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ORIGINAL ARTICLE

Use of hornbeam, pine and MDF waste in wood-polymer composites as construction elements

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Abstract Wood-plastic composites, produced from lignocellulosic materials such as wood fiber and wood flour as reinforcement, are renewable, recyclable, and biodegradable materials, especially suitable for the structural design. In this study, wood-polypropylene composites were produced by co-rotating twin-screw extrusion technique, while polypropylene (PP) was used as the composite matrix, hornbeam, pine, and medium density fiberboard wastes were used as reinforcement materials. The additive ratio was changed to 10%, 20%, and 30% in each different type of wood powder, and maleic anhydride grafted polypropylene (MAPP) was used as coupling agent at 3% to 6%. The PP, wood fibers and MAPP blended in the mixer were processed in the extruder and turned into granules. Test samples were prepared for the evaluation of their physical and mechanical properties with a compression molding machine. The structural and morphological properties of the composites were investigated by X-ray diffraction (XRD), Fourier Transform Infrared Radiation, and Scanning Electron Microscopy with energy-dispersive X-ray spectroscopy. Tensile and flexural strength analyses were conducted to determine the mechanical properties of the materials. In the tensile test, maximum stress value and elastic modulus were obtained with the sample of M30M6 (%30 MDF, %6 MAPP) as 42.41 MPa and 2050.04 MPa, respectively. In the flexural test, maximum stress value and elastic modulus were achieved with the sample of M30M3 (%30 MDF, %3 MAPP) as 63.18 MPa and 2103.03 MPa, respectively. Looking to the all kind of additives, almost all samples have better properties than pure PP. It was concluded that waste of pine, hornbeam, and MDF have been shown to have great potential for the production of wood-polymer composites.

Keywords Wood-polymer composites · Recycling · Hornbeam · Pine · Medium density fiberboard · Wood waste

Introduction

With the increasing population in the world, the consumption of wood and wood-based products is increasing, and accordingly, the amount of waste generated during the production and consumption of these products is also increasing. In fact, with the correct use of these wastes, it is possible to create a rich raw material base that can significantly reduce the use of natural wood raw materials. Unfortunately, such a situation does not exist at the moment, and after the use of wood-based materials, new trees continue to be cut for the need for new wood raw materials. To put an end to this, finding ways to use the waste generated seems like the best solution. Here, recycling approaches should be evaluated. However, it is generally seen that recycling processes are based on the physical or chemical transformation of waste wood material. In these processes, in which heat plays an important role, thermal transformation of waste takes place (Clemons 2008; Mengeloglu and Karakus 2008; Dalvag et al. 1985). In these methods, called Waste-to-energy (WTE) or Energy from Waste (EfW), the energy gain obtained as a result of burning waste wood comes to the fore. However, these systems require more waste wood to continue burning efficiently. When you build an incinerator, you have to

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"feed the machine" for the next 50 years to get your investment back. When you build an incinerator, resource conservation, recycling, and waste reduction become your "enemy" because your machine has to be fed tons of garbage every day. This leads to the need for more waste wood, more wood consumption, and more wood production. Unfortunately, the result will be more tree cutting. On the other hand, incineration produces hazardous wastes in the form of gas and ash. These toxic substances, which are not found in raw waste (such as dioxins and furans), create new dangers for both human health and other living things in the environment. To put an end to this, finding ways to use the generated waste (without burning/destroying) seems to be the best solution, one of which is the method of reinforcing wood-polymer composites (Mudgal et al. 2014).

Wood-Polymer Composite (WPCs) materials are a combination of matrix polymers, and woods, and their individual properties. It may contain different components of wood (flour, fiber, or chips), plastics (polymers) and additives. These additives can be pigments, light stabilizers, and coupling agents. It is seen that the usage areas of WPCs in different applications have been increasing gradually since the 1990s. These areas can extend from areas such as decking, railing, window, and door frames, to areas such as construction, shipping, and marine. Usage areas in transportation are automotive or train interior panels, dashboards, and some simple interior materials. The use of wood fibers, flours or sawdust as reinforcement material for thermoplastic polymers are examples of natural cellulose material applications that have some advantages over the synthetic and inorganic fillers traditionally used in polymer composites. It is seen that wood-filled composites are on the rise as a competitive product compared to inorganic-filled materials. Related to this, an analysis of the life cycle of car door panels examined the cost-effectiveness of replacing glass fibers with wood fillers (Han et al. 1989; Bledzki et al. 2002). The panels used contained a polypropylene matrix and a filler with a mass content of 40%. In the study, it was determined that the use of organic fillers encourages reducing the negative impact on the environment. It can be also said that wood fillers have a lower cost, greater usability, and significantly lower density compared to glass fibers. In addition to these, another advantage is that wood fiber composites are easy to recycle (Stanaszek-Tomal 2019).

The use of polymer as a matrix in wood polymer composite provides flexibility to the composite, but also makes the composite product resistant to the external environment, especially to the effects of moisture and water. The polymers used are mostly thermoplastics, which are cheap raw materials that flow easily when melted. For example, polyvinylchloride (PVC), polyethylene (PE) and polypropylene (PP), are commercial polymers that are widely used in this sense. In this study, polypropylene—$(C_3H_6)n$ was used as a polymer matrix. It is one of the thermoplastics with a semi-crystalline polymer structure similar to polyethylene, and its production is carried out by polymerization of propylene gas. The specific gravity of polypropylene is very low; 0.85 g/cm^3 in amorphous structure, 0.95 g/cm^3 in crystalline structure. It has high mechanical properties such as good resistance to stress and excellent impact resistance. The melting point of PP is 160–165 °C. The application area of polypropylene is very wide. It can be used in many fields including food packaging, plastic parts, reusable containers, everyday parts, shipping industry, and construction (Hietala 2011).

