficient material design. The experimental effect of using non-continuous glass fibres of varied lengths on the mechanical properties of WPCs was explored by Zolfaghari *et al.*[101] Mechanical properties such as tensile, flexural and impact tests were investigated and compared with continuous glass fibre-reinforced WPCs. An insignificant effect of the short glass fibre on the flexural properties of WPCs was observed. It was found that continuous glass fibres showed better performance in terms of both modulus and strength. Continuous glass fibres showed about 14% better strength and 370% improved modulus as compared to non-continuous glass fibre-reinforced composites. Impact and tensile properties showed a similar pattern as flexural properties, where continuous glass fibre-reinforced composites showed about 50% better tensile strength than their counterparts. The authors suggested different mechanisms of failure for such unnoticeable results; non-continuous glass fibre-reinforced composites showed sudden and catastrophic failure, which might be the main

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cause for differences in mechanical performance between continuous and non-continuous fibres. In a subsequent study, the effect of wood species, content and size on the mechanical properties of bark-HDPE composites was investigated by Yemele *et al.*[102] Their performance was compared with control composites made with WF and HDPE. WF was found to be more thermally stable than bark fibres, which showed weight loss of around 1.2% and 1.5% in the same temperature range. The addition of bark fibres results in a reduction in flexural MOR and MOE; it also decreases the tensile MOR but improves the tensile MOE. These results suggest bark fibres as fillers and not reinforcing agents. The stress–strain behaviour of both bark species was different; it was observed that black spruce bark (BSB) fibre composites have more linear and brittle curves, while trembling aspen bark (TAB) fibre composites have less linear and more ductile curves. Moreover, the inefficiency of coupling agents to form ester bonds with bark fibres was observed, which results in reduced mechanical properties as compared to the control composites. The differences in the chemical compositions of wood species also contribute to this unnoticeable performance of bark fibre-based composites since lignin-rich fibre surfaces block the formation of ester bonds between coupling agents and fibres. The addition of 10% talc improves around 30% MOE of wood–plastic composite but showed no effect on strength.

2.2 PP-based composites

Polypropylene is synthesized by polymerizing propylene monomers with a titanium-based catalyst, leading to the formation of three distinct structures: isotactic, syndiotactic, and atactic. The isotactic form, which is the most common, is a semi-crystalline polymer arranged in a helical structure, offering strong mechanical properties that can be further enhanced with fiberglass reinforcements and mineral fillers. In contrast, syndiotactic polypropylene is characterized by alternating head-to-tail monomer units, resulting in a more flexible structure with superior impact resistance and clarity to isotactic polypropylene. Meanwhile, atactic polypropylene, an amorphous by-product of the polymerization process, does not contribute to process efficiency but finds applications in roofing tars and adhesives, particularly in the shoe industry.[103] The performance of polypropylene-based composites with different WF contents has been examined, and is discussed in Table 2, Fig. 15 and 16.

The influence of wood particle size and specimen cross-section on the mechanical properties of wood–plastic composites (WPCs) has been widely studied to optimize the performance. In their study, Gozdecki *et al.*[104] investigated the impact of varying wood particle sizes and cross-sectional areas on WPC performance. They considered four sizes for wood particles, *i.e.*, minimal (S1, 0.25–0.5 mm), small (S2, 0.5–1 mm), large (L1, 1–2 mm) and very large (L2, 2–4 mm), while three cross-sectional areas, *i.e.*, 4×10 mm^2, 6×15 mm^2 and 8×20 mm^2, of injection-moulded specimens were taken. The mechanical properties were reported to be increased with the increase in wood particle size from S1 to L1. It was observed that WPC with L1 particles showed around 28% increment in tensile modulus and 25% increment in tensile strength, while about 35% enhancement in flexural modulus and 24% increase in flexural strength were reported as compared to WPC with S1 particles. These results were directly related to wood particle properties such as size and aspect ratio. However, a further increment in particle size from L1 to L2 results in a reduction of about 6% in both flexural and tensile properties, which might be due to the breaking of large wood particles during the mixing process. The impact strength of WPC with L1 particles was found to be maximum, while WPC with S2 particles showed minimum impact strength. The varied effect of the cross-section size of specimen on the tensile properties of WPC with smaller (S1 and S2) and larger (L1 and L2) wood particles was found. The tensile

Table 2 Mechanical and physical properties of WPCs reported by other researchers

S. no.	Type of polymer	Coupling agent/ catalyst	TS (MPa)	TM (GPa)	FS (MPa)	FM (GPa)	WA (%)	IS (kJ m^{-2})	Processing condition	References
1	Polypropylene (PP)	—	20.7	3.83	46.6	3.81	—	10.01	Injection-moulding, 180 °C	104
2		MAPP	47.80	7.07	73.98	5.11	—	0.006	Twin-screw extruder assisted injection-moulding, 160–180 °C	105
3		PPgIA	—	—	42.17	2.27	—	0.029	Twin-screw extruder assisted injection-moulding, 170–180 °C	106
4		—	28.5	2.05	54.6	3.55	—	0.025	Twin-screw extruder assisted injection-moulding, 160–170 °C	107
5		MAPP	21.0	2.77	33.3	3.26	—	—	Twin-screw extruder assisted compression moulding, 170 °C, 5 minutes	108
6		MAPP	34.45	3.49	50.6	3.02	—	—	Twin-screw extruder assisted injection-moulding, 200 °C	109
7		—	21.07	—	41.44	—	—	3.30	Injection-moulding, 200–240 °C	110
8		MAPP/Zn stearate	15.31	2.91	29.51	2.86	1.40	—	Extrusion moulding, 150–180 °C	111
9		MAPP	41.3	4.02	—	—	0.06	0.16	Twin-screw extruder assisted injection-moulding, 165–180 °C	112
10		MA	34.6	0.20	47.4	2.23	—	3.48	Twin-screw extruder assisted injection-moulding, 190 °C	113

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properties were significantly reduced with the increase in the cross-section size for WPCs with decreasing wood particles. The tensile modulus and strength of specimens with a cross-section of 8 × 20 mm^2 dropped by 13% on average when compared to specimens with a cross-section of 4 × 10 mm^2. A different trend was observed for WPC with a larger wood particle. When the cross-section size increases from 4 × 10 to 6 × 15 mm^2, the tensile properties increase by 8% on average and drop by 14% when the cross-section size expanded to 8 × 20 mm^2. Flexural modulus was increased by 8% with the increase in cross section size from 4 × 10 to 6 × 15 mm^2 and then decreased by 2% when the cross-section size increased to 8 × 20 mm^2. A gradual decrease in flexural strength and impact strength with the increase in cross-section size was observed. A specimen with a cross-section size of 8 × 20 mm^2 showed around 22% smaller flexural strength and 28% lower impact strength than the specimen with a cross section size of 4 × 10 mm^2. The authors also compared the mechanical properties of WPCs prepared with industrial wood particles and commercial WF. The tensile properties of WPCs with industrial wood particles showed better performance than those with commercial WF, while flexural and impact properties of WPCs with industrial wood particles were found to be lower by 6% than those with commercial WF. In a different investigation, the effect of thermal treatment of wood on the mechanical and morphological properties of WPCs was investigated by Arwinfar *et al.*[105] Wood chips were thermally treated using a digester under saturated steam at 120 °C, 150 °C and 180 °C for 30 and 120 minutes. The flexural strength of WPCs treated at 150 °C for 30 min and 120 °C for 120 min was found to be similar and higher among all treated WPCs. It was observed that all treated composites showed higher flexural strength than the untreated composites. The flexural modulus of composites treated at 120 °C and 150 °C for 30 min was found to be higher than that of untreated and other treated WPCs. The composites with other treatments such as at 180 °C for 30 min, 120 °C for 120 min and 150 °C for 120 min showed less difference in the values of flexural modulus than the untreated composites. In addition, the composites treated at 180 °C for 30 min and 120 min showed a lower flexural modulus than the control WPCs. The better performance of the treated WPCs was probably due to the fact that hemicelluloses were greatly degraded at these temperatures, which results in a reduction in hydroxyl groups and polarity of wood fibres. Significant improvement in the tensile properties of treated WPCs was observed. Maximum tensile strength was obtained for WPCs treated at 120 °C for 120 min, while maximum tensile modulus was obtained for WPCs treated at 150 °C for 30 min. The impact strength of WPCs treated between 180 °C for 30 min and 150 °C for 120 min showed no significant difference. The impact resistance of composites treated at 180 °C for 120 min was increased by 4.5% as compared to the control composite. This increment was attributed to the softening of lignin and the improvement in interfacial adhesion between the filler and the matrix. Morphological analysis revealed the presence of holes and fibre pull outs in untreated composites, whereas fewer holes and good interfacial bonding was observed in thermally treated composites which facilitate better mechanical performance of WPCs. Exploring environmentally friendly alternatives to traditional coupling agents in composite materials has attracted significant attention in recent studies. The effect of utilisation of an environmentally friendly polypropylene-grafted itaconic acid coupling agent over commonly used polypropylene-grafted maleic anhydride coupling agents was studied by Poletto *et al.*[106] The effects of both coupling agents on the mechanical, morphological and thermal properties of WPCs were investigated and compared. The reported results showed no significant improvement in the flexural strength of WPCs with the incorporation of about 30% WF. These results suggest that WF only act as a filler in the PP matrix without a coupling agent. In addition, chemical incompatibility between the polymer, which is non-polar, and the filler, which is polar, is responsible for the agglomeration of wood particles, and poor interfacial adhesion between the matrix and the filler induces gaps, which further leads to a reduction in mechanical properties. The addition of a coupling agent results in improved performance of composites. The flexural strength of composites with polypropylene-grafted itaconic acid coupling agents and with polypropylene-grafted maleic anhydride coupling agents was increased by 29% and 35%, respectively, as compared to WPCs without any coupling agent, as the presence of coupling agent improved the chemical compatibility of the filler and matrix, which is facilitated by the presence of hydroxyl groups on the surface of wood particles. A gradual decrease in flexural strain was observed while the flexural modulus was increased in the presence of coupling agents. The impact strength was drastically decreased by WF incorporation even in the presence of coupling agents. Probable reasons for such results were less interfacial adhesion, stress concentration sites and reduced polymer chain mobility, which initiate fracture. Morphological analysis showed the presence of gaps and fibre pull-outs in composites without coupling agents, while composites treated with the polypropylene-grafted itaconic acid coupling agent showed strong bonding, improved adhesion and absence of holes around the polymer matrix. Thermogravimetric analysis results suggest that the composites treated with the polypropylene-grafted itaconic acid coupling agent were more thermally stable than the composites treated with the polypropylene-grafted maleic anhydride coupling agent. The effect of different types of wood powder on the mechanical properties and biodegradability and the effect of weathering on the properties of WPCs were investigated by Kumar *et al.*[110] They have used four types of wood powders (mango, sheesham, babool and mahogany wood powders) for their study. The mechanical properties of WPCs such as tensile strength, flexural stiffness, wear, impact strength and hardness are affected by the type of wood dust used. It was observed that babool wood dust composites had a higher average tensile strength than sheesham wood dust composites; babool wood dust-based WPCs had the greatest average bending strength while mango wood dust-based WPCs had the lowest bending strength. It was found that at a lower wood proportion, babool wood dust-based WPCs were hardest, and mango wood dust-based WPCs had the highest average impact strength and were most wear resistant. A

