CELLULOSE CHEMISTRY AND TECHNOLOGY

MECHANICAL, WEATHERING, THERMAL, AND FIRE PERFORMANCE OF TREE BARK REINFORCED WOOD PLASTIC COMPOSITES

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This study investigated some technological properties of wood plastic composites (WPCs) containing tree bark. Tree bark led to a decrease in the mechanical properties of WPCs. The flexural strength (FS) and modulus of elasticity (MOE) decreased with an increasing tree bark content by 23% and 39%, respectively, while the decrease of tensile strength was of 35%. On the other hand, outdoor weathering testing revealed that increasing tree bark content slowed UV degradation and reduced surface color fading. This effect is attributed to the inhibition of photodegradation reactions due to the higher antioxidant activity of the bark. TGA and DSC analyses have revealed the potential of tree bark to significantly influence material properties. The TG analysis indicated that tree bark enhances the degradation onset temperature, while the high lignin content in tree bark, compared to wood, increases the maximum degradation temperature. Moreover, the DSC analysis showed that the melting enthalpy (ΔHm) increases with adding tree bark. The high extractive content in tree bark not only enhances thermal movement, but also promotes crystallization. However, an increase in tree bark content led to a limited improvement in fire performance by LOI values, possibly because of the higher extractive content.

Keywords: tree bark, TGA analysis, DSC analysis, LOI test, natural weathering, wood plastic composites

INTRODUCTION

Wood plastic composites (WPCs) are wood-based composites produced from virgin or recycled plastic and waste wood or other lignocellulosic materials. The biological durability, high strength, acoustic performance, low maintenance requirements, resistance to cracking at high temperatures, and eco-friendly nature of WPCs have increased their popularity in recent years.[1] Therefore, WPCs are widely used in various applications, from construction to furniture. WPCs are used primarily outdoors, and are exposed to UV light, humidity, exhaust gases, snow, rain, and pollution, reducing WPCs' service life.[2,3]

One of the significant disadvantages of WPCs is that their color fades outdoors. The chromophoric groups in wood and polymer are mainly responsible for UV absorption. During UV exposure, the reactive oxygen groups occur due to UV absorption of chromophoric groups, interacting with it releasing hydrogen peroxide, which decomposes quickly into new chromophoric groups, resulting in color fade.[4] Many studies aimed to stabilize surface color with coatings, pigments, dyes, and photostabilizers.[5-9] However, in all of these studies, the color fade was inevitable. Therefore, the deterioration starting with the aesthetic appearance reduces the service life of WPCs.

Wood harvesting is about 4 billion m^3 worldwide.[10] The tree bark content is nearly 15% of wood, roughly 600 million m^3 worldwide.[11] Tree bark is a significant raw material, mostly left to rot after harvesting in the forest or burned to obtain energy.[12] The anatomical and chemical differences between bark and wood distinguish them significantly from each other.

The fibrous structure of bark is not similar to that of wood, which has a higher ratio. Li *et al.* compared the fiber lengths of bark and wood from various trees, finding that the fiber length in the secondary xylem is greater than that in the secondary phloem.[13] Moreover, Safdari *et al.* also highlighted that the difference between the chemical structure of wood and bark is significant, which also impacts mechanical properties and limits its usage.[14] However, the cost-effectiveness, renewability, natural resistance, thermal insulation properties, lightweight nature, texture, and aesthetic appeal of tree bark make it attractive.[15]

Wood bark has higher extractive contents, which has drawn much research interest.[16-18] The photostabilization effect of bark extracts has an impact on color stabilization. Antioxidants are free-radical scavengers and can inhibit photooxidation.[19] Vàzquez *et al.* highlighted that the phenolic contents and antioxidant activity correlate.[20] Pietta revealed that the antioxidant activity of phenolics limits the reactive oxygen groups and scavenges free radicals.[21] In another study, Chinese fir bark extract was shown to have a higher free radical scavenging ability related to the phenolic content.[22] On the other hand, moisture intake increases the severity of damage by UV light.[23] However, the hydrophobic nature of oleoresin, gum resin, suberin, and other components makes bark more resistant and limits water intake, which is vital for long service life.[24,25]