When viewed as an additive material, it is seen that wood is used in the form of wood flour, fibers, or sawdust in WPCs. Due to their high strength property, wood fibers have a very good reinforcing potential. However, wood fibers are not used as easily as wood flour, due to their high cost and some difficulties experienced in the processing step, especially when feeding into the extruder (Bledzki et al. 2005; Arrakhiz et al. 2012; Li et al. 2000). The flour form of wood, which is the most preferred material in WPC production, contains small wood particles consisting of fiber bundles. Therefore, the strengthening performance of wood flour is not as good as fibers. Although wood flour is obtained in different particle sizes, it can be said that its general use is between 180 µm and 840 µm (Baiardo et al. 2004; Mrówka et al. 2021). Besides polymer matrix and wood additives, WPCs contain small amounts of some useful additives such as coupling and foaming agents, lubricants, pigments, the light stabilizers, coupling agents, charcoal, antioxidants, wax. The use of these additives positively affects the production and material performance (Kumar et al. 2021).

Coupling agents are particularly important in WPCs. Considering that natural fibers are generally hydrophilic materials, it turns out that they do not bond well with the hydrophobic polymer. To overcome this problem, coupling agents are used to increase the interfacial adhesion between the hydrophilic wood and the hydrophobic polymer matrix. In the studies, it is seen that Maleic anhydride grafted polypropylene (MAPP) is generally used. MAPP's enhancement of interfacial adhesion is accomplished by two different mechanisms: (1) the anhydride forms an ester bond with a wood cell wall hydroxyl group, and (2) the polypropylene portion attached to the anhydride mixes with the Polypropylene network in the melt. Accordingly, the operation of the mechanism first begins when the anhydride end of MAPP reacts with a hydroxyl group on the surface of the natural filler forming an ester bond. In the next step, the Polypropylene tail on the grafted MAPP circulates with the molten thermoplastic. This creates a

mechanical bond between the hydrophobic thermoplastic Polypropylene and the hydrophilic natural fiber. The resulting structure also improves the mechanical properties of the composite (Pokhrel et al. 2021; López et al. 2018; Lazrak et al. 2019; Bütün et al. 2019; Adhikary et al. 2008). Mengeloğlu et al. (2008) stated that the most common problem of wood polymer composite processing is non-compliance. Since wood is hydrophilic and polymers are hydrophobic materials, the mixture of these two different materials cannot be homogeneous easily, but it is possible to mix well with the help of coupling agents. Dalvag et al. (1985) showed that the tensile strength, bending strength, and elastic modulus were increased by the use of maleic anhydride grafted polypropylene (MAPP) as a bonding agent in wood-polypropylene composites. Han et al. (1989) reported that the use of MAPP in PP/cellulose composites improved the mechanical properties of the composite. This can be achieved due to the action of reactive hydroxyl groups on the filler surface. Bledzki et al. (2002) investigated the effect of MAPP on wood polymer composite and found that mechanical properties were improved. Arrakhiz et al. (2012) investigated the mechanical properties of pine cones treated with alkali and pine cones compatibilized with Maleic anhydrite. Ultimately, they showed a clear improvement in the mechanical properties of both, which is a 43% and 49% gain in Young's modulus, respectively. The reason for this gain is the improved adhesion between the fibers and the matrix at the interface (López et al. 2018; Lazrak et al. 2019; Bütün et al. 2019; Adhikary et al. 2008).

On the other hand, Bledzki et al. (2005) investigated the effects of the production methods of wood flour and PP composites on their mechanical performance. For this purpose, they produced the composites using three joining techniques: two-roll mill, high-speed mixer and twin-screw extruder. As a result, they determined that the best mechanical strength and the lowest water absorption ability were obtained from the composites combined in the extruder.

In this study, wood polymer composite materials using polypropylene (PP) as base material were produced. Hornbeam (*Carpinus betulus L.*), pine wood (*Pinus sylvestris l.*) and medium-density fiberboard (MDF), which are generally abundant as waste materials in furniture manufacturers, were used as reinforcing wood additives in the composite. Maleic anhydride grafted polypropylene (MAPP) was used as a coupling agent between the polymer and the additive materials. The production was made with the twin screw extrusion technique by turning it together with the coupling agent. The samples were prepared using certain proportions of wood additives (10%, 20%, 30%), two different amounts of coupling agent MAPP (3% or 6%) and PP at the remaining ratio. The obtained composite samples were characterized in terms of their morphological properties. Tensile and bending mechanics analyses were performed to determine the mechanical properties of the materials. Spectroscopic characterizations of wood-polymer composites were carried out to examine the bonding bond between wood species and polypropylene.

Materials and methods

In this study, polypropylene (Petoplen EH 251) was purchased from PETKİM Petrochemical Holding A.Ş. Its properties are as follows: density 0.905 g/cm^3, melt flow index 24 g/10 min. (230 °C/2.16 kg), melting point (Tm) 163 °C, flexural modulus 1450 MPa and tensile strength at yield 38 MPa. While polypropylene was used as composite matrix, hornbeam (*Carpinus betulus L.),* pine *(Pinus sylvestris l.)*, medium density fiberboard (MDF) sawdust were used as reinforcement materials. Hornbeam and pine were provided by a furniture workshops called OSABYA Design Co. MDF lamina was purchased from STARWOOD construction market. As a coupling agent maleic anhyride-modified polypropylene (Bondyram 1001), was purchased from RESINEX BMY A.S. It is a kind of homo-polypropylene recommended for coupling of glass and other fillers in polypropylene composites.