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significant effect of the weight percentage of filler was observed. It may be established that the filler material's weight percentage plays an important role in determining the properties of WPCs. They reported that for all types of WPCs, increasing the wood content resulted in a lower tensile strength for proportions evaluated. It was observed that the impact of increasing wood dust content on the bending strength of WPCs relies on the type of wood powder; for example, increasing wood dust proportion decreases the tensile strength for babool dust-based WPCs; however, 20% of wood dust produced the highest bending strength for mango dust-based WPCs. The effect of changing the quantity of wood dust on the impact strength and hardness of WPCs is dependent on the type of wood dust. Wear resistance for all types of WPCs decreases with the increase in the amount of wood dust. The authors reported the significant effect of weathering on the properties of WPCs; properties such as impact, tensile and bending strength decrease, while the wear resistance increases due to weathering. The biodegradability of WPCs increases with the increase in wood dust content; in addition, WPCs that are more biodegradable are less resistant to natural weathering. The effect of processing conditions on the properties of wood–plastic composites (WPCs) has been widely studied. In this regard, the effect of varying extrusion processing conditions on the properties of WPCs was studied by Yeh *et al.*[112] They reported that changes in extrusion processing factors have a little effect on tensile properties such as strength

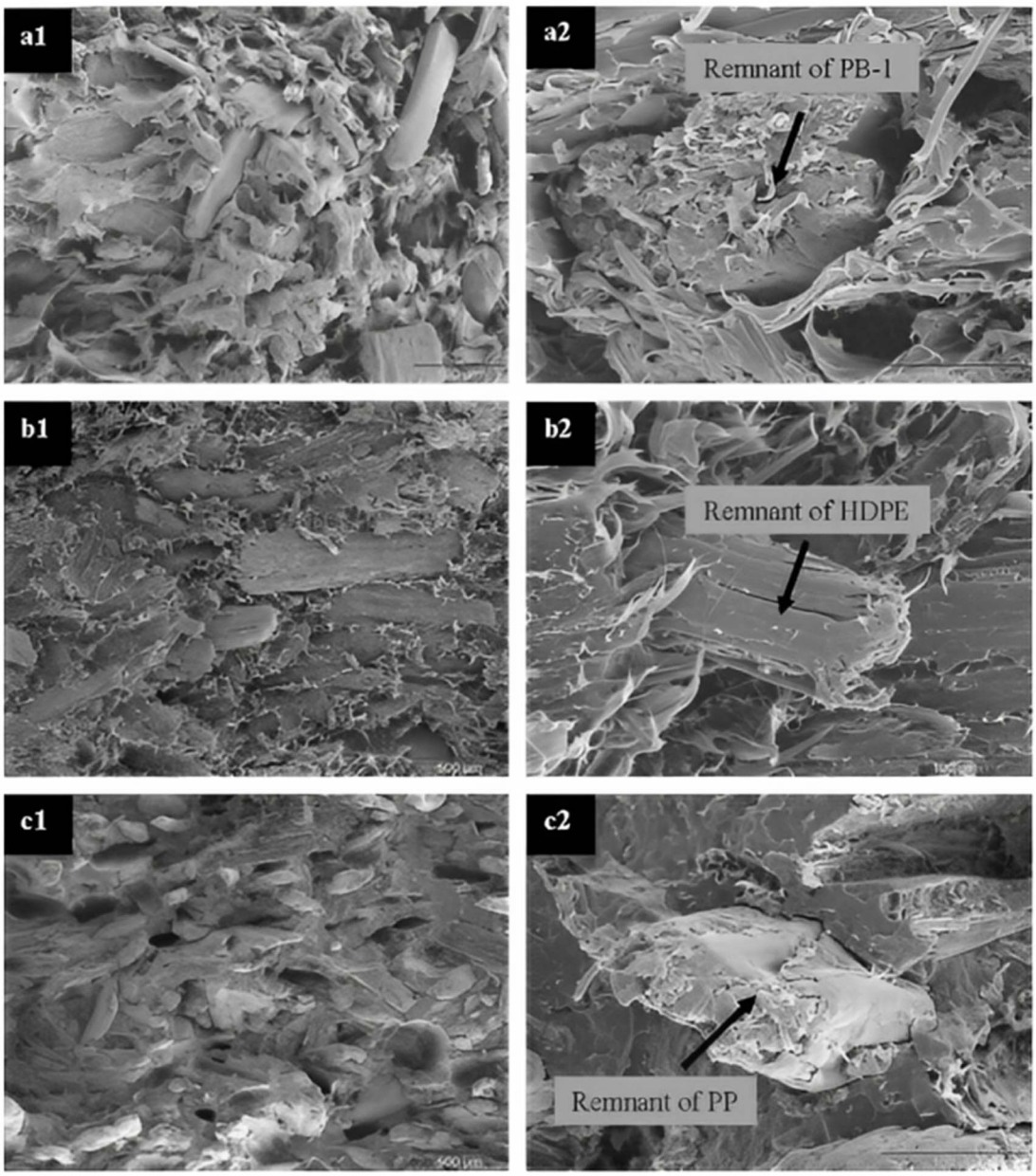

Fig. 13 SEM images of WPCs at two magnifications (50× and 400×) (al and a2) PB-l, (bl and b2) HDPE, and (c1 and c2) PP. Reprinted with permission.[107] Copyright 2010, Elsevier.

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and modulus of WPCs, while it showed a significant impact on moisture absorption. The impact strength of all samples with different extrusion conditions was found to be almost similar. It was observed that faster screw speeds and longer residence times result in smaller particle sizes in compounded WPCs as well as a slower rate of water absorption. A decrease in the water absorption rate varies from 10 to 40% with no effects on the mechanical properties of WPC_S. It was found that extreme compounding conditions result in a dropping rate of water absorption and a reduction in density, probably due to the increase in temperatures under these conditions, which further results in the deprivation of certain hydrophilic volatile organic components from WF. In a different study by Afrifah *et al.*,[107] WPCs were prepared using three different matrix systems, namely polybutene, HDPE and PP, and their properties were compared. The processability of WPCs with three different polymers revealed that the polybutene-based composite process is easier than the processing of HDPE- and PP-based WPCs. The highest mechanical properties were obtained for HDPE-based composites, followed by PP and polybutene. The lowest tensile and flexural properties of polybutene were attributed to its lower stiffness and strength. The observed impact strength was greater for polybutene-based composites, followed by HDPE- and PP-based WPCs due to the ductile nature of the polybutene matrix, which increases the toughness of WPCs and, hence, enhances the impact resistance. Elongation at break was also higher for polybutene-based WPCs than for their counterparts due to notable necking of polybutene-based composites since polybutene is more ductile and flexible than HDPE and PP. This flexible and ductile nature of polybutene was confirmed by morphological analysis. SEM analysis also showed the presence of a high amount of polybutene residues on fibres in the fractured surfaces of composites compared to HDPE- and PP-based composites (Fig. 13).

The incorporation of recycled materials into wood–plastic composites (WPCs) and their comparison with virgin counterparts have become key areas of focus in advancing both sustainability and performance. In this context, Bhaskar *et al.*[109] compared properties such as melt flow index and mechanical properties of WPCs prepared using recycled and virgin polypropylene. The reported melt flow index of virgin PP was found to be higher than that of recycled PP, which means virgin PP has less viscosity and molecular weight than its recycled counterpart. The obtained tensile and flexural properties such as strength and modulus were higher for recycled PP-based WPCs than those with virgin PP. This is most likely owing to enhanced stability generated by chemical impurities present, which results in improved fibre dispersion within the recycled PP matrix. Even though recycled PP has a lower MFI than that of virgin PP, chemical impurities during processing may allow for higher wettability in recycled PP processing. Moreover, the addition of coupling agents further contributes to enhancing properties due to better interfacial adhesion between WF and the matrix and reduces water uptake by composites. In another investigation, WPCs were developed using decayed wood and polypropylene, and their mechanical and thermal properties were compared with those of sound wood composites. Tensile and flexural properties of WPCs containing sound wood were higher than those containing decayed wood owing to the damaged surface of decayed wood, which causes less cross-linking interaction between the coupling agent and wood. Ayrilmis *et al.*[108] observed that while increasing the wood content decreases the tensile and flexural strengths for both types of wood-based composites, the flexural modulus and tensile

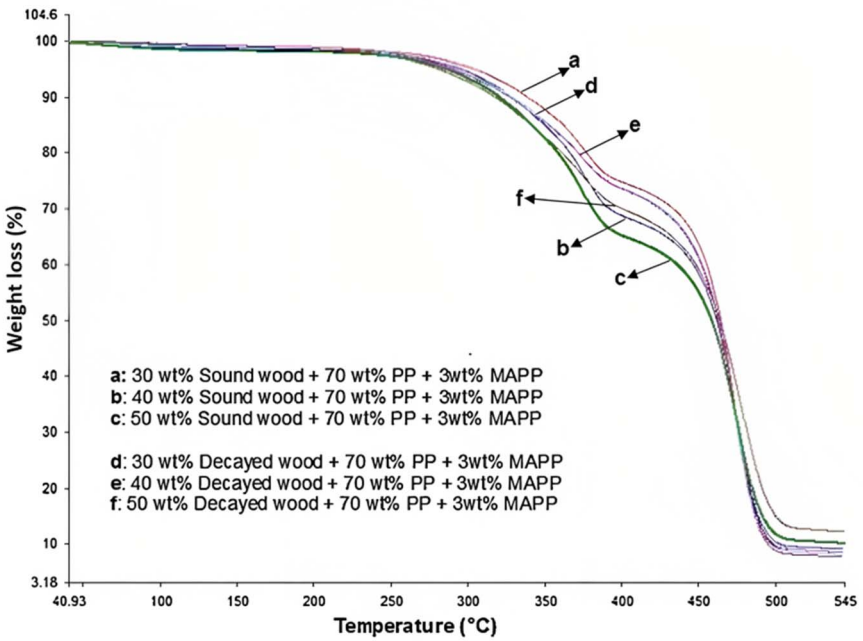

Fig. 14 TGA thermogram of WPCs based on decayed and sound wood. Reprinted with permission.[108] Copyright 2015, Elsevier.