The chemical composition of bark is different, as discussed above, and it also influences its thermal behavior and fire performance. Tree bark is rich in extractives, which usually decompose at 160 °C.[26] Therefore, degradation starts at lower temperatures than in wood.[27] However, the degradation rate of bark is lower than that of wood due to its higher lignin content.[26] Lignin, having a higher thermal degradation temperature, also contributes to char formation.[28] Moreover, another study also stated that it contributes to char formation, due to the bark samples' higher ash content with Ca^{2+}, K^{+}, and Si.[29] When wood is heated, pyrolysis causes char formation on the surface of wood, providing a thermal barrier, hindering oxygen penetration and heat transfer.[30,31] The charring acts as an insulator and slows down thermal degradation during combustion.

With these considerations, this study aimed to produce novel WPCs by using different ratios of tree bark flour (TBF) to replace wood flour. The effect of TBF on WPCs' mechanical, weathering, and thermal properties was investigated. The flexural strength, modulus of elasticity, and tensile strength of WPCs were determined. WPC samples underwent a six-month natural weathering test, during which the color changes on the surface of WPCs were meticulously monitored. The thermal behavior of WPCs was comprehensively examined using differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA). The fire performance of WPCs was also investigated by the limit oxygen index (LOI) test.

EXPERIMENTAL

Materials

Pine wood flour (*Pinus sylvestris* L.) (Trabzon, Türkiye), as well as cedar (*Cedrus libani* L.) (Antalya, Türkiye), Calabrian pine (*Pinus brutia* L.) (Muğla, Türkiye), and oak (Trabzon, Türkiye) tree bark flour (TBF), with 20-80 mesh dimensions, were used as a lignocellulosic filler. The thermoplastic polymer LDPE was received from a commercial supplier (Ucar Plastic, İzmir, Türkiye). The fine-grain polymer (~200 mesh) produced a homogenous mixture. The melt flow index (MFI) and density of LDPE were 22 g/10 min (190 °C/2.16 kg) and 0.919 g/cm^3, respectively. Maleic anhydride grafted polyethylene (Licocene PE MA 4351 Fine Grain) was used as a coupling agent to improve the bonding between the materials. The MAPE softening point and density were 123 °C and 0.99 g/cm^3, respectively.

Production of WPCs

The wood flour (WF) and tree bark flour (TBF) were oven-dried at 80 ºC to obtain the moisture content below 2%. The WF, TBF, and polymer were mixed in a mechanical mixer (1200 rev/min) and then a rotary drum blender (30 rev/min) for 5 minutes to obtain a homogeneous mixture, according to Table 1. The mixture was laid on an aluminum plate with dimensions of 500x500x4 mm^3. The draft was pressed at 170 ºC with a pressure of 100 bar for 15 min (CemilUsta SSP 125, Istanbul, Türkiye). The boards were removed from the press after cooling. The panels were conditioned according to the ASTM D618-21.

Mechanical properties

The flexural strength (FS) and modulus of elasticity (MOE) were investigated in a three-point bending test, with a universal testing machine (Marestek, Istanbul, Türkiye) according to the ASTM D790. Dimensions of 12.7 x 12.7 x 4 mm^3 of eight samples were prepared for each group. The tension side of the samples was the side exposed to light. The tensile strength (TS) tests were carried out with a universal testing machine (Marestek, Istanbul, Türkiye) according to ASTM D 638-14. Percent elongation was calculated by the change in gage length relative to the original specimen gage length. Eight replicates were tested for each group.

Table 1
Composition of produced WPC sample series

Sample series	LDPE (%)	WF (%)	TBF (%)	MAPE (%)
LDPE	98	-	-	2
WPC	58	40	-	2
C10	58	30	10	2
C20	58	20	20	2
C40	58	-	40	2
O10	58	30	10	2
O20	58	20	20	2
O40	58	-	40	2
P10	58	30	10	2
P20	58	20	20	2
P40	58	-	40	2

Note: C is cedar, O is oak, and P is Calabrian pine

Natural weathering

WPC samples with dimensions of 130 x 70 x 4 mm^3 were placed at a 45° angle facing south in the experimental area for the natural weathering test in the Menteşe district of Muğla province of Türkiye. According to the EN 927-3 standard, samples underwent an aging test for six months. Three replicates were tested for each group.