Before starting manufacturing, first of all, pure sawdust of hornbeam, pine and MDF were collected by Koparan KP2000 dust collector in furniture workshop. Then polypropylene, MAPP, and wood sawdust separately were put into the mixer (LabTech Engineering Company LTD) for 5 min to make them homogeneous. Twin-screw extruder (LabTech Engineering Company LTD, screw diameter: 20 mm, L/D ratio of 32:1) was used to produce wood-polypropylene (Wood/PP) composites. Afterward, prepared mixture was placed to the hopper of the extruder. Zone temperatures of extruder were selected between the temperatures 170 °C and 185 °C. Screw speed was adjusted as 190 rpm. Pressure was 10 bar. After passing through the extruder die, composite was cooled with water in cooling bath and transferred to pelletizer to obtain pellet type composite materials.

Finally, sample plates were obtained by using the hydraulic laboratory press (Labtech). First, the hot press was heated until it reached the operating temperature of 200 °C. The produced composite pellets were placed in the mold cavity (15 cm × 15 cm) between the Teflon sheets used to prevent direct contact of the PP composites with the hot press. The samples were pressed under 40 bar pressure for 20 s in the hot part of the press and for 2 min in the cold part. The codes and the contents of the composite samples, obtained for testing and characterization, are shown in Table 1.

Table 1 The codes and the contents of the composite samples

Sample name	Wood (%)	MAPP (%)	PP (%)	Wood amount	MAPP amount	PP amount
Neat	0%	0%	100%	0	0	500 g
H10M3	10%	3%	87%	50 g	15 g	435 g
H20M3	20%	3%	77%	100 g	15 g	385 g
H30M3	30%	3%	67%	150 g	15 g	335 g
H30M6	30%	6%	64%	150 g	30 g	320 g
P10M3	10%	3%	87%	50 g	15 g	435 g
P20M3	20%	3%	77%	100 g	15 g	385 g
P30M3	30%	3%	67%	150 g	15 g	335 g
P30M6	30%	6%	64%	150 g	30 g	320 g
M10M3	10%	3%	87%	50 g	15 g	435 g
M20M3	20%	3%	77%	100 g	15 g	385 g
M30M3	30%	3%	67%	150 g	15 g	335 g
M30M6	30%	6%	64%	150 g	30 g	320 g

H Hornbeam, *P* Pine, *M* MDF, P10M3 means %10 Pine %3 MAPP

Regarding the characterization, Fourier transform infrared radiation (FTIR) was used to obtain an infrared spectrum of absorption of the produced samples by Thermo Scientific/ Nicolet I S5 device in between 5000 and 400 cm^{-1}. To investigate of elemental and morphology of specimens, scanning electron microscope (SEM) and energy dispersive X-ray spectroscopy (EDX) analysis were performed by Carl Zeiss/Gemini Sigma 300 Vp machine by secondary electron detectors at 30 kV. X-ray diffraction (XRD) analysis was performed to determine their phase content and to understand that how the crystallographic orientations of the grains changes by Bruker D2 Phaser X-ray diffractometer. Before this analysis all samples were coated with gold for electron conductivity by Quorum/Q 150R ES machine. Tensile testing samples were obtained by using a mold which cut the plate with blades with respect to standard of ASTM D638. Tensile test machine SHIMADZU AGS-X 5 kN was used for woodreinforced composites at room temperature with a crosshead speed of 50 mm/min. The flexural strength and flexural modulus of samples were tested with respect to DIN EN ISO 178 in SHIMADZU AGS-X 5 kN machine, which includes a three-point bending test at a crosshead speed of 1 mm/min.

Results and discussion

XRD patterns of hornbeam, pine and MDF composites are demonstrated in Fig. 1. It is seen that peaks occurred at 15°, 17°, 19°, 21°, 25°, 29°, and 42°. PP and composites show semi-crystalline forms. Intensity of H30M3, P30M3, and M30M3 higher than H30M6, P30M6, and M30M6 at 19°. It means that when the amount of MAPP increased from 3 to 6%, these peaks are decreased. Danyadi et al. (2007) reported that wood was shown to modify the crystalline structure of PP and to induce transcrystallization. Same affects can be seen in our study.

The FTIR technique was used to study the main functional groups present in wood fibers composites with coupling agents. The results are depicted in Fig. 2. Sosiati and Harsojo (2014) stated that the bands assigned in O–H stretch at 3300 cm^{-1}, regarding lignin and cellulose intramolecular OH stretching vibration (Garside and Wyeth 2003; Zain et al. 2014; Blackwell et al. 1970). Woods are organic materials, for this reason in the three different wood types of composites at nearly 2900 cm^{-1} C-H asymmetrically stretching vibration of CH and CH2 groups in cellulose and hemicellulose are shown in spectra. Those C-H asymmetric stretches at 2900 cm^{-1} are related with C-H asymmetrically stretching vibration in cellulose and hemicellulose (Blackwell et al. 1970; Bicu and Mustata 2011). The C–H symmetric stretch at 2850 cm^{-1} corresponds to cellulose CH stretching vibration (Keshk et al. 2015; Murigi et al. 2014; Rosli et al. 2013). The C=O stretch of a carboxylic acid and ester at 1700 cm^{-1} accounts for stretching vibration of C=O hemicellulose or carboxylic acid (Garside and Wyeth 2003; Zain et al. 2014; Blackwell et al. 1970; Bicu and Mustata 2011). The C=O stretch of an acid salt at 1600 cm^{-1} is regarding adsorbed water and oxygen-containing group [21–23]. Cellulose and hemicellulose C–H bending vibration is observed in 1372 cm^{-1} (Keshk et al. 2015; Murigi et al. 2014; Rosli et al. 2013). CH in plane deformation of CH2 groups is acquired in 1315 cm^{-1} (Murigi et al. 2014). Cellulose and hemicellulose C–O–C bending vibration is seen in 1163 cm^{-1} (Zain et al. 2014; Blackwell et al. 1970; Bicu and Mustata 2011). And C–O, C–H stretching vibrations of