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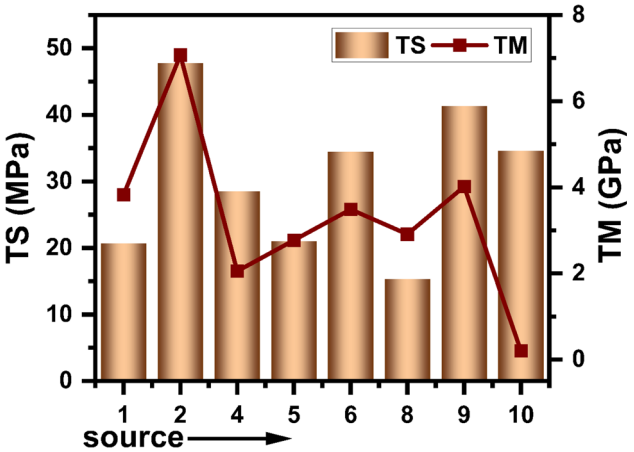

Fig. 15 Tensile properties of PP-based WPCs.

modulus were observed to be improved. The tensile and flexural moduli of WPCs with 30–40% sound wood were increased by 16.5% and 15.9%, whereas the tensile and flexural moduli of WPCs with 30–40% decayed wood were increased by 12.7% and 13.9%, respectively. TGA and DSC analysis revealed that the thermal stability, crystallization degree and enthalpy of WPCs with decayed wood were higher than those of the composites with sound wood. In addition, it is worth noting that WPCs made using decayed wood had more residues than WPCs made with sound WF. This was mostly due to decayed wood's increased ash percentage (0.63 wt%) compared to sound wood's (0.34 wt%) (Fig. 14).

The importance of exploring the effects of varied raw material compositions on the performance of wood–plastic composites (WPCS) lies in their potential to optimise both mechanical and physical properties, leading to more sustainable and efficient materials. Leu *et al.*[111] investigated the effects of altering the raw material composition on the mechanical and physical properties of WPC_S. The authors also reported adequate conditions for factors such as wood and plastic ratio, size of wood particles, amount of coupling agent and lubricant.

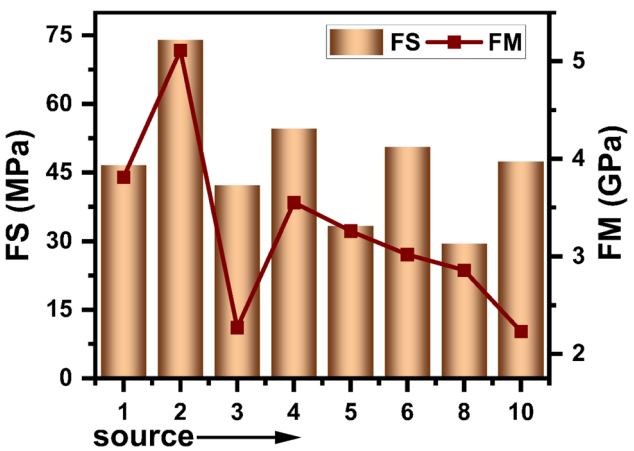

Fig. 16 Flexural properties of PP-based WPCs.

It was observed that WPCs made with finer WF particles (<125 μm) have better physical and mechanical properties, such as reduced moisture content, swelling, and greater flexural and tensile strengths. In addition, when the wood content in WPCs was increased, it resulted in enhanced flexural and tensile moduli but had negative effects on moisture content, modulus of rupture, tensile modulus of rupture and thickness swelling. The relevance of lubricant and coupling agent to the characteristics of WPC was reported. It was found that other than the optimum concentration (3%) of the coupling agent, higher or lower mass concentrations considerably decreased the coupling agent's positive effects on the mechanical and water adsorption performance of WPCs. Adding lubricant at a concentration of 3% lowered all mechanical and physical performances of WPCs except the modulus of rupture. When the lubricant concentration was increased to more than 3%, the thickness swelling increased by 4–5.5 times. Higher amounts of lubricants lead to fibre pull out and prevent bonding between the matrix and the wood, which contributes to the reduction of the mechanical performance of composites. The effect of reinforcing graphitic carbon nitride ($g\text{-}C_3N_4$) in WPCs on the physical and mechanical properties of WPCs was studied by Lei *et al.*[113] They reported a significant effect of $g\text{-}C_3N_4$ on the mechanical and physical properties of WPCs. It was observed that the flexural strength increases with the $g\text{-}C_3N_4$ content till 1 wt% and begins to decrease when the amount of $g\text{-}C_3N_4$ increases, owing to the fact that at lower concentrations, there was uniform dispersion and better interfacial adhesion present between the matrix and wood, which results in better stress transfer between them. Higher concentrations of $g\text{-}C_3N_4$ result in cluster formation and poor dispersion, thereby reducing the flexural strength. It was observed that the flexural strength decreased by 7.6% with 10 wt% $g\text{-}C_3N_4$. However, under the same conditions, the flexural modulus of WPCs was found to be increasing since the flexural modulus of $g\text{-}C_3N_4$ was higher than that of wood. A similar trend for the tensile properties of WPCs was observed. The impact strength of WPCs was reduced with an increasing amount of $g\text{-}C_3N_4$ since it increases the brittleness of composites, and 1 wt% and 3 wt% of $g\text{-}C_3N_4$ showed almost similar values of impact strength. The incorporation of $g\text{-}C_3N_4$ significantly improved WPC's decomposition temperature and colour. Water absorption of WPCs increases with the addition of WF attributed to the hydrophilic nature of WF and decreases with the addition of $g\text{-}C_3N_4$ till 1 wt% and then again increases due to the agglomeration of $g\text{-}C_3N_4$ in the formation of cracks, which contributes to voids in composites during the compounding process.

2.3 LDPE-based composites

LDPE (low-density polyethylene) is produced through free radical polymerization and is characterized by a high degree of short- and long-chain branching. This branching prevents the polymer chains from packing efficiently in the crystal structure, resulting in low density (0.910–0.940 kg m^{-3}). The low-density nature of LDPE is also attributed to its weak intermolecular forces, as it has low instantaneous dipole–dipole interactions.

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Table 3 Mechanical and physical properties of WPCs reported by other researchers

S. no.	Type of polymer	Coupling agent/catalyst	TS (MPa)	TM (GPa)	FS (MPa)	FM (GPa)	WA (%)	IS (kJ m^{-2})	Processing condition	References
1	Low-density polyethylene (LDPE)	—	18.7	—	41.2	—	14.3	—	Compression moulding, 180 °C, 15 minutes	114
2		—	27.2	—	—	—	0.69	20.01	Twin-screw extruder assisted injection-moulding, 160 °C	115
3		MA	16.25	1.35	—	—	—	8.4	Injection-moulding, 180 °C	116
4		MA	9.20	0.53	20.3	0.54	—	—	Twin-screw extruder assisted injection-moulding, 185–200 °C	117
5		—	—	—	8.5	1.1	13.3	—	Flat-platen pressing, 170 °C	118
6		—	—	—	10.0	1.0	—	—	Flat-platen pressing, 170 °C	119
7		MA	12.3	0.85	—	—	—	—	Twin-screw extruder assisted injection-moulding, 120–150 °C	120
8		—	19.35	—	19.35	1.61	—	0.002	Hydraulic press, 180 °C	121
9		Silane KH-570 and industrial alcohol	—	—	24.43	1.51	19.64	—	Hot pressing, 180 °C, 8 minutes	122
10		MAPP	30.2	—	59.0	—	—	—	Injection-moulding, 175–205 °C	123

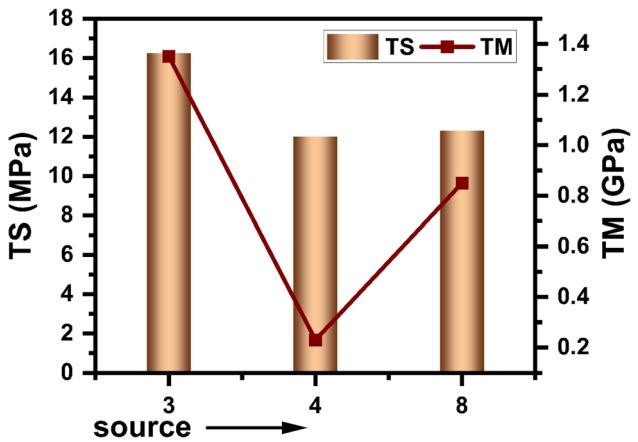

Fig. 17 Tensile properties of LDPE-based WPCs.

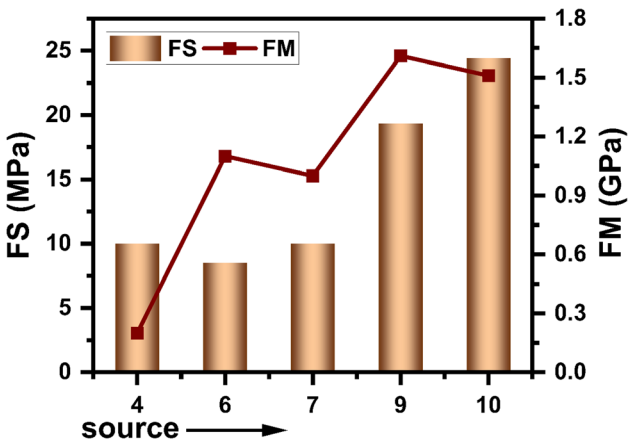

Fig. 18 Flexural properties of LDPE-based WPCs.

These structural characteristics give LDPE its increased ductility and relatively low strength.[92] The performance of low-density, low-polyethylene-based composites with different WF contents has been examined, and is discussed in Table 3, Fig. 17 and 18.

Incorporating recycled materials into wood–plastic composites (WPCs) has attracted significant attention due to its potential for sustainability and performance optimization. Acheampong *et al.*[114] explored the impact of various raw material sources, including recycled LDPE from old shopping bags, packaging trash, and irrigation pipes, combined with virgin LDPE. They examined the effect of different wood species, Port Jackson, Black Wattle, and Blue Gum, on the mechanical properties of the WPCs, while considering the influence of material impurities and blending ratios. It was observed that the mechanical characteristics of composites manufactured with Port Jackson wood and LDPE from company A were superior in general as to those with Black Wattle and *Eucalyptus*-based composites. The probable reason for these results was the chemical composition of the Port Jackson wood type. The water absorption of all composites was found to be below 20%. They reported insignificant differences in the properties of WPCs made with complete trees or wood only. The mechanical properties of recycled LDPE from various sources appear to be significantly more affected than the mechanical properties of wood. It was found that composites manufactured with LDPE from company A performed far better than those created with LDPE from company B due to differences in exposure to weathering conditions. The effect of the type of matrix on the physical and mechanical properties of WPCs was compared by Lee *et al.*[118] It was observed that HDPE (virgin and recycled)-based composites had the highest dimension stability and water absorption resistance, whereas PS-based composites had the lowest. In terms of mechanical performance of WPCs, the MOR of the PP-based composite was highest, followed by HDPE, recycled HDPE, PS, and LDPE-based composites. This is due to poor interfacial adhesion between matrix and wood

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particulates, resulting in a lack of effective stress transmission between the two material phases. The dispersion pattern of wood and plastic components inside WPCs has been effectively determined using ATR-FTIR spectroscopy. The highest distribution of wood particles in the polymeric matrix was found in LDPE-based composites, whereas PS-based composites showed the lowest dispersion.