Color measurement

The color measurement was carried out by an X-Rite SP60 spectrophotometer (Grand Rapids, Michigan, USA), equipped with an integrating sphere, according to the ISO 7724 standard. Standard illuminant D65 was preferred. The color measurements were conducted in an area of 8 mm^2 in the 400-700 nm wavelength range. Six measurements were taken from each sample's surface.

The Commission International de l'Eclairage colour parameters: L* (lightness), a* (red [+] to green [-] along the x-axis) and b* (yellow [+] to blue [-] along the y-axis), were calculated using X-Rite SP60 Software, from which the color difference (ΔE*) was calculated according to Equation (1):

$$\Delta E^* = (\Delta L^2+\Delta a^2\Delta b^2)^{1/2} \qquad (1)$$

TG analysis

The thermal behavior of WPCs was investigated with a Perkin–Elmer STA 6000 thermogravimetric analyzer 4000 (USA). Samples were heated from 30 °C to 1000 °C, at a heating rate of 10 °C/min under nitrogen gas. Two samples were tested for each group.

DSC analysis

The thermal behavior of WPCs was investigated on a Netzsch DSC 200F3 tool (Netzsch Group, Germany). 4-6 mg of samples were embedded in aluminum pans. The tests were performed with a heating rate of 10 °C/min under a nitrogen flow rate of 30 mL/min, starting from 20 °C and ending at 220 °C. Two samples were tested for each group. The crystallization degree (Xc) of polymers was estimated according to the Wunderlich equation:

$$Xc\ (\%) = \frac{\Delta H_m}{\Delta H_0 \times W} \times 100 \qquad (2)$$

where ΔH_m is heat fusion of material, ΔH_0 is 100% crystalline polyethylene (293 J/g), W is plastic ratio.

Fire performance

The LOI test, conducted using a Dynisco LOI analyzer (Franklin, USA), evaluated the fire performance of WPCs by measuring the oxygen concentration required for flammable combustion, by ASTM D2863-19. Five samples, measuring 127 × 12.7 × 5 mm^3, were tested for each group.

Statistical analysis

Statistical analysis was carried out to investigate the data according to the analysis of variance (one-way ANOVA) with the Duncan test ($p < 0.05$).

RESULTS AND DISCUSSION

Mechanical properties

The effect of TBF on the mechanical properties of WPCs was investigated, as seen in Table 2. LDPE is a soft polymer, mostly used in the production of plastic bags, bottles, packaging, insulants, films, *etc*. Therefore, adding WF to the polymer significantly enhanced the mechanical properties, especially flexural properties. The increase in FS was up to 115%, while it was 370% for MOE. On the other hand, there was a nearly 13% loss with the addition of WF to neat-LDPE for TS. Meanwhile, elongation at the break of WPCs decreased because adding WF breaks the LDPE chain, decreasing ductility.[32]

Adding TBF instead of WF resulted in a decrease in mechanical properties. Although the lowest ratio of TBF did not significantly affect mechanical properties, there were notable decreases in flexural and tensile properties with an increasing TBF ratio. The reduction in FS reached 23%, and it was 39% for MOE. However, the results are still higher than those of neat LDPE. As stated above, the degradation of extractives at lower temperatures might result in migrating from the inner parts to the surface of TBF.[33] Therefore, the higher extractive content of bark hinders bonding and results in decreased mechanical properties. The losses in mechanical properties also vary depending on the tree type, thus the difference in chemical composition has an influence. Therefore, the mechanical losses result from the weak adhesion between the components.

