

MECHANICAL, PHYSICAL, THERMAL, AND BIOLOGICAL CHARACTERIZATION OF RECYCLED POLYPROPYLENE-BASED WOOD-PLASTIC COMPOSITES REINFORCED WITH HETEROGENEOUS FURNITURE-FACTORY WASTE SAWDUST



İbrahim Kılıç^{1,*}

<https://orcid.org/0000-0003-0567-5923>

ABSTRACT

This study investigates sustainable wood-plastic composites produced from heterogeneous furniture-factory waste sawdust and recycled polypropylene, with maleic anhydride-grafted polypropylene as a compatibilizer. Composites containing 0-40 wt% furniture-factory waste sawdust and 0 or 3 wt% maleic anhydride-grafted polypropylene were melt compounded and injection molded. Mechanical, physical, thermal, morphological, and biological performances were systematically evaluated. Increasing furniture-factory waste sawdust content significantly increased tensile and flexural moduli, while tensile strength, elongation at break, and impact strength decreased in the absence of maleic anhydride-grafted polypropylene due to weak interfacial adhesion. The addition of 3 wt% maleic anhydride-grafted polypropylene markedly enhanced mechanical performance, increasing tensile strength to 22,80 MPa and flexural strength to 43,58 MPa at 40 wt% furniture-factory waste sawdust (improvements of up to 42,9 % and 35,7 % respectively, relative to the uncompatibilized counterparts). Scanning electron microscopy analysis confirmed improved fiber encapsulation and reduced interfacial defects. Water absorption increased with furniture-factory waste sawdust content, while fungal mass losses remained below 2 % for all formulations. Thermal analysis revealed reduced initial degradation temperatures with furniture-factory waste sawdust and a broader decomposition range in the presence of maleic anhydride-grafted polypropylene. These results demonstrate that heterogeneous furniture-factory waste sawdust can be successfully incorporated into recycled polypropylene-based wood-plastic composites and that MAPP compatibilization significantly enhances composite performance. The findings provide valuable insights into the mechanical, physical, thermal, morphological, and biological characteristics of FFWS/rPP composites produced from real industrial waste streams.

Keywords: Compatibilization, interfacial adhesion, maleated polypropylene (MAPP), lignocellulosic composites, fungal decay resistance, industrial residues, recycled polymers

INTRODUCTION

The depletion of natural resources, the accumulation of plastic waste, and the environmental burdens associated with conventional manufacturing have intensified the search for sustainable alternatives in materials science. Within the framework of the circular economy, wood-plastic composites (WPCs)-hybrid materials combining lignocellulosic fillers with thermoplastic polymers-offer a practical pathway to divert industrial residues into durable and cost-effective products (La Mantia and Morreale 2011, Wechsler and Hiziroglu 2007). Owing to their low density, ease of processing, and renewable content, WPCs are now widely utilized in decking, construction components, and furniture applications (Wechsler and Hiziroglu 2007, Çavuş and Mengeloğlu 2020, Başboğa *et al.* 2022).

A wide range of lignocellulosic resources has been successfully incorporated into WPCs, including hardwood and softwood flour, agricultural residues (e.g., rice husk, hemp, tea), and wood-based panel wastes

¹Yozgat Bozok University. Department of Material and Energy. Hemp Research Institute. Yozgat, Türkiye.

*Corresponding author: ibrahimoem25@gmail.com

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(Bledzki and Faruk 2003, Yang *et al.* 2004, Çavdar *et al.* 2011, Özmen *et al.* 2014, Vallejos *et al.* 2023). Among these, the furniture industry is particularly significant, as it generates heterogeneous mixtures of particleboard (PB), medium-density fiberboard (MDF), and solid-wood residues. Valorizing these wastes in WPCs both alleviates disposal challenges and adds material value. Previous studies have shown that incorporating sawdust collected from a furniture factory into virgin polypropylene (PP) matrices can provide acceptable mechanical properties and enable prototype production under practical filler and compatibilizer loadings (Mengeloğlu *et al.* 2015, Kılıç *et al.* 2023). However, while these studies used virgin PP, research systematically examining the performance of WPCs produced by combining similar furniture-factory sawdust with recycled PP (rPP) remains limited.