The manufacturing process of wood–plastic composites (WPCs) plays a crucial role in determining the material's final properties such as strength, durability, and environmental sustainability. The solid-state shear milling (S3M) process was used to enhance the dispersion and size reduction of WF in the LLDPE matrix, resulting in improved performance of composites without any surface treatment and compatibilizers, as reported by Yang *et al.*[115] Composites developed *via* S3M showed outstanding WF dispersion and reduction in size, which is far superior to that achieved by direct melt processing. The processability of such well-dispersed WF is significantly improved, with noticeable decreases in apparent viscosity and higher melt flow index values. The maximum tensile strength of WPCs prepared with the S3M method increased by 26.5%. Smaller wood particle size achieved *via* the S3M process provides a greater surface area, which results in good dispersion and interfacial adhesion of wood flour and polymer and, thus, transfers tensile stress from the matrix to the filler. In addition, composites had a greater retention of impact strength values at higher filler loadings, such as 50 wt%. Reduced size and good dispersion lead to less stress concentration sites for the initiation of crack under impact load. The benefits of better dispersion and small size of WF were also observed in the water absorption of WPCs. S3M composites showed low water absorption since most wood surfaces were blanketed by the polymer, effectively blocking water infiltration into composites. Moreover, the S3M process increased the crystallinity of the polymer and composites and showed better thermal barrier as compared to neat LLDPE. The effect of matrix and lignocellulose type on the physical and mechanical properties of WPCs was investigated by Hillig *et al.*[117] They have used coconut shell powder and pine WF as reinforcement in LDPE, HDPE and PP matrix systems. The authors also analysed the dispersion of two types of lignocellulosic mass into a polymeric system. It was attributed that composites exhibited a good distribution of WF in a thermoplastic matrix, but the inclusion of coconut shell powder caused bubble formation in finished pieces, which interfered with material characteristics. Compared to composites manufactured with pine WF, the inclusion of the coconut shell reduced all the characteristics. Furthermore, the addition of both types of WF to the LDPE matrix reduced the tensile strength when compared to the pure matrix. These results suggest weak adhesion between he polymeric matrix and reinforcements. Moreover, the smaller particle size of the coconut shell powder contributes to the reduced performance of composites. The addition of coupling agents caused improved interfacial adhesion in all types of polymeric composites, and thus, improved the properties of WPCs. However, LDPE-based composites showed the least performance even after the addition of coupling agents.

The effects of various material compositions including different plastic matrices, wood flour, and coupling agents on the mechanical properties of wood–plastic composites (WPCs) manufactured by injection moulding were investigated by Kuo *et al.*[123] They found that the tensile strength and modulus of rupture (MOR) of WPCs made with low-density polyethylene (LDPE) and polypropylene (PP) (*i.e.*, reinforced with wood flour) were higher than those of LDPE and PP alone. Among the WPCs studied, those made from PP mixed with 47% wood flour and 3–4.5% maleic anhydride-grafted polypropylene (MAPP) exhibited superior tensile strength, MOR, and storage modulus to the other WPCs in the study. Compatibilizers play a crucial role in wood–plastic composites (WPCs) by enhancing the interfacial bonding between the hydrophobic plastic and hydrophilic wood fibres. This improved adhesion helps to increase the mechanical strength, durability, and moisture resistance of WPCs, making them more suitable for outdoor and high-performance applications. Additionally, compatibilizers can contribute to better processing properties, allowing for smoother manufacturing processes and more consistent product quality. Therefore, the selection of compatibilizers is crucial, as the right choice can significantly impact the final performance of WPCs. A comparison between different compatibilizers is necessary to identify the most effective option for specific applications, ensuring optimal performance and cost-efficiency. The effect of several compatibilizers such as EVOH, PE-*g*-MA and dPE on the WPCs containing different types of wood species was investigated by Effah *et al.*[116] The tensile modulus of all composites increased dramatically with the addition of WF since WF makes composites more rigid, which requires higher stress to initiate a crack. It was observed that for all wood species, composites containing PE-*g*-MA as a compatibilizer had the highest tensile modulus, while EVOH composites were less stiff and had a low tensile modulus. When compared to pure LDPE and other compatibilizers, composites containing EVOH showed a reduction in composite strength. However, PE-*g*-MA-containing composites exhibited a greater tensile strength and were less susceptible to wood species. It was found that composites utilising dPE as a compatibilizer exhibited the highest tensile strength across all wood types with the least variation. The tensile strength of composites containing 30% wood was equivalent to the tensile strength of WPCs, including compatibilizers, when wood loading was increased. Varied chemical interactions of wood with different compatibilizers could be the reason for such variations in the tensile properties of composites. Since wood particles do not contribute to elasticity, increased wood loading decreased elongation at break in composites without compatibilizers. It was found that for most wood species, composites containing dPE compatibilizers showed maximum elongation at break while composites containing PE-*g*-MA exhibited the lowest elongation at break, indicating that they are more brittle than composites containing other compatibilizers. In terms of impact strength, softwood-based composites executed better performance than hardwood composites due to the presence of longer tracheid in softwoods, which absorbs and distributes stress uniformly as compared to smaller fibres in hardwoods.

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The incorporation of waste materials into the production of wood–plastic composites (WPCs) has attracted significant attention due to its potential for sustainable manufacturing. In this context, researchers have explored the use of low-density polyethylene (LDPE) waste and wood fibre (WF) waste to create high-performance WPCs. Moreno *et al.*[120] assessed the morphological, mechanical, and thermal properties of these WPCs, offering valuable insights into their viability and performance. They reported morphological, mechanical and thermal behaviours of WPCs. It was observed that as a function of wood content integrated into the material, WPCs showed significant variations in their characteristics, primarily mechanical performance. A wood content of 1.5 wt% results in an increase in the tensile strength of composites as compared to neat LDPE. However, further addition of wood fibre results in a reduction in tensile strength. Similarly, elongation at break also decreases with wood content since wood fibres possess less strain as compared to the polymeric matrix. At more than 15 wt% wood content, elongation at break drops significantly. Contrary results were obtained for Young's modulus of composites, where Young's modulus increases with the wood content. Morphological analysis suggests that wood fibres with rough surfaces have varied shapes and sizes. Morphological images of composites with a low fibre content showed that wood particulates are completely covered with a polymeric matrix, and good adhesion between fibre and matrix was observed. Moreover, composites displayed thermal stability during thermomechanical processing. In a distinct study, the influence of processing conditions such as temperature, pressure and time on the mechanical and microstructural properties of WPCs was investigated by Atuanya *et al.*[121] They have used recycled LDPE for the development of wood composite boards and compared their properties with the recommended standards for general-purpose boards. Microstructural analysis revealed that wood particles have smooth surfaces and were uniformly distributed within the matrix without fibre pullouts. The modulus of elasticity was found to be increasing with wood particles, as it provides stiffness to composites. Data obtained for the modulus of rupture was found within the range of recommended standards for general-purpose boards. It was observed that pressing time and pressure positively influence the tensile strength of composites, as these parameters were found to be responsible for strengthening interfacial bonding between the wood and the matrix. The impact strength of all composites was found in almost the same range, and improvement in strength was achieved due to good bonding between the matrix and wood particles.

The use of regenerated wood fibre (RWF) in the production of wood–plastic composites (WPCs) offers a sustainable solution by enhancing material properties while reducing reliance on virgin wood fibres. When incorporated into different polymer matrices, the RWF significantly influences the mechanical and weathering characteristics of WPCs. The weathering resistance of these composites, developed from matrices such as polyethylene, polypropylene, and polyvinyl chloride, varies based on the polymer's chemical structure and the efficiency of fibre–polymer bonding. Polymers with higher resistance to UV degradation, moisture absorption, and thermal expansion tend to produce WPCs that perform better under outdoor conditions, maintaining their strength, appearance, and dimensional stability over time. In a study done by Tao *et al.*,[122] low-density polyethylene powder (LDPE) was combined with regenerated wood fibre to make WPC. The research investigated the influence of processing parameters such as board density, coupling agent quantity, hot pressing temperature and pressure on product characteristics. It was observed that hot-pressing duration had the greatest impact on the characteristics of WPC composites, the effect of hot-pressing temperature was larger than the density of composites, and the amount of coupling agent had only a little impact on performance. They reported that WPC board characteristics were linked not only to raw ingredients but also to the chemical structure and the type of coupling agent employed. In a varying study, Lee *et al.*[119] compared the weathering properties of WPCs developed from different polymer matrices. Recycled plastics displayed less colour change as compared to virgin plastics; the presence of contaminants and additives might provide a shield against photo discolouration on composites. It was observed that the mechanical properties of composites were greatly affected by the type of plastic, wood material and interfacial adhesion between wood and plastics. An increase in weathering time results in a decrease in flexural properties. Polyethylene-based composites showed the highest strength, while polystyrene-based composites exhibited the least strength.

2.4 PVC-based composites

Polyvinyl chloride (PVC) is a versatile polymer made from vinyl chloride through addition polymerization. Typically rigid PVC can be made more flexible by adding plasticizers. It is widely used in extrusion processing due to its ease of manipulation; however, its thermal instability is a notable drawback, as it can degrade and release harmful hydrochloric acid (HCl) gas at high temperatures. PVC is categorized into three main types: Type I, Type II, and CPVC. Type II offers higher impact resistance than Type I but has reduced chemical resistance, while CPVC is known for its superior resistance to high temperatures. These PVC types are considered "unplasticized" because they are less flexible compared to plasticized PVC formulations.[124,125] The performance of polyvinyl chloride-based composites with varying WF content has been examined, and is discussed in Table 4, Fig. 20 and 21.