Table 2
Mechanical properties of WPCs (MPa)

Sample series	Flexural properties		Tensile properties	
	Strength (MPa)	Modulus (MPa)	Strength (MPa)	Elongation at break (%)
LDPE	9.46^{f} (0.53)	312^{g} (25)	9.27^{a} (0.16)	10.01^{e} (0.48)
WPC	20.31^{a} (1.67)	1465^{a} (72)	8.10^{bcd} (1.07)	1.04^{b} (0.17)
C10	20.52^{a} (0.79)	1346^{abc} (50)	9.57^{a} (0.47)	1.33^{cd} (0.12)
C20	17.05^{d} (1.65)	1138^{de} (162)	7.38^{de} (0.58)	1.01^{b} (0.07)
C40	15.60^{e} (0.91)	1024^{ef} (93)	5.26^{f} (0.81)	0.67^{a} (0.15)
O10	20.56^{a} (1.57)	1382^{ab} (228)	8.32^{bc} (0.66)	1.18^{bc} (0.22)
O20	18.82^{bc} (1.10)	1215^{cd} (129)	7.86^{cd} (0.35)	1.31^{c} (0.08)
O40	18.53^{c} (0.52)	891^{f} (36)	6.86^{e} (1.02)	1.48^{d} (0.14)
P10	19.85^{ab} (0.97)	1462^{a} (157)	8.84^{ab} (0.71)	1.24^{c} (0.17)
P20	18.29^{c} (1.32)	1390^{ab} (124)	7.64^{cde} (0.69)	1.05^{b} (0.17)
P40	16.54^{d} (0.82)	1263^{bcd} (189)	6.92^{e} (1.07)	1.02^{b} (0.18)

Note: Values in parentheses are standard deviations; letters indicate the differences ($P < 0.05$) between groups depending on the Duncan test

Surface color

The effect of TBF on the surface color change in WPCs was investigated over a six-month natural weathering test, as seen in Figure 1. The color change increased with increasing exposure time. UV light is absorbed by chromophoric groups, which cause surface oxidation. Therefore, the color change was inevitable when exposed to outdoor conditions. The color fade was more remarkable after three months. Meanwhile, the lignocellulosic materials accelerated the surface color changes. Lignin is responsible for over 90% of UV light absorption as a main cell wall component. The chromophoric groups in the chemical structure of lignin absorb UV light, which results in color fade. This phenomenon is seen in Figure 1. ΔE results indicated that there were nearly no color changes on the surface of neat-LDPE, while it was more severe for WPCs. Therefore, the lowest color change was obtained from neat-LDPE, while the highest was C10. However, the increase in the TBF content limited the color fade.

The primary drawback of WPCs in outdoor use is their tendency to develop a whitish appearance. ΔL results showed that the whiteness increased with increasing exposure time. Similarly, there were nearly no changes in the surface whiteness of neat-LDPE. Adding lignocellulosic materials increased the surface whiteness of WPCs. However, the increase in TBF content in the matrix limited the surface whiteness of WPCs. Similar to ΔE, the highest whiteness was on the surface of C10, while the lowest was neat-LDPE. WPCs containing 40% tree bark showed reduced surface color changes. Extractives, such as phenolic components, flavonoids, lignan, tannin, and quinone, can absorb UV lights and bring photodegradation under control.[34,35] As stated above, tree bark is rich in extractives, which can limit surface color changes.

Additionally, antioxidant activity plays a key role in photodegradation. It is well-known that the higher the phenol content, the higher antioxidant activity. In a previous study, the phenol content and antioxidant activity of cedar, Calabrian pine, and oak were 46.62, and 63.61%, 172.34 and 88.61%, and 135.29 and 89.44%, respectively.[36] The tree bark's high phenol content and antioxidant activity provided higher protection against outdoor conditions, especially UV light.