Polypropylene is one of the most widely used matrices owing to its low density, chemical resistance, and recyclability. The use of recycled polypropylene (rPP) further reduces cost and environmental footprint, while still enabling competitive performance in many applications (Momanyi *et al.* 2019). Indeed, studies have demonstrated that, when appropriately formulated, rPP-based WPCs can retain or even match the mechanical properties of their virgin PP counterparts (Çavuş and Mengeloğlu 2020, Burgada *et al.* 2021, Singh *et al.* 2023). Although several studies have explored rPP-based WPCs with various lignocellulosic fillers and furniture-derived wastes with virgin PP, the combined use of heterogeneous, real-world furniture-factory waste streams (containing particleboard, MDF, solid wood, and PVC edge-banding residues) with post-industrial rPP has not been systematically investigated. Accordingly, integrating post-industrial rPP into WPCs is consistent with both sustainability objectives and industrial feasibility in the context of furniture-sector waste valorization (Çavuş and Mengeloğlu 2020).

A principal challenge in PP-based WPCs is the interfacial incompatibility between hydrophilic lignocellulosic fillers and the hydrophobic PP matrix, which reduces stress transfer and overall mechanical performance. Maleic anhydride-grafted polypropylene (MAPP) is a widely used and effective compatibilizer to overcome this limitation: interactions between anhydride groups and hydroxyl functionalities on the filler surface improve interfacial adhesion and dispersion, thereby enhancing strength and stiffness (Keener *et al.* 2004, Maziero *et al.* 2019). Even at low dosages, MAPP has been shown to yield significant improvements, including in composites derived from furniture-waste fillers (Panthapulakkal and Sain 2007, Arsad *et al.* 2013, Hernández-Díaz *et al.* 2020, Kılıç *et al.* 2023).

In this context, the present study aims to develop and characterize WPCs manufactured from untreated, heterogeneous lignocellulosic residues directly collected from a furniture factory's central dust-extraction system-including particleboard (PB), medium-density fiberboard (MDF), solid wood, and PVC edge-banding wastes-combined with post-industrial recycled polypropylene (rPP) and maleic anhydride-grafted polypropylene (MAPP) as a compatibilizer.

While previous works have utilized either recycled PP with other fillers or furniture wastes with virgin PP, the specific combination of highly heterogeneous, real industrial furniture-factory sawdust with rPP, along with a broad characterization encompassing mechanical, physical, thermal, morphological, and especially biological (fungal decay resistance) properties, remains largely unexplored. To the best of our knowledge, no prior study has systematically evaluated the effects of such mixed, real-world waste streams in rPP-based WPCs across this comprehensive set of properties. Therefore, this study addresses an important knowledge gap by providing a systematic evaluation of the mechanical, physical, thermal, morphological, and biological performance of FFWS/rPP composites and the influence of MAPP compatibilization on these properties.

MATERIALS AND METHODS

Recycled polypropylene (rPP) granules were used as the thermoplastic matrix, and furniture-factory waste sawdust (FFWS) served as the filler. Maleic anhydride-grafted polypropylene (MAPP) (Licocene® PP MA 7452 granules; Clariant, Berlin, Germany), a highly grafted metallocene polypropylene wax with a maleic anhydride content of 7 wt%, softening point of 155-161 °C, and density of 920-940 kg/m³, was employed as the compatibilizer. The FFWS was collected from the central dust-extraction system of a furniture plant in Kırıkkale, Türkiye, and consisted of a heterogeneous mixture of particleboard (PB), medium-density fiberboard (MDF), and PVC edge-banding residues. The rPP granules were obtained from the same company's plastic recycling facilities.

The furniture factory wood waste (FFWS) used in this study was collected directly from an industrial

furniture manufacturing facility and represents a heterogeneous mixture of lignocellulosic residues, including particleboard, medium-density fiberboard, edge banding materials, and wood shavings. The FFWS was ground into flour using a Wiley mill (Altundal, Kahramanmaraş, Türkiye), and fractions passing a 60-mesh screen ($\leq 0,25$ mm) were selected for composite production. Prior to processing, the FFWS was oven-dried at 103 ± 2 °C for 24 h to reduce its moisture content to below 1 %, thereby minimizing moisture-related processing defects. This heterogeneous composition reflects real industrial waste streams and differs from the single-type wood flour commonly employed in laboratory-scale studies.