The properties of wood–plastic composites (WPCs) are significantly influenced by various factors including the content and type of wood fibre (WF), as well as the molecular weight of the polymer matrix. These elements play a crucial role in determining the composites' overall mechanical strength, durability, and processing characteristics. Understanding how these factors interact is essential for optimizing the WPC performance for specific applications. The effect of WF content, its type and molecular weight of PVC on the properties of WPCs was studied by Rocha *et al.*[126] They reported that the developed composites showed changes in appearance with the addition of WF. It was observed that the amount of WF in composites has

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Table 4 Mechanical and physical properties of WPCs reported by other researchers

S. no.	Type of polymer	Coupling agent/ catalyst	TS (MPa)	TM (GPa)	FS (MPa)	FM (GPa)	WA (%)	IS (kJ m^{-2})	Processing condition	References
1	Polyvinyl chloride (PVC)	—	5.27	0.14	84.30	3.83	—	—	Two-roll milling followed by compression, moulding, 170 °C	126
2		—	—	—	47.00	4.60	—	—	Hot pressing, 180 °C, 7 minutes	127
3		—	—	—	34.00	2.08	—	—	Compression moulding, 180 °C, 7 minutes	128
4		—	35.20	5.29	58.50	4.93	—	10.6	Injection-moulding, 180 °C	129
5		—	4.44	1.31	—	1.89	9.01	1.56	Compression moulding, 185 °C	130
6		—	30.86	3.82	52.09	3.94	—	—	Twin-screw extruder assisted hot pressing, 180 °C	131
7		MA	28.90	0.36	44.70	2.99	3.08	3.20	Extrusion moulding, 150–165 °C	132
8		—	42.5	0.18	—	—	0.35	5.6	Compression moulding, 180 °C, 10 minutes	133
9		Chitosan	42.45	—	74.7	—	10.92	—	Twin-screw extruder, 125–185 °C	134
10		CPE	—	—	41.8	3.62	—	—	Compression moulding, 190 °C, 3–5 minutes	135

a little effect on the properties of WPCs, such as wettability and flexural strength. However, with high WF concentration, there is a tendency for wettability and flexural strength to decline. They suggested that these characteristics might be directly linked to the PVC matrix employed, as demonstrated by the flexural behaviour of composites. The investigation of the tensile characteristics of composite materials revealed that a low proportion of WF results in a more brittle material that breaks immediately after the yield point. It was found that reduced tensile strength and elongation at the yield point and lower elongation at break are the results of increasing WF content. When compared to bubinga flour, walnut flour produces a material with greater tensile properties. PVC with a lower molecular weight produces composites with lower tensile properties when compared to PVC with higher molecular weight composites. The addition of WF increases the degradation temperature of the primary

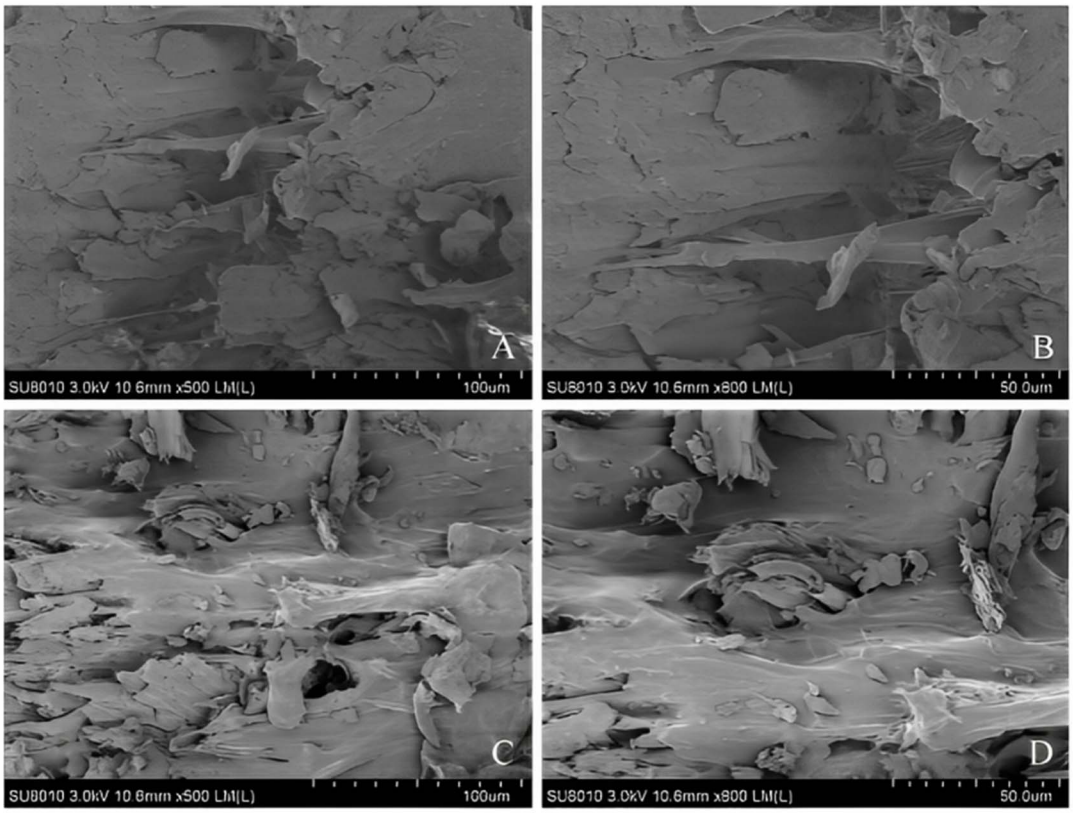

Fig. 19 Microstructural observation of PVC-based WPCs (A–D). Reprinted with permission.[127] Copyright 2019, The Royal Society of Chemistry.

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matrix, according to the morphological and thermal tests. In an exclusive study, Li *et al.*[127] analysed the influence of PVC perforation diameter, pressing duration, and hot pressing temperature on the thermal and mechanical properties of WPCs. Pre-treatment of PVC showed a significant influence on the MOR of WPCs, which is trailed by pressing duration on the MOR, while pressing temperature influences more on the MOE of composites. The authors found that 15 mm pore size of PVC, 7 minutes of pressing time and 170 °C of pressing temperature were the optimum processing conditions of composites with the highest mechanical properties. They reported that pressing times of less than 7 minutes result in incomplete melting of PVC, while increasing the pressing duration, for example, from 8 to 9 minutes, may result in a rise in the flow of melt PVC and infiltration into the veneer crack, reducing the bonding strength. A temperature below 170 °C influenced the efficiency of heat transfer, while a too high temperature results in untimely melting of PVC. The PVC pore size also has a significant impact; small holes may not provide enough heat transmission channels. However, increasing the hole size is comparable to reducing the amount of PVC injected. Appropriate pre-treatment of PVC results in improved thermal stability of composites. FESEM analysis showed better melting and penetration of PVC into veneer, forming improved adhesion between the reinforcement and the matrix (Fig. 19).

The reinforcement materials and processing parameters used in wood–plastic composites (WPCs) significantly affect their overall properties and performance. Various studies have focused on understanding the influence of different fibres and particle sizes in enhancing the mechanical and thermal characteristics of WPCs. Lei *et al.*[132] investigated the effect of utilisation of three different types of fibres (aluminium silicate fibre, zirconia fibre and basalt fibre) as reinforcements and the influence of simulated soil ageing on the properties of WPCs. It was observed that for the overall properties of composites, interfacial adhesion between the fibre and the matrix plays a significant role. The addition of three different types of inorganic fibres resulted in the improvement of thermal stability and physical and mechanical properties of composites.

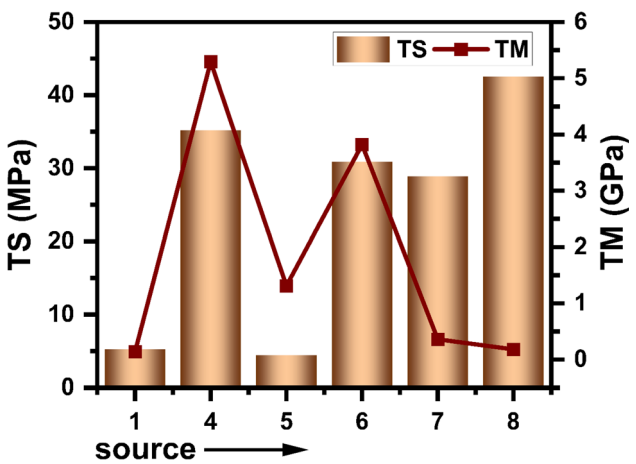

Fig. 20 Tensile properties of PVC-based WPCs.

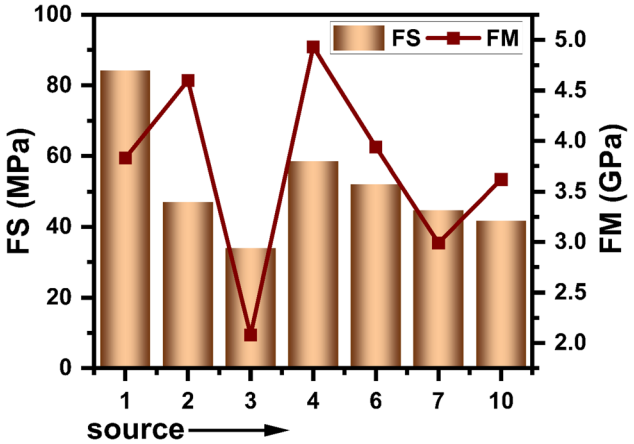

Fig. 21 Flexural properties of PVC-based WPCs.

Compared to the other two inorganic fibre-reinforced composites (AS and BF), ZF-reinforced composites offer greater heat and wear resistance qualities. Furthermore, for each simulated soil ageing stage, a tight interface resulted in improved mechanical and physical properties. Wear resistance, moisture absorption and antiaging properties of composites were also improved with the addition of three inorganic fibres. In different research, the effect of wood particle size on the mechanical, morphological and thermal properties of WPCs was studied by Saini *et al.*[133] To accomplish this study, they have taken two wood particle sizes, namely 100–150 μm (macro filler) and <50 μm (micro filler). The water absorption of composites increased with the addition of WF, and composites with micro-sized wood fibres absorbed more water than their macro-sized counterparts. A similar trend was observed for the modulus of all composites. The tensile modulus was found to increase with the addition of WF. The obvious reason behind this result was the stiffer nature of wood particles, which adds more stiffness to composites. However, micro-sized wood fibre-based composites showed higher modulus than the macro-sized wood fibre-based composites. On the contrary, the tensile strength and elongation at break decreased with the increase in the amounts of WF. The impact strength of micro-sized wood fibre-based composites was almost double that of macro-sized wood fibre-based composites. No negative effects on the thermal properties of composites were seen with the addition of WF. Morphological analyses of WPCs showed agglomeration at higher wood contents, whereas at a lower wood loading, uniform dispersion was seen. The influence of specimen cross-section size and wood particle size on the mechanical properties of WPCs was investigated by Kociszewski *et al.*[129] They have taken four different sizes of wood particles: very small (S1, 0.25–0.5 mm), small (S2, 0.5–1 mm), large (L1, 1–2 mm), and very large (L2, 2–4 mm), as well as three different cross-section areas of injection-moulded specimens: 4 × 10 mm^2, 6 × 15 mm^2, and 8 × 20 mm^2. Flexural and tensile properties increased from S1 to L1 and then decreased at L2. WPCs with larger particles (L1 and L2) showed about 11% increment in tensile strength and 12% increment in tensile modulus compared to composites with

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smaller particles (S1 and S2). Composites with larger particles showed 18% greater flexural strength and 11% greater flexural modulus than smaller particle-based composites. Similarly, the impact strength of larger particle composites was found to be around 9% greater than that of smaller particle composites. Mechanical properties such as tensile, flexural and impact strength were found to decrease with the increase in cross-section size.