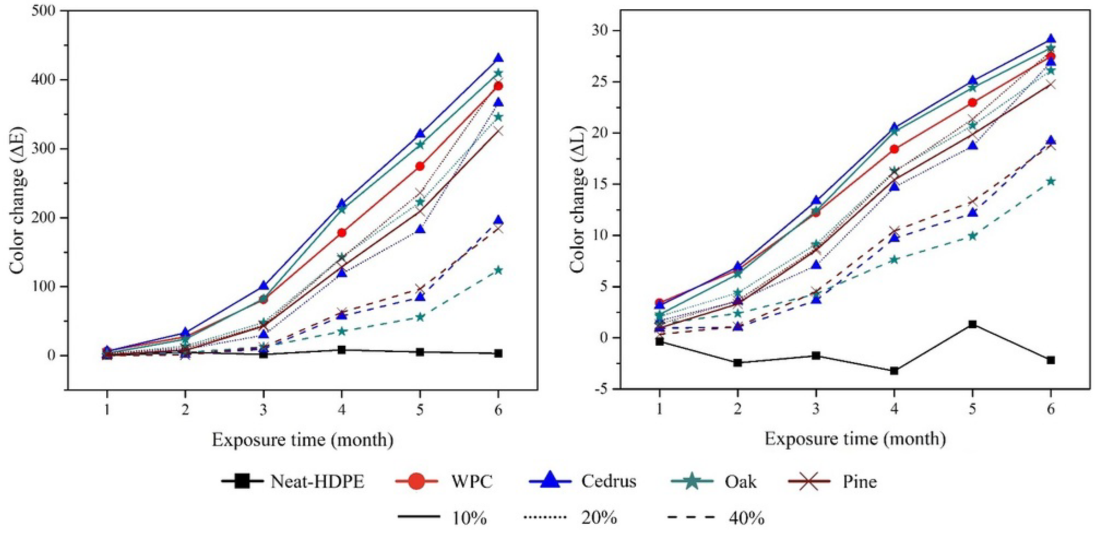

Figure 1: Color changes of WPCs

Thermal properties

TG analysis

The effect of TBF on the thermal behavior of WPCs with gradual temperature increases was investigated by thermogravimetric analysis (TGA), as seen in Table 3. Thermal decomposition took place in three stages, as seen in Figure 2. Mészáros *et al*. stated that significant quantities of CO, CO_2, and H_2O were generated during the thermal decomposition of lignocellulosic material due to its higher hydroxyl content and oxygen atoms.[27] Therefore, humidity release occurs in the first stage due to the hydrophilic nature of lignocellulosic materials, initiating nearly at 50 ºC and proceeding up to 200 ºC, causing mass loss of ~3%. Gao *et al.* also stated that the small portion of extractives as well as water caused limited weight loss.[37] On the other hand, there was only one stage in thermal degradation for LDPE, starting at 341.58 ºC and ending at 505 ºC.

In the second stage, the cell wall components of wood and bark initiate degradation above 150 °C, when hemicelluloses first degrade, followed by cellulose and lignin. Meanwhile, lignin is known to have a broad degradation temperature range, spanning from 200 to 600 °C.[27] Moreover, Renner *et al*. stated that hemicelluloses degrade between 158.7-212 °C, cellulose – between 333.7-419 °C, and lignin at 714.3-799 °C under inert atmosphere.[38] The degradation of WF reinforced WPC sample started at 176.88 °C, while it was above 180 °C for the WPCs containing bark. The hemicellulose content of bark is lower than that of wood, which could be the reason for the higher thermal degradation temperature onset (T_{onset}). Moreover, the TBF improved the maximum degradation temperature (T_{deg}) compared to WF, except in samples O10 and C40. The higher lignin content of bark enhances char formation, which could also improve thermal stability.

The third stage involves the decomposition of the polymer. Under an inert atmosphere, pyrolytic degradation triggers cleavage reactions, causing rapid weight loss for LDPE. Although polymer degradation occurs at higher temperatures, it is more severe than WPCs. Therefore, no residue remained for LDPE above 550 °C, as it transformed into volatile compounds during thermal degradation.[39] However, TBF significantly improved the T_{deg} of WPCs, except for O10 and O40. The degradation severity was more moderate than in the case of the polymer, as seen in DTG thermograms. The char formation provides a shielding effect for oxygen for lignocellulosic materials, making it difficult to penetrate the inner part. The TBF also caused an increase in the residue by up to 15%, playing an essential role in fire performance due to their char forming ability, as discussed below. Moreover, the higher char formation of TBF, attributed to its higher lignin content, enhanced the T_{deg} and reduced degradation severity by increasing thermal stability.