Composite preparation

WPCs were fabricated via a two-step process involving extrusion and injection molding. The formulations are presented in Table 1. The required amounts of dried rPP granules, FFWS flour, and MAPP (when included) were first manually premixed in a laboratory-scale dry mixer at room temperature for 5 minutes to obtain a visually homogeneous blend. This premixed material was subsequently fed into a single-screw extruder operating at a screw speed of 50 rpm. The barrel temperature profile was controlled from the feed zone to the die as follows: 180 °C (feed zone), 185 °C, 190 °C, 195 °C, and 200 °C (die zone). The extruded strands were cooled in a water bath maintained at 23 ± 2 °C, pelletized, and subsequently oven-dried at 103 ± 2 °C for 24 h to reduce the moisture content to below 1 %. Pellets were injection-molded into test specimens using a HAIDA HDX-88 machine (Ningbo, China) with barrel temperatures of 170 °C - 190 °C, an injection speed of 85 mm/s, injection pressure of 9 MPa - 10 MPa and cooling time of 40 s (Figure 1).

Table 1: Experimental Design for Composites Manufacturing.

ID	rPP (%)	FFWS (%)	MAPP (%)
G1(R)	100	0	0
G2 (R+M ₃)	97	0	3
G3 (R+F ₁₀)	90	10	0
G4 (R+F ₁₀ +M ₃)	87	10	3
G5 (R+F ₂₀)	80	20	0
G6 (R+F ₂₀ +M ₃)	77	20	3
G7 (R+F ₃₀)	70	30	0
G8 (R+F ₃₀ +M ₃)	67	30	3
G9 (R+F ₄₀)	65	40	0
G10 (R+F ₄₀ +M ₃)	62	40	3

Sample codes are reported as Gx (R+Fxx±M#), where R denotes recycled polypropylene (rPP), Fxx denotes xx wt% furniture-factory waste sawdust (FFWS), and M# denotes # wt% maleic anhydride-grafted polypropylene (MAPP); percentages are given relative to the total composite mass.

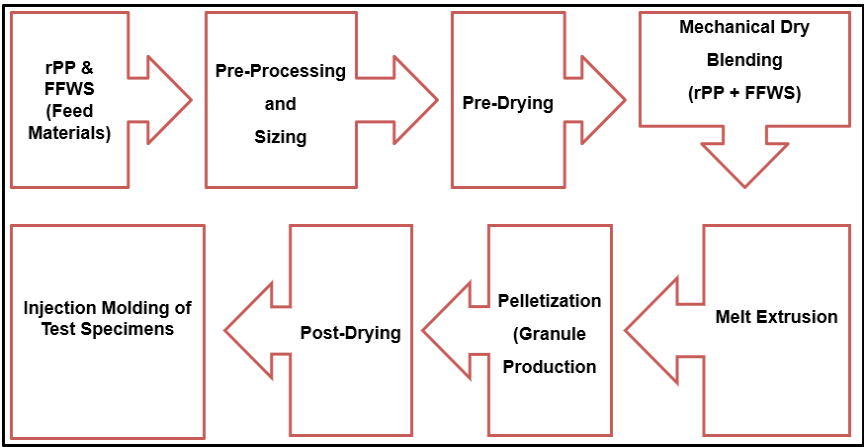


Figure 1: Schematic representation of WPC manufacturing process.

Conditioning and testing

All specimens were conditioned at 23 ± 2 °C and 65 ± 2 % RH before testing. Five replicates were tested for each formulation to evaluate both physical and mechanical properties. Physical properties, including density (determined via the water displacement method according to ASTM D792-20 (2020) and water absorption, were assessed alongside mechanical properties such as tensile strength (TS), tensile modulus (TM), elongation at break (EatB), flexural strength (FS), flexural modulus (FM), and notched impact strength (IS), all measured in accordance with relevant ASTM standards. Density measurements were performed on specimens with dimensions of 20 mm × 20 mm × 4 mm. Water absorption was assessed by immersing specimens (20 mm × 20 mm × 4 mm) in distilled water at 23 ± 2 °C, with mass measurements recorded at 2, 24, 48, 72, 168, 336, 504 and 672 hours. Tensile properties were evaluated using dog-bone specimens (165 mm × 13 mm × 4 mm) per ASTM D638-22 (2022) on a Zwick/Roell universal testing machine (10 kN capacity) at a crosshead speed of 5 mm/min. Flexural properties followed ASTM D790-17 (2017) using specimens (165 mm × 13 mm × 4 mm) in a three-point bending configuration with a support span of 80 mm and a crosshead speed of 2 mm/min on the same Zwick/Roell universal testing machine (10 kN capacity). Notched impact strength was tested using a Zwick HIT5.5P impact tester with a 5,5 J hammer and a Polytest notching cutter (Ray-Ran™) according to ASTM D256-24 (2024). Specimen dimensions for impact testing were 65 mm × 13 mm × 4 mm. All mechanical tests were conducted under ambient laboratory conditions (23 ± 2 °C and 50-70 % RH).