The modification of wood fibre (WF) composites with natural biopolymers has attracted attention as a means to enhance their properties. In particular, chitosan, a natural polysaccharide, has been explored for its potential to improve the performance of PVC-based WF composites. Studies on these modified composites have revealed significant improvements in various properties such as mechanical strength, moisture resistance, and biodegradability. Xu *et al.*[134] investigated various properties of PVC-based WF composites modified by natural chitosan. Mechanical properties such as tensile and flexural strength decrease initially with the addition of chitosan, then increase and reach a maximum with the addition of 30 phr of chitosan. It was observed that chitosan's particle size also significantly affects composites' mechanical properties. Flexural strength was higher with the smaller particle size of chitosan. On the contrary, the tensile strength decreased with particles passed through 220 mesh. The water absorption of composites was reported to increase with the addition of chitosan, as it provides more hydroxyl groups and attracts more water molecules. Morphological analysis suggests that a bigger specific surface corresponding to a smaller particle size (higher mesh number) provides a more effective connection at the wood fibre–PVC matrix interface. The effect of wood type, content and glass fibres on various properties of WPCs was investigated by Jeamtrakull *et al.*[128] The addition of WF tends to increase the hardness, roughness, wear resistance and flexural modulus of composites. Flexural strength was found to increase to 40 phr of wood content and then decrease to a wood amount of 60 phr. The probable reason for the decrease in flexural strength at a higher wood content was the improper dispersion of wood particles into the matrix. The addition of glass fibre results in the improvement of flexural strength by 21–93% and flexural modulus by 52–129%.

The addition of specific additives can significantly influence the properties of wood–plastic composites (WPCs). One such additive, zinc borate, when incorporated with wood fibres (WF) and a PVC matrix, has been studied for its potential to enhance various performance characteristics. Research on this combination has shown that zinc borate can improve the flame retardancy, thermal stability, and overall durability of WPCs. Fang *et al.*[131] investigated the effect of incorporation of zinc borate along with the WF and PVC matrix on the mechanical, thermal, smoke suppression and fire retardancy of WPCs. They reported that mechanical properties such as tensile and flexural strength of composites with the addition of zinc borate decreased by 19% and 8%, respectively. The reduction in the strengths of the composite suggests incompatibility of the filler and matrix and poor interface adhesion. However, the modulus of composites tends to increase with the addition of zinc borate. The authors stated that WF was more rigid as compared to PVC, and the addition of zinc borate improved the rigidity of composites, hence resulting in better modulus. It was observed that WF possesses improved flame retardancy but has no influence on smoke suppression. Moreover, the addition of zinc borate to the WF PVC composite did not considerably improve its flame retardancy. In a separate investigation, Binhussain *et al.*[130] utilised date palm leaves and plastic waste for the development of WPCs and compared their performance with MDF, naturally soft and hardwood. The authors stated that due to the underlying high strength, lower elongation at break and stiffness of the PVC matrix, the developed PVC-based composites showed higher strength and modulus (in both tensile and flexural) and lower elongation at break than the other matrices. The density of composites differed by 45–80% with a density of MDF, soft and hardwood. Composites displayed less water absorption than natural woods and MDF due to the presence of a plastic matrix, which is hydrophobic in nature and restricts the absorption of water. The hardness of composites was found within the range of the hardness of natural softwood samples. The linear burning rate of composites was higher than that of natural wood and MDF. Kositchaiyong *et al.*[135] conducted a study to evaluate the influence of different types of woods, MI, XK and HB, and algaecides on the properties of WPCs. The authors reported that the addition of WF influenced the flexural properties of composites, and all composites exhibited improved flexural properties as compared to pristine PVC except XK wood-based composites. Among the three wood types, it was discovered that HB and MI wood composites had stronger flexural properties and reduced surface roughness than XK wood composites. This was most likely due to the fact that the surface area and pore volume size of those two types of wood were significantly larger than those of the XK wood. As a result, interfacial adhesion between the PVC matrix, MI and HB wood, which is related to composite compatibility, was possibly stronger than that of the XK wood. Flexural properties were significantly increased by 10–47% with the addition of isoproturon algaecide. Polarity in the chemical structure of isoproturon might have contributed to the molecular interaction of polar PVC and wood. Therefore, it can serve as a potent coupling agent for WPCs. The addition of wood and algaecide results in a colour change of composites. The results from DSC, FT-IR measurements, and contact angle recommended that isoproturon had a better affinity towards PVC molecules, which is responsible for the dehydrochlorination reaction in PVC molecules, while terbutryn algaecide had a lower interaction with PVC molecules, which resulted in its greater anti-algal performance.

2.5 PS-based composites

Polystyrene (PS) is a simple plastic derived from styrene and is available in three primary forms: general purpose PS, oriented PS, and high-impact PS (HIPS). High-impact PS is especially important because of its enhanced characteristics. This modified version of PS includes an impact modifier, often rubber-like polymers such as polybutadiene, which significantly improves

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Table 5 Mechanical and physical properties of WPCs reported by other researchers

S. no.	Type of polymer	Coupling agent/ catalyst	TS (MPa)	TM (GPa)	FS (MPa)	FM (GPa)	WA (%)	IS (kJ m^{-2})	Processing condition	References
1	Polystyrene (PS)	—	20.2	1.15	30.7	3.4	2.45	0.64	Twin-screw extruder assisted compression moulding, 170–190 °C	123
2		—	29.9	15.0	25.9	4.1	5.02	1.21	Twin-screw extruder assisted compression moulding, 170–195 °C	124
3		SMA	—	—	51.28	4.45	—	0.095	Twin-screw extruder assisted injection-moulding, 180 °C	125
4		SMA	37.66	5.80	56.04	5.74	—	0.07	Twin-screw extruder assisted injection-moulding, 180 °C	126
5		PMAA	54.01	4.48	—	—	0.59	—	Twin-screw extruder assisted transfer moulding, 185 °C	140
6		MA	14.17	1.38	27.55	3.38	—	—	Compression moulding, 140–200 °C, 10–20 minutes	141
7		—	—	—	21.24	2.83	19.07	—	Solvent casting	142
8		—	12.58	0.58	—	—	—	0.022	Compression moulding, 230 °C	143
9		DAP	—	—	52	3.9	0.64	—	Twin-screw extruder assisted injection-moulding, 160–190 °C	144
10		SEBS-MA	16.38	1.02	36.4	3.73	—	0.015	Twin-screw extruder assisted compression moulding, 170–200 °C	145

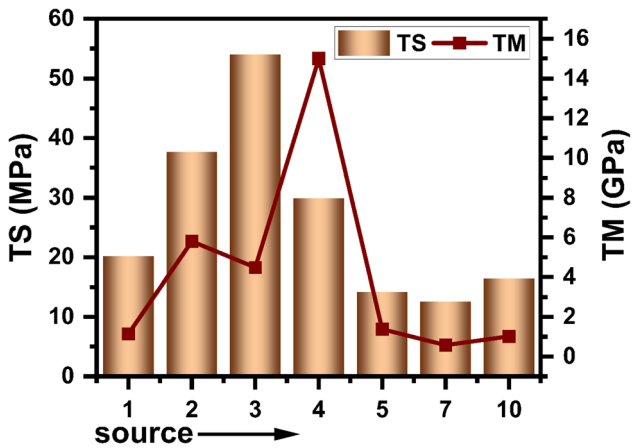

Fig. 22 Tensile properties of PS-based WPCs.

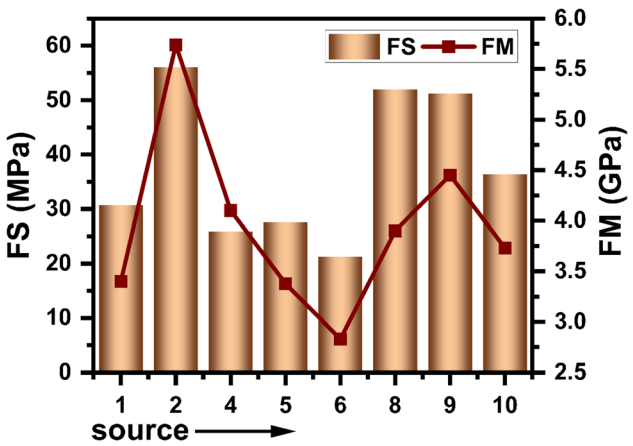

Fig. 23 Flexural properties of PS-based WPCs.

its toughness and resistance to impact.[125] The performance of polystyrene-based composites with varying WF content has been examined, and is discussed in Table 5, Fig. 22 and 23.