DSC analysis

The effect of TBF on WPCs' behavior with heat flow was investigated by differential scanning calorimetry (DSC), as seen in Figure 3. WF decreased the WPCs’ melting temperature onset (T_{onset}) (Table 4). The WF might lead to chain breaking, which restricts heat flow, resulting in lower T_{onset} values.[40] Using TBF instead of WF resulted in a slight increase in T_{onset}; however, the influence of TBF content on T_m was minimal. Similarly, WF has a significantly reduced melting enthalpy (ΔHm). However, the effect of TBF content on ΔHm could have been more considerable. Guo *et al.* stated that the decreased polymer content with the addition of WF reduces heat fusion, decreasing ΔHm.[41] However, as noted above, the increase in ΔHm might be attributed to the high lignin content of barks, which has high thermal stability. Moreover, the extractives may have also increased thermal movement.

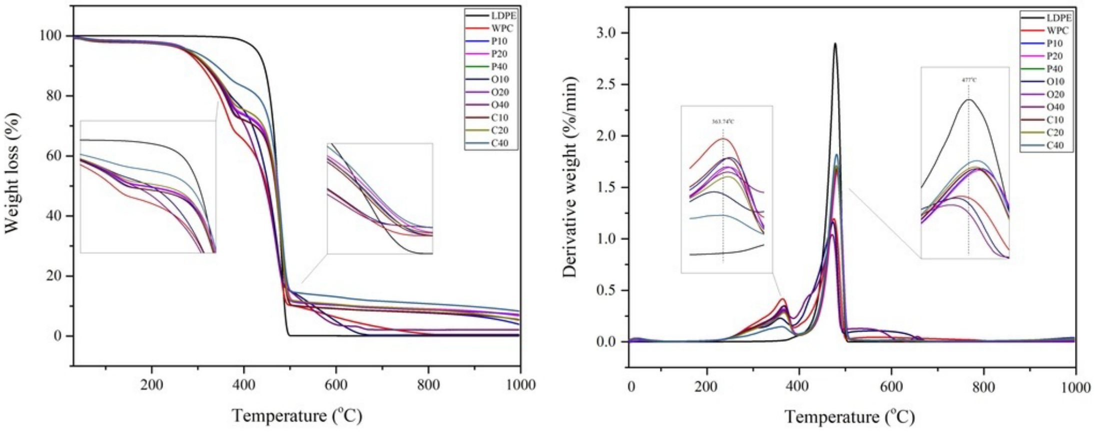

Figure 2: TGA and DTG thermograms of WPCs

Table 3
TGA values of WPCs

Sample series	Stage	T_{onset}	T_{endset}	$T_{deg.}$	Weight loss (%)	Weight at T_{onset}	Weight at T_{endset}
LDPE		341.58	505	477	99.54	99.66	0.12
Control	2nd stage	176.88	389.46	363.74	30.91	97.65	66.74
	3nd stage	389.46	502.73	474.82	56.56	66.74	10.18
P10	2nd stage	180.98	396.30	367.57	25.57	97.82	72.25
	3nd stage	399.86	510.94	482.21	61.92	72.02	10.10
P20	2nd stage	182.90	395.75	367.30	23.65	97.89	74.24
	3nd stage	400.41	514.77	482.21	62.26	73.90	11.64
P40	2nd stage	183.99	383.72	358.27	22.47	97.85	75.38
	3nd stage	383.72	496.71	472.64	62.44	77.89	15.45
O10	2nd stage	183.72	384.26	358.27	20.05	97.85	77.80
	3nd stage	384.26	496.99	472.64	62.37	77.80	15.43
O20	2nd stage	182.35	395.21	366.21	24.31	98.19	73.88
	3nd stage	399.04	521.61	480.84	62.52	73.60	11.08
O40	2nd stage	182.07	386.45	366.48	23.92	97.95	74.03
	3nd stage	388.04	493.43	470.99	57.87	73.67	15.80
C10	2nd stage	180.16	393.57	365.93	25.51	97.79	72.28
	3nd stage	400.13	512.85	480.57	61.76	71.87	10.11
C20	2nd stage	182.35	393.84	366.75	22.1	97.89	75.79
	3nd stage	396.85	515.86	480.30	63.96	75.59	11.63
C40	2nd stage	184.54	391.65	362.10	14.16	97.78	83.62
	3nd stage	396.03	514.50	480.57	68.82	83.29	14.47