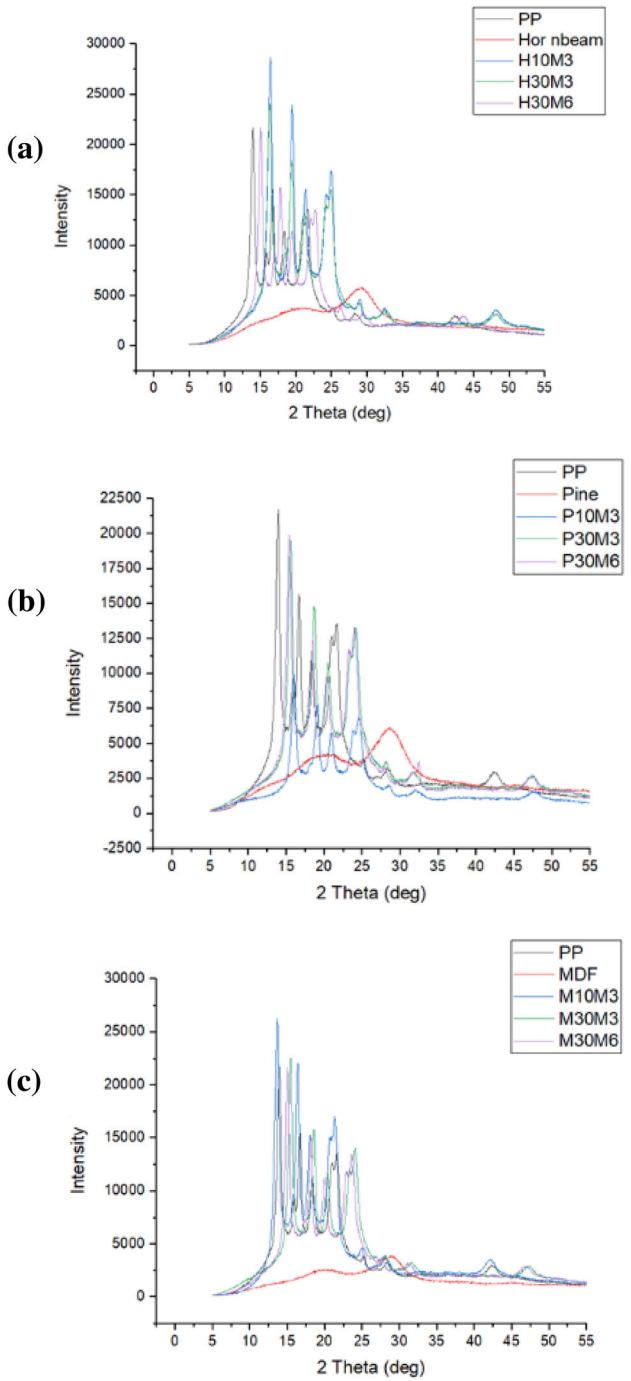

Fig. 1 XRD patterns of **a** Hornbeam and polypropylene composites, **b** Pine and polypropylene composites, and **c** Medium density fiberboard and polypropylene composites