The selection of coupling agents plays a crucial role in improving the interfacial bonding and overall performance of wood–plastic composites (WPCs). In this context, Liang *et al.*[140] developed WPCs using three different types of copolymer coupling agents such as MAA, MAAL and VA. The authors examined the bonding efficacy of different coupling agents and reported their effect on the properties of WPCs. It was observed that the tensile strength of composites was decreased with fibre loading, and the addition of a coupling agent does not significantly improve the strength when compared to pure polystyrene. However, the tensile strength of WPCs with no coupling agent was observed least as compared to other WPCs with different coupling agents. This result indicates lower bonding between wood fibres and the polymer, which is increased by the addition of coupling agents. PMAAL was observed as the most potent coupling agent at a maximum fibre loading, which maintains the original tensile strength. On the contrary, the tensile modulus was found to increase with the addition of wood fibre. At a maximum fibre loading, PMAA was observed as the most effective coupling agent, which increased tensile modulus by 23.9%. The water absorption of WPCs increased with the addition of wood fibres. It implies the fact that wood fibres are hydrophilic in nature and, therefore, absorb more water than the pure polymer, which is hydrophobic in nature. The incorporation of flame retardants is an important factor in enhancing the safety and performance of wood–plastic composites (WPCs). In this regard, Chindaprasirt *et al.*[144] investigated the effect of flame retardant (DAP) on the properties of WPCs manufactured using expanded polystyrene waste and WF. The flexural strength of WPCs was decreased with the addition of DAP due to the poor compatibility of DAP with the fibre and matrix. However, when compared to commercial WPCs and other wood composites modified with flame

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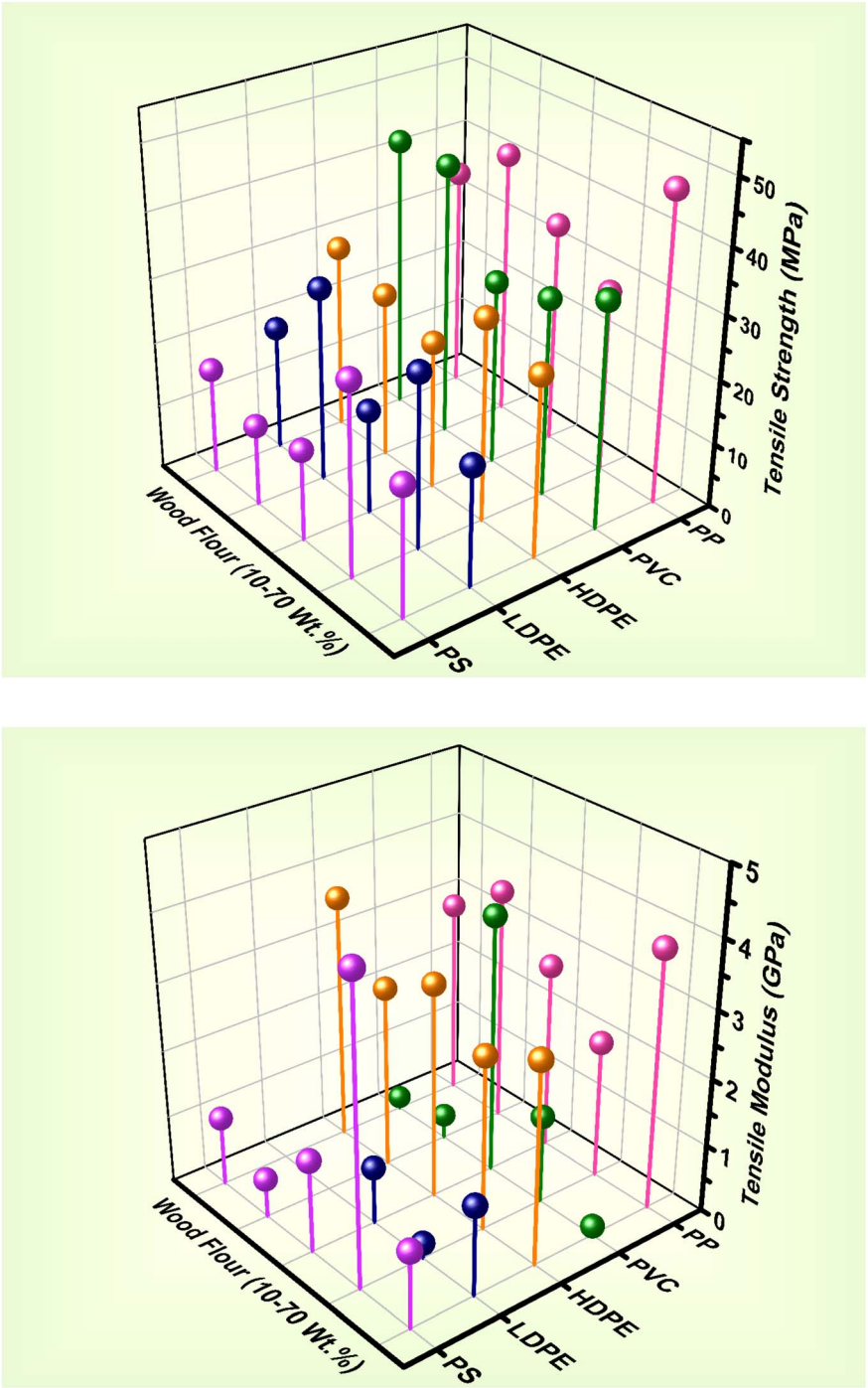

Fig. 24 Comparative tensile properties of WPCs based on different matrix types.

retardants, the flexural strength and modulus of WPCs tend to increase. It was observed that the fire resistance of WPCs was likely to improve as the DAP level increased. The thermal degradation rate of WPCs dropped from 1.57 to 0.86% $°C^{-1}$. The best linear burning rate was found in WPCs treated with DAP up to 20% by weight. In addition, water absorption of WPCs increased with the content of DAP due to the formation of hydrogen bonding between water molecules and free hydroxyl groups found in the DAP structure, and moreover, the propagation of water molecules into WPCs was likely responsible for water absorption by composites.

The expanded polystyrene (EPS) is a lightweight, rigid, and highly versatile material produced by expanding polystyrene beads through heat and pressure. This process results in a foam-like structure that provides excellent thermal insulation, buoyancy, and cushioning properties, which makes EPS widely used in packaging, construction, and insulation. The combination of wood fibres and expanded polystyrene (EPS) in

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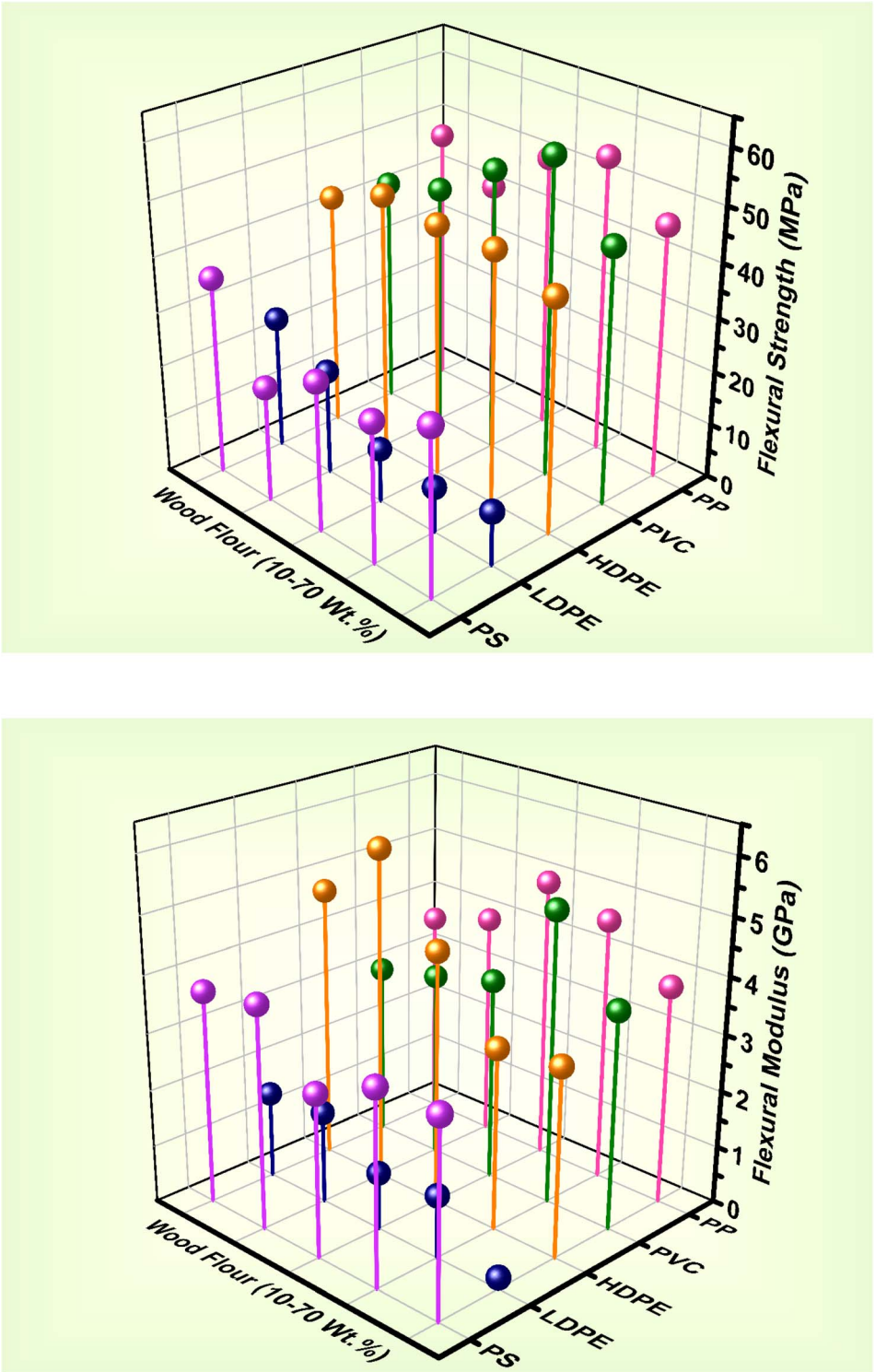

Fig. 25 Comparative flexural properties of WPCs based on different matrix types.

composite materials presents a promising approach to enhance the properties of these materials for various applications. In light of this, Doroudiani *et al.*[143] developed expanded wood fibre polystyrene composites (EPSC) and their mechanical properties were examined and addressed in relation to their processing conditions and structure. An enlarged interphase between the fibre and the matrix was identified, which is expected to have a significant impact on mechanical properties. The effect of fibre content and foaming time was observed to be significant for tensile strength, while the foaming temperature and saturation pressure were insignificant. It was observed that at a higher fibre content and pressure saturation, the tensile

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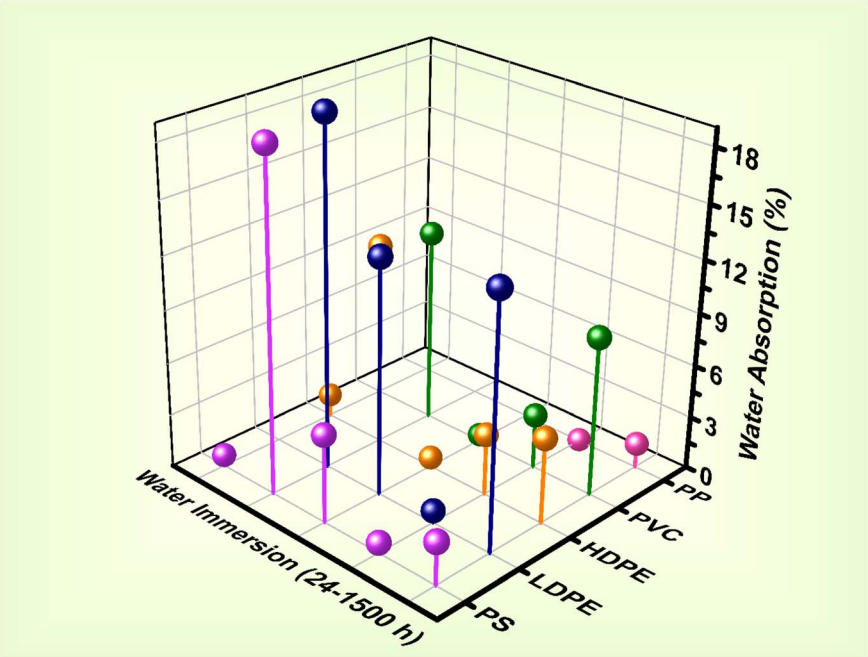