There was no significant difference in crystallization temperature onset (T_{onset}). However, WF slightly led to an increase in crystallization temperature peak (T_c). The nucleating effect of wood causes an increase in T_c values due to the occurring physical barrier.[42] The crystallization enthalpy (ΔHc) values also notably decreased with WF. On the other hand, TBF improved the ΔHc. However, they were still below the LDPE. The polymer reinforcement with lignocellulosic material limits the thermal movement in the structure, while there was an increase in TBF.

Moreover, the decreased thermal movement also decelerates the crystallization rate. The nucleating effect of natural fibers also limits and slows the crystallization process.[43] As in Table 4, the crystallization rate of WPCs decreased compared to LDPE. However, TBF increased thermal movement compared to WF, resulting in a higher crystallization rate. The extractives in the tree bark may contribute to a higher crystallization rate. They degrade at lower temperatures, potentially increasing thermal movement. The thermal degradation severity of TBF was also shown in DTG thermograms, in which it was lower than LDPE but higher than WF, which might correlate with extractives degraded at lower temperatures playing a vital role in these results.

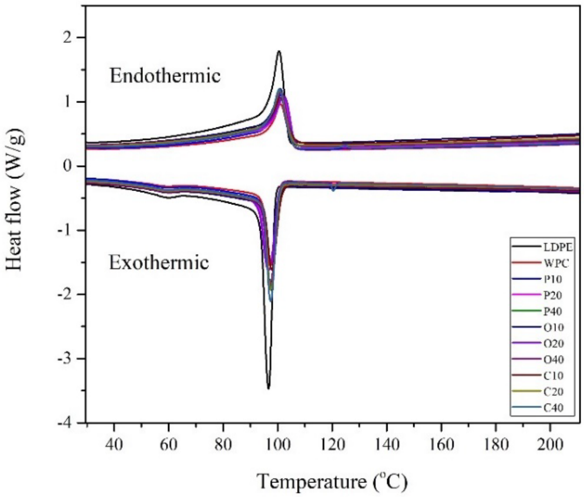

Figure 3. DSC curves of WPCs.

Table 4
DSC values of WPCs

Sample	Melting			Crystallization			
series	Tm	ΔHm	T_{onset}	Tc	ΔHc	T_{onset}	Xc
LDPE	98.58	96.79	97.74	95.08	120.3	90.68	41.06
WPC	98.39	52.97	95.02	97.06	60.91	91.07	34.65
C10	97.86	56.02	98.16	97.93	66.75	91.49	37.97
C20	98.25	67.91	97.86	97.11	73.48	91.46	41.80
C40	98.23	73.3	97.66	96.8	78.37	91.39	44.58
O10	98.41	62.38	98.41	97.2	68.83	91.52	39.15
O20	97.94	70.63	97.87	96.88	75.19	89.78	42.77
O40	98.44	68.78	97.97	97.09	73.19	91.12	41.63
P10	98.44	66.34	98.03	97.05	71.27	91.28	40.54
P20	98.22	66.2	98.08	96.87	71.87	90.02	40.88
P40	98.42	70.78	97.89	96.92	76.43	91.04	43.48

Fire performance

LOI test

The effect of TBF on the fire performance of WPCs was investigated with the LOI test, as seen in Table 5. The LOI values of WPCs vary between 18 and 21.8%. Being petroleum-based, LDPE has a low LOI value and is classified as a combustible material under ISO 4589. However, adding WF to the polymer increased the LOI value to 21%. On the other hand, TBF had no significant effect on LOI values. The increasing TBF is first limited and the LOI values are improved, which then leads to a decrease with increasing content. As discussed above, during the production of WPCs, extractives might migrate to the outer part of fibers, which negatively influenced the combustion. As stated in previous studies, extractives, such as resin, are prone to enhancing the heat values of wood.[44,45] Küçük and Aktepe also stated that lignin, terpene, tannin, and flavonoids significantly affect ignition.[46] Therefore, the decrease in the LOI values results from the chemical structure of tree bark. The decrease is more remarkable for pine tree bark, which has a higher resin content. Moreover, Baysal *et al*. also stated that extractives negatively influenced fire performance.[47]