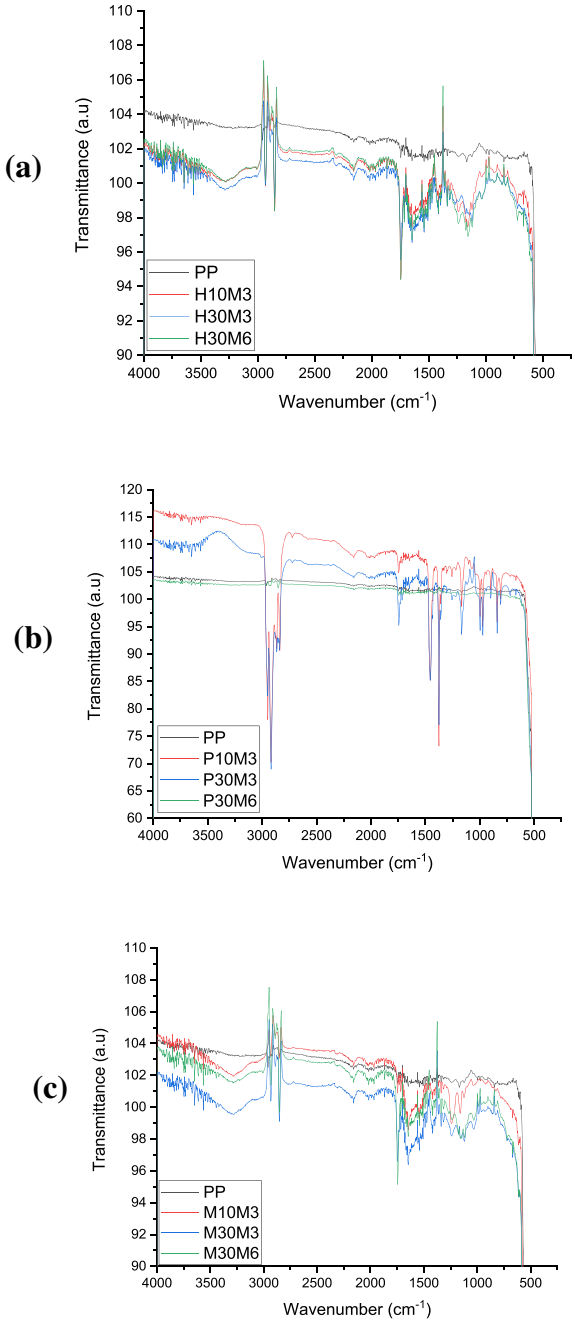

Fig. 2 The FTIR spectroscopic analysis of **a** Hornbeam and polypropylene composites, **b** Pine and polypropylene composites, and **c** Medium density fiberboard and polypropylene composites

cellulose are observed in 1060 cm^{-1} and 1163 cm^{-1} (Blackwell et al. 1970; Bicu and Mustata 2011).

SEM images of the hornbeam / PP composites can be seen in Fig. 3. The authors observed that good dispersion was obtained in hornbeam in the polypropylene matrix. The degree of agglomeration decreased as the hornbeam and PP matrix is compatibilized. H30M3 and H30M6 have some air gaps, they cause the mechanical properties to be affected such as fractures in cavities. H30M6 seems more compatible than H30M3, because of the effect of coupling agent (MAPP). In fact, higher amount of MAPP caused better interfacial adhesion bounding. In Fig. 4, SEM images of pine / PP composites show good dispersion of pine in the polypropylene matrix (P30M3). P10M3 and P30M6 have some small cavities. P30M6 is more compatible then P30M3 because of same effect of coupling agent (MAPP).

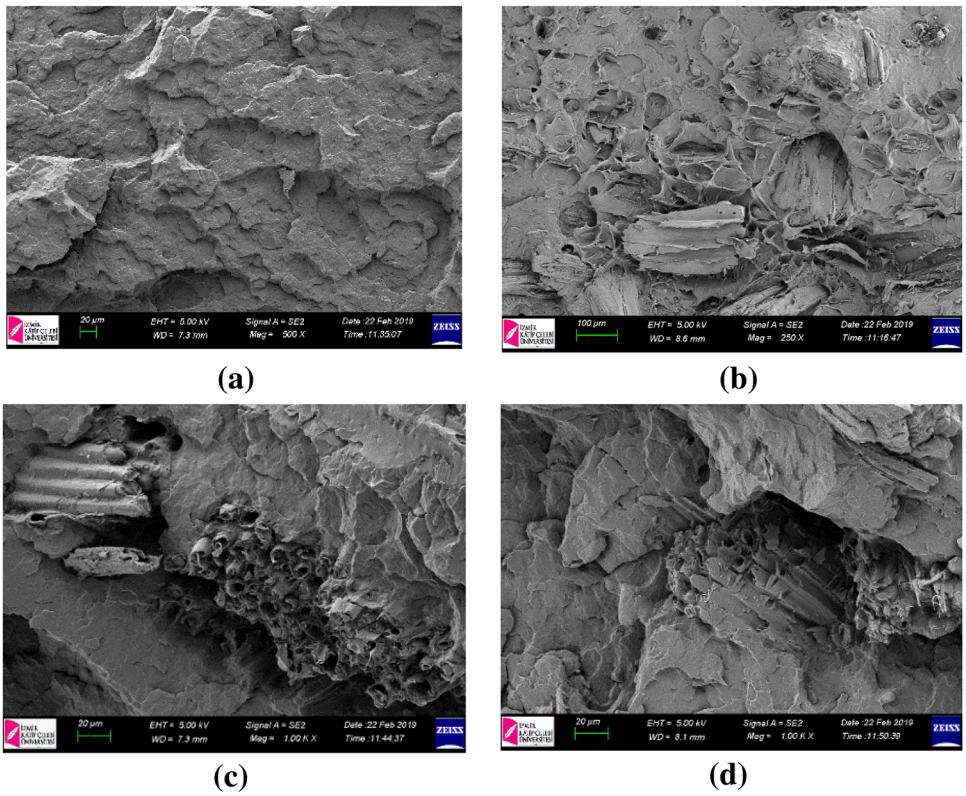

Fig. 3 SEM images of hornbeam and polypropylene composites samples **a** Neat PP **b** H10M3 **c** H30M6 **d** H30M6