Fig. 26 Comparative water absorption of WPCs based on different matrix types.

modulus increased by about four times, while it dropped when the foaming time and the temperature increased. However, the fibre content does not show considerable effects on impact properties. In addition, the incorporation of fibres was observed to be favourable for improving the mechanical properties. The effect of the amount of WF and coupling agents on the morphological and mechanical performance of WPCs developed from recycled expanded polystyrene was investigated by Poletto *et al.*[138,139] They also investigated the shape, size and surface morphology of WF. It was observed that when the amount of WF increases, the flexural modulus also increases since WF is more rigid than the polystyrene matrix. The flexural strength and strain decrease with the fibre loading due to poor dispersion of WF into the polymer matrix and weak interfacial bonding between the matrix and the polymer. In addition to the coupling agent, the flexural strength and modulus both increase substantially due to the probable reaction between acid anhydride groups of the coupling agent and hydroxyl groups of hydrophilic WF. The optimum amount of coupling agent was found to be 2 wt%, which was responsible for the improved flexural strength by 23% and flexural modulus by 18% when compared to composites without any coupling agent. However, further addition of coupling agent by 4 wt% results in decreased flexural properties. The tensile strength and strain without a coupling agent were decreased with the fibre loading due to the hydrophobic behaviour of the polymer and the hydrophilic behaviour of the wood fibre, which leads to low compatibility between the matrix and the fibre. The presence of a coupling agent considerably improved the tensile properties. The impact strength of WPCs decreased with the addition of WF due to enhanced stress sites and weak interfacial regions. However, the addition of a coupling agent improves the dispersion of WF, which provides uniform distribution of applied stress and further results in improved impact resistance of composites. Morphological analysis showed that the surface of composites without the coupling agent was smooth and voids were present. In contrast, the surface of composites with a coupling agent was rough, which suggests good wetting and interfacial adhesion between the polymer and the matrix, responsible for improved mechanical properties.

The performance of wood–plastic composites (WPCs) is greatly influenced by the choice and concentration of various additives and fillers. In particular, the type and dosage of these materials can significantly alter the mechanical characteristics of the composites. Mengeloglu *et al.*[145] examined the effect of concentration of additives, filler dosage and type on the properties of WPCs. It was observed that the mechanical properties were significantly affected by filler and additive loadings. The tensile and flexural strength of composites was found to be reduced with the addition of WF, while the modulus of elasticity and impact strength were improved. The modulus performance of composites was better with filler loadings. The addition of additives results in a reduction of all properties except elongation at break and impact strength. These poor mechanical properties of composites may be brought about by the poor performance of additives in matrix systems. Compared to unfilled polystyrene samples, the morphological images of composite foams revealed that the composite samples exhibited larger and more diverse cells. In another research, Hernandez *et al.*[136,137] investigated the effect of size and concentration of WF on the properties of WPCs. They reported that when the concentration of wood particles was increased, the ultimate tensile strength and Young's modulus fell due to poor compatibility between the reinforcement and the matrix. Larger

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wood particles result in a reduction in flexural strength. It was observed that the flexural modulus of composites with smaller particle sizes paired with a higher reinforcing content increased. This may be attributed to the fact that cellulosic fibres already have a high modulus, and moreover, they are arranged perpendicular to the applied force. However, the flexural modulus of WPCs with larger wood particles was reduced. It was found that the impact strength of composites increases with the wood content and smaller particle sizes. Longer wood fibres induce more stress concentration sites and thereby cause rupture. Furthermore, the water absorption of composites is significantly affected by the size and content of wood particles. Higher wood content and large wood particles absorb more water than their counterparts.

The selection of the polymer matrix is a critical factor influencing the overall performance and properties of wood–plastic composites (WPCs). Different matrix systems can significantly alter the composite material's mechanical, thermal, and chemical characteristics, making it essential to carefully choose the appropriate matrix for specific applications. Regarding this, Ratanawilai *et al.*[141] used five different matrix systems, namely LDPE, HDPE, PP, PVC and PS, for the synthesis of WPCs. They studied the effect of the type of matrix on the mechanical and weathering properties of WPCs. The type of plastic has a significant effect on the flexural and tensile strength; among the five types of plastics, PP-based composites showed maximum flexural strength, followed by polystyrene composites, while WPCs with LDPE showed the least flexural strength. However, polystyrene WPCs showed maximum tensile strength, followed by PP-based composites. They suggested that the chemical structures of the matrix were responsible for the varied mechanical properties. In general, the flexural strength of composites increased with the plastic content due to better dispersion of wood particles in the matrix system, which is responsible for the dissemination of stress. Furthermore, under natural weathering, flexural and tensile strength tend to drop as compared to the unexposed samples. This is attributed to the changes in the crystallinity of plastics and oxidation reactions on the surface of WPCs. In addition, the plastic-type significantly affects the flexural and tensile moduli of all WPCs. Polystyrene showed maximum flexural and tensile moduli with 40% and 50% plastic concentration, respectively. Similar to flexural strength under natural weathering, flexural and tensile moduli were found to decrease. The growing need for sustainable materials has led to the exploration of alternative resources for producing wood–plastic composites (WPCs). One promising approach is using waste materials such as plastic and sawdust to create composites that can serve in various applications including construction. In their research, Chanhoun *et al.*[142] utilised plastic waste and sawdust waste for the synthesis of WPCs for building applications. The mechanical and physical performances of WPCs are in line with the current wood particle board requirements. The flexural properties of composites revealed the plastic and ductile behaviour of ruptures and not a flow threshold. They reported that, as per ANSI, all of the composite boards used in this study meet the criteria for the modulus of elasticity and the modulus of rupture for general uses and furniture fabricating applications. However, when referring to EN312-2, particleboards made from polystyrene-based polymer met the MOR requirements. It was found that the tensile strength of the composite panel fulfils the standard requirements for general applications. It was observed that boards or sheets which contain a high level of fine particles have a superior compaction rate since small particles fill up voids and thus provide better water absorption, thickness swelling, permeability and density.

3. Conclusions

The conclusions drawn from this study underscore the critical need for effective recycling and management of wood waste to address pressing environmental, economic, and societal challenges. The development of high-quality Wood–Plastic Composites (WPCs) relies on the careful selection of a matrix that is not only cost-effective and non-hazardous but also delivers superior performance. Extrusion and injection moulding remain the most widely used production methods for WPCs due to their high efficiency, scalability, and consistent output, making them industry standards capable of meeting the rising demand for WPCs across multiple sectors.

The performance of these composites is significantly influenced by parameters such as the aspect ratio, particle size, and concentration of wood flour, highlighting the need for precise formulation and control during manufacturing. Advanced strategies including pre-treatment techniques, coupling agents, reinforcements, nano-additives, and mineral fillers have been employed to further enhance the WPC properties, resulting in improved mechanical strength, thermal stability, and long-term durability. These innovations have broadened the applicability of WPCs in infrastructure, packaging, automotive, household products, and the construction industry, where their biodegradability, low density, cost-effectiveness, and excellent mechanical characteristics are highly valued.

Looking forward, future research should focus on developing bio-based and fully biodegradable polymer matrices to enhance the environmental sustainability of WPCs. Additionally, the integration of smart functionalities such as self-healing, fire resistance, or sensing capabilities could further expand their application in advanced engineering and smart infrastructure. Life cycle assessments, large-scale field testing, and optimization of recycling pathways will also be essential to support the circular economy and ensure long-term viability. These directions will help WPCs evolve into next-generation sustainable materials, playing a vital role in the transition toward greener industrial practices.

4. Future challenges and opportunities

Natural fibres, such as wood flour and other lignocellulosic materials, typically possess polar hydroxyl groups on their surfaces, which makes it challenging to form a strong interphase with a nonpolar matrix when incorporated into a thermoset or thermoplastic material. This results in poor interfacial interaction between the components, leading to reduced

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mechanical, physical, and thermal properties in Wood–Plastic Composites (WPCs). Various approaches can be applied to improve interfacial adhesion, such as pre-treating wood flour, reinforcing with mineral fillers and nano-additives, and adding compatibilizers. The matrix's inherent hydrophobic nature and the wood flour's hydrophilic nature further exacerbate the incompatibility between the two components. One significant drawback is the water absorption of WPCs, which negatively impacts the durability and mechanical performance of the composites. Additionally, designing a more efficient compounding system that minimizes damage to the wood particles is another challenge in the production of WPCs.

Continuous research and development efforts are necessary to overcome these challenges to create advanced WPCs with superior performance for a wide range of global applications. Furthermore, agricultural waste, such as rice husks, wheat straw, and sugarcane bagasse, can be utilized as an alternative reinforcement material in WPCs instead of wood. Incorporating agricultural waste into WPCs offers several benefits, including reducing the reliance on wood as a raw material, lowering production costs, and enhancing the sustainability of the composites. Agricultural waste is abundant, renewable, and biodegradable, making it an eco-friendly solution that not only improves the mechanical properties of WPCs but also contributes to waste reduction and environmental conservation. It is estimated that in terms of revenue, the worldwide wood–plastic composite market is expected to approach US$12.99 billion by the end of 2028, creating better opportunities for the future.[146]

Abbreviations

WF	Wood flour
WPCs	Wood–plastic composites
IPBC	3-Iodo-2-propynyl butyl carbamate
Irgaguard	2-Thiazol-4-yl-1*H*-benzoimidazole
EVOH	Polyethylene-*co*-vinyl alcohol
PE-*g*-MA	Polyethylene-graft maleic anhydride
dPE	Thermally degraded LDPE
MI	*Mangifera indica* Linn
XK	*Xylia kerrii* Craib and Hutch
HB	*Hevea brasiliensis* Muell
Algaecides	Isoproturon and Terbutryn
MAA	Methacrylic acid
MAAL	Low-molecular-weight methacrylic acid
VA	Vinyl acetate
DAP	Diammonium phosphate
TS	Tensile strength
TM	Tensile modulus
FS	Flexural strength
FM	Flexural modulus
WA	Water absorption

Data availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request. Any relevant datasets, including raw and processed data, have been documented and can be provided in accordance with institutional and publisher guidelines. Where applicable, publicly available sources have been cited within the manuscript.

Conflicts of interest

There are no conflicts to declare.

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