During the LOI test, flaming dripping was observed for neat LDPE. However, lignocellulosic material reinforcement inhibited dripping, which makes the spreading of combustion difficult, as seen in Figure 4. The char formation plays a crucial role in flaming combustion for lignocellulosic materials. The high ash content of tree bark caused an increase in the residue content, which is higher than that of wood, as seen in Figure 2. Therefore, the higher residue content also contributed to char formation. Moreover, the high lignin content of tree bark led to improved char formation, as seen in Figure 4. Meanwhile, it was also observed that tree bark caused explosive burning, which might have resulted from the high extractive content. The lower LOI results with higher TBF content may also be associated with higher extractive content.

Table 5
LOI values of WPCs

Sample series	LOI (O_2)
LDPE	18
WPC	21
C10	21.5
C20	21
C40	20
O10	21
O20	20.7
O40	20
P10	21
P20	21.8
P40	20.5

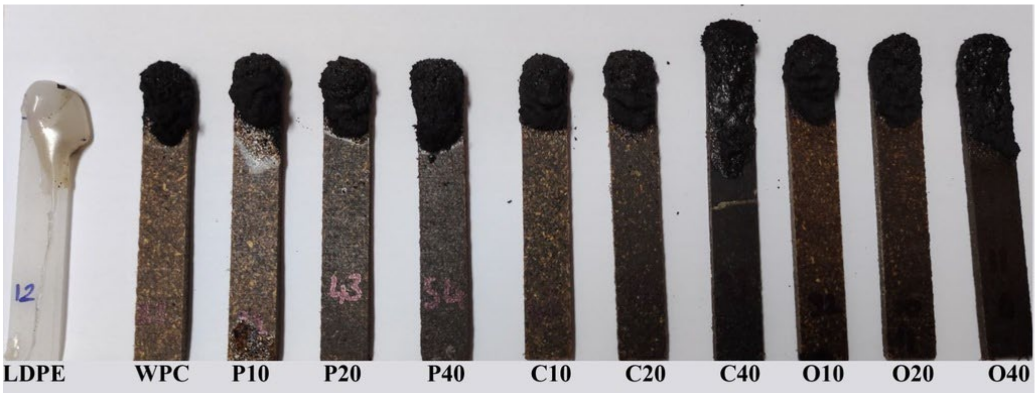

Figure 4: WPC samples after the LOI test

CONCLUSION

This study investigated the effect of adding tree bark flour, with higher phenol content and antioxidant activity, to wood plastic composites (WPCs) on their mechanical, weathering, thermal, and fire performance. A series of experiments were conducted to measure the impact of tree bark extractives on the properties of the composites. As revealed by this study, the higher extractive content of tree barks caused losses in mechanical properties. The migration of extractives from the inner part to the surface during the production, a vital implication of this study, hindered bonding, reducing the mechanical properties. These losses were substantial, reaching up to 23% for flexural strength and 35% for tensile strength. Although MOE values of WPCs were still above that of neat LDPE, there were up to 39% decreases with increasing tree bark flour content.

On the other hand, the higher phenol content of tree bark restricted photodegradation during the outdoor weathering test. The higher antioxidant activity of tree bark restrained the photooxidation reactions by absorbing UV light. The color changes occurred more moderately for oak TBF than WF. TGA analysis showed that the onset degradation temperature of WPCs was enhanced by tree bark addition, although extractives had a lower degradation temperature. This study has shown that higher lignin content of tree bark can significantly improve the degradation temperature.

Additionally, DSC analysis suggests that the high lignin content of tree bark flour and thermal movement due to the high extractive content led to a rise in the melting enthalpy (ΔHm). Furthermore, tree bark's higher residue and lignin content enhance char formation. Nevertheless, the LOI test also showed limited improvements in fire performance. This practical study suggests that tree bark could serve as a valuable resource for WPC production, particularly for outdoor applications, such as decking, siding, gardening furniture, *etc*.

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