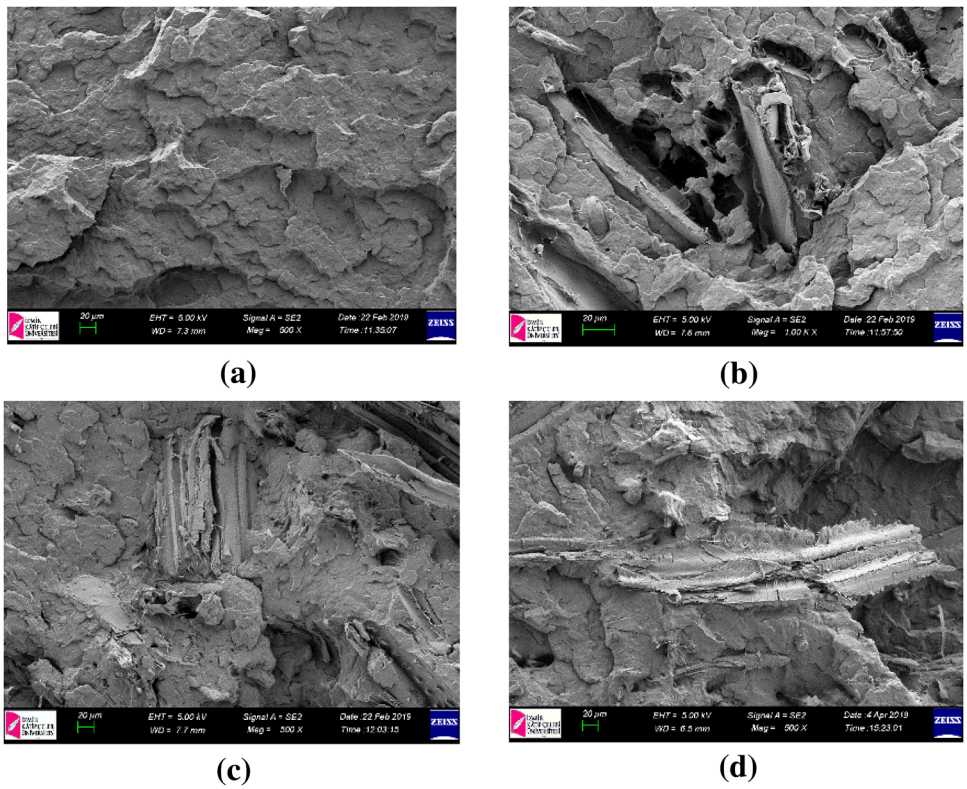

Fig. 4 SEM images of pine and polypropylene composites samples **a** Neat PP **b** P10M3 **c** P30M3 **d** P30M6

SEM images of medium density fiberboard consist of mix wood fibers are shown in Fig. 5. It is demonstrated that M10M3 and M30M3 polymer matrix and wood flour made strong adhesion bounding. In M30M6, some cavities exist.

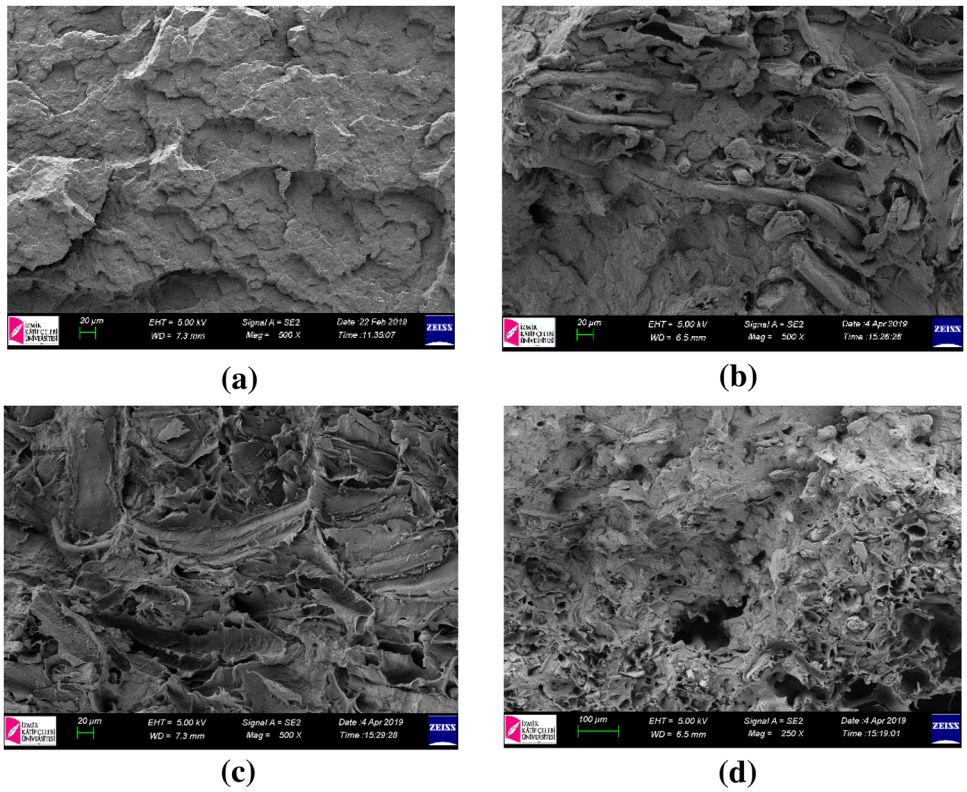

Fig. 5 SEM images of MDF and polypropylene composites samples **a** Neat PP **b** M10M3 **c** M30M3 **d** M30M6

The reason for these voids mentioned in the structure may be that the polymer is not subjected to drying before extrusion. Because the composite passed through the extruder die was cooled with water in the cooling bath, and pressed without any drying. Although drying is achieved close to the surface due to the hot press, it is possible for steam pockets to form on the inside of the material. It is also possible that the polymer composite can absorb moisture from the air during pressing. Drying before pressing and increasing the working pressure of the extruder are seen as solution options.

Tensile test results of all composites can be seen in Table 2 and Fig. 6. In Fig. 6a, it is observed that in hornbeam / PP composites, tensile strengths are varied in between 36.74 MPa and 39.65 MPa. Maximum tensile strength was observed in H30M6, because MAPP addition improved interfacial adhesion. According to Fig. 6b, Elastic modulus increased with respect to wood amount. Besides, when MAPP amount increased, stiffness of material increased. Accordingly, strain values were decreased because of the weak bounding between matrix and additive. It is observed that in pine/PP composites, tensile strengths and strain are getting reduced with respect to loading amount of pine flours. Also, they are lower than neat PP. On the other hand, elastic modulus increased when pine flour amount increased. It is observed that in medium density fiberboard (MDF), tensile strengths and elastic modulus increased with respect to amount of MDF. As a result, when amount of MAPP is increased from 3 to 6%, elastic modulus and tensile strength of three different wood types composite also increased. MAPP provided stronger bounding between polymer matrix and additives. This result was supported with various studies (Kaymakci and Ayrilmis 2014; Kaymakci et al. 2017; Krause et al. 2018).

Table 2 Tensile test result of wood-polymer composites

	Max stress (MPa)	Strain (%)	Elastic modulus (MPa)
PP	38.16	3.28	1360.71
H10M3	36.74	1.67	1554.08
H20M3	38.69	1.71	1672.13
H30M3	36.86	1.29	1715.62
H30M6	39.65	1.30	1813.20
P10M3	32.63	1.44	1395.95
P20M3	31.65	1.15	1594.09
P30M3	29.65	0.78	1762.92
P30M6	33.22	0.89	1862.47
M10M3	34.13	1.46	1446.77
M20M3	39.89	1.62	1752.11
M30M3	40.81	1.59	1938.71
M30M6	42.41	1.52	2050.04
*Std Dev**	*3.92*	*0.60*	*209.78*

**Standart Deviation*

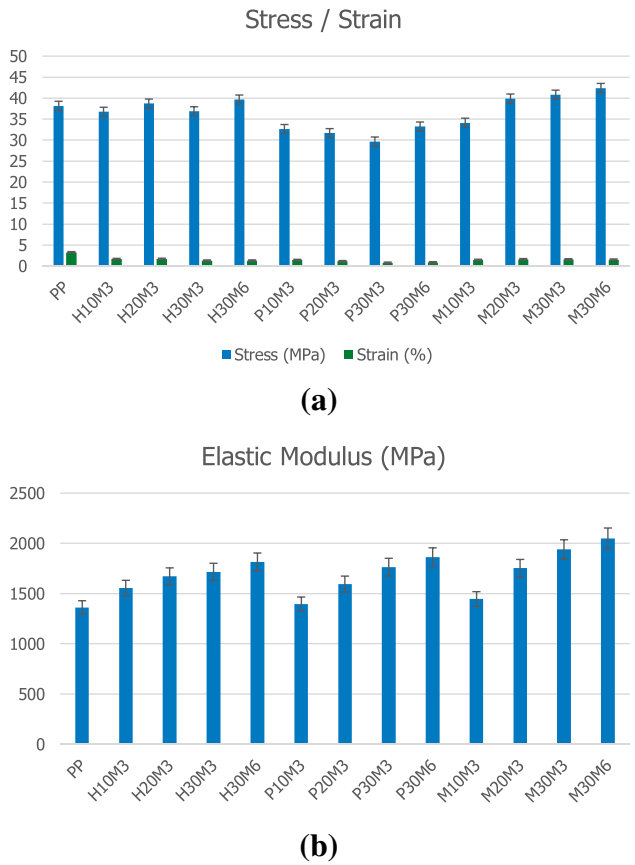

Fig. 6 **a** Tensile stress/strain, and **b** Elastic modulus of Wood-polymer composites

The observed increase in the tensile strength and stiffness is attributed to the improved interfacial bonding between the wood flour and the polymeric matrix as well as the modification of individual components (Lu et al. 2005; Balsuriya et al. 2002). Such improvements are due to the formation of ester bonds between the anhydride carbonyl groups of MAPP and hydroxyl groups of the wood fibers (Felix and Gatenholm 1991). This hypothesis is confirmed by previous studies (Kazayawoko et al. 1997; Matuana et al. 2001) that show anhydride moieties of functionalized polyolefin coupling agents entered into an esterification reaction with the surface hydroxyl groups of wood flour. Upon esterification, the exposed polyolefin chains diffuse into the polymer matrix phase and entangle with polymer chains during hot pressing. These changes create chemical bonds at the interface between the wood flour and the polymer matrix and thereby improve the compatibility between the wood flour and PP matrix. This, in turn, enhances the mechanical properties of the composites (Li et al. 2000).

The elastic modulus of all the PP-wood flour composites under tensile loading is presented in Fig. 6b. The composite material becomes stiffer with the addition of wood flour, however, the corresponding strain at failure decreases. As the wood flour loading increases so do the tensile modulus, but in opposing trend, the ductility of the material falls. In similar manner, addition of MAPP leads to improvement in elastic modulus (Dányádi et al. 2007; Sosiati and Harsojo 2014).

Flexural strength and elastic modulus values of composite samples are shown in Table 3 and Fig. 7. It is observed that flexural strength values of hornbeam/PP composites are higher than neat PP. Comparing H30M3 and H30M6, it is seen that stress and strain values increased by increasing MAPP amount. It is because of improved interfacial adhesion of PP and wood flour. As the amount of hornbeam increased, stress values decreased because of the weak bounding between matrix and the wood. Another reason can be some gaps existing in the composite. MAPP improved stiffness. In pine/PP composite samples, flexural strength and strain decreased when amount of pine wood flour increased. Flexural strength, strain and flexural modulus values increased by increasing MAPP amount. In medium density fiberboard / PP composite samples, tensile strength and elastic modulus increased with respect to increasing amount of MDF. The apparent deteriorations in flexural strength and elastic modulus of M30M6 comparing to M30M3 may be due to air gaps and weak bonding that occur in the production process.

The addition of wood flour in the composites increased the brittleness together with stiffness. The stress concentration at the fiber ends and poor interface bonding between wood and polymer matrix have been recognized as the leading causes for the embrittlement. Nevertheless, it is observed that coupling agent (MAPP) improved interfacial

Table 3 Flexural test result of wood-polymer composites

	Max stress (Mpa)	Strain (%)	Flexural modulus (Mpa)
PP	52.23	8.20	1308.24
H10M3	59.26	7.10	1749.81
H20M3	57.33	5.76	1700.20
H30M3	55.55	4.63	1862.10
H30M6	58.81	5.35	2012.92
P10M3	53.34	7.97	1573.25
P20M3	52.61	5.97	1834.93
P30M3	50.85	4.30	1941.41
P30M6	54.14	4.37	1932.66
M10M3	58.42	7.34	1656.09
M20M3	58.76	6.31	1878.80
M30M3	63.18	5.55	2103.03
M30M6	62.05	5.65	1982.23
*Std Dev**	*3.87*	*1.29*	*212.97*

**Standard Deviation*

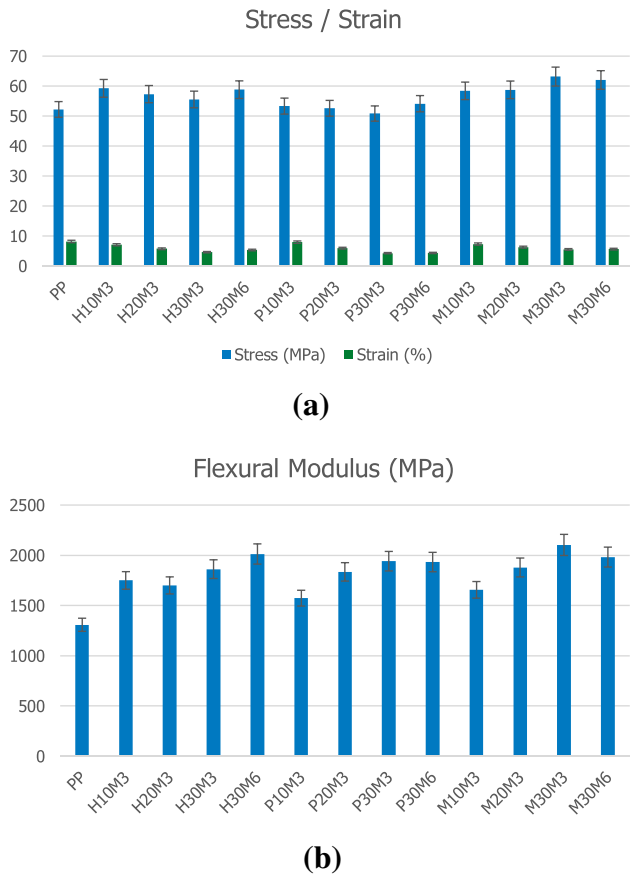

Fig. 7 **a** Flexural stress/strain, and **b** Elastic modulus of Wood-polymer composites

bonding between the filler and the matrix and improved the flexural strength. When SEM images are evaluated, it is confirmed that fractures occurred at the filler locations, and these fracture locations were more brittle than other parts of the matrix. This is probably due to the higher degree of brittleness introduced by the incorporation of wood fibers into the PP matrix. It was found that effect of wood was notable in material properties of the composites (Walker 2004; Mothilal et al. 2020; Gulitah and Liew 2019; Delviawan et al. 2019). Wood is a lignocellulosic material made up of three major constituents (cellulose: 42–44%, hemicelluloses: 27–28%, and lignin: 24–28%) with some minor constituents (extractives: 3–4%) (Walker 2004). The major portion of wood is crystalline cellulose. The aligned fibril structure of cellulose along with strong hydrogen bond has high stiffness thus addition of the wood flour can increase the stiffness of the thermoplastic based composites. Lignin as an amorphous polymer does not greatly contribute to the mechanical properties of wood flour but plays an important role in binding the cellulose fibrils that allow efficient stress transfer to the cellulose molecules. Hence, wood filler increases the stiffness of PP without excessively increasing the density. Furthermore, these composites have potential to take up water under humid conditions due to the presence of numerous hydroxyl groups available for interaction with water molecules via hydrogen bonding. The addition of a coupling agent improved the compatibility between the wood filler and PP through esterification (Adhikary et al. 2008).

Conclusion

The use of waste materials made of lignocellulosic materials such as wood fiber and wood flour in the wood manufacturing sector, where tons of waste is generated every year, in the construction industry is of great importance in terms of both reducing raw material consumption and protecting nature. In this study, while polypropylene was used as the matrix, recyclable and biodegradable wood-plastic composite materials, especially suitable for structural design, using hornbeam, pine and MDF wastes as reinforcement were produced. When the wood-plastic composites successfully produced by the co-rotating twin-screw extrusion technique were compared according to the tensile test results, it was observed that the tensile strength and elastic modulus increased strongly as the amount of hornbeam, pine and MDF increased. In order to improve the interfacial interaction between the matrix and the wood phase, the adhesion bond increased with the increase in the amount of MAPP used as the binding agent. Maximum tensile value and elastic modulus values were obtained with the sample containing 30% MDF and 6% MAPP in the tensile test, and with the sample containing 30% MDF and 3% MAPP in the bending test. When the interface morphology was examined in the SEM analysis, hornbeam and pine flours showed a moderately homogeneous distribution. In MDF composite, the distribution is more homogeneous, which explains its additional high tensile and flexural strength values. The air pockets seen in some samples are thought to be due to the manufacturing process. As after the pellets were cooled by water, they have not been dried prior to compression molding. This can be eliminated by drying and increasing the working pressure of the extruder.

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Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

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