Morphological and thermal analyses

Fracture surfaces were examined using scanning electron microscopy (SEM, Zeiss Gemini 300). Samples were cryo-fractured in liquid nitrogen, sputter-coated with gold, and observed at 250× magnification.

Thermogravimetric analysis (TGA/DTG) was performed with an EXSTAR SII TG/DTA 6300 instrument (LabX, Canada) under nitrogen flow (100 mL/min) from 25 °C to 800 °C at 10 °C/min.

Biological durability

Decay resistance tests were conducted according to JIS K 1571 (2010). WPC specimens (20 mm × 20 mm × 4 mm) were exposed for 12 weeks to *Coniophora puteana* (brown-rot) and *Trametes versicolor* (white-rot) fungi. Oriental beech (*Fagus orientalis* Lipsky) and scots pine (*Pinus sylvestris* L.) served as references. Mass loss was calculated from oven-dried weights before (M_1) and after exposure (M_2).

Statistical analysis

Statistical analyses were performed in Design-Expert version 13 (State-Ease, Inc., Minneapolis, MN, USA). A two-factor factorial ANOVA was used to evaluate the effects of FFWS content (0, 10, 20, 30, and 40 wt%) and MAPP level (0 and 3 wt%), as well as their interaction, on the physical and mechanical response variables, including density, water absorption, tensile strength, tensile modulus, elongation at break, flexural strength, flexural modulus, impact strength, and fungal mass loss.

RESULTS AND DISCUSSION

In this study, recycled polypropylene (rPP) composites filled with furniture-factory waste sawdust (FFWS) and compatibilized with maleic anhydride-grafted polypropylene (MAPP) were characterized with respect to mechanical and physical properties (density, water absorption), morphology (SEM), thermal stability (TGA), and biological durability against brown-rot and white-rot fungi.

The mechanical properties and density of the composite groups are reported in Table 2 (mean ± standard deviation, $n = 5$). To better illustrate the interaction effects of FFWS content and MAPP addition, these data are also presented as interaction plots in Figure 2, Figure 3, Figure 4, Figure 5. These graphical representations facilitate the visual assessment of the significant main effects and interactions revealed by the two-factor ANOVA.

Table 2: Mechanical properties and density of the composite groups.

ID	TS (MPa)	TM (MPa)	EatB (%)	FS (MPa)	FM (MPa)	IS (kJ/m ²)	Density (kg/m ³)
G1(R)	18,57* (0,29)**	496,65 (14,28)	6,58 (0,60)	27,82 (0,64)	863,89 (30,50)	5,96 (0,37)	953 (15)
G2 (R+M ₃)	18,05 (0,55)	519,98 (11,29)	5,20 (0,29)	28,42 (0,43)	884,14 (23,49)	5,32 (0,18)	960 (2)
G3 (R+F ₁₀)	17,20 (0,27)	609,99 (11,49)	5,56 (0,16)	31,16 (0,45)	1195,89 (52,95)	5,43 (0,27)	976 (7)
G4 (R+F ₁₀ +M ₃)	18,46 (0,14)	652,99 (23,97)	4,50 (0,33)	33,00 (0,61)	1223,91 (20,03)	4,85 (0,51)	973 (10)
G5 (R+F ₂₀)	16,88 (0,14)	742,62 (20,06)	4,21 (0,13)	31,67 (0,84)	1465,58 (80,54)	4,65 (0,20)	993 (9)
G6 (R+F ₂₀ +M ₃)	20,03 (0,27)	813,73 (16,20)	3,85 (0,26)	37,40 (0,35)	1634,64 (49,84)	4,58 (0,12)	989 (6)
G7 (R+F ₃₀)	16,47 (0,17)	770,34 (34,84)	3,22 (0,10)	32,79 (0,44)	1864,13 (57,50)	4,35 (0,19)	1010 (10)
G8 (R+F ₃₀ +M ₃)	21,55 (0,17)	968,11 (27,72)	3,55 (0,13)	40,26 (0,76)	2030,40 (49,63)	4,28 (0,10)	1014 (4)
G9 (R+F ₄₀)	15,96 (0,14)	762,50 (52,07)	2,67 (0,23)	32,19 (0,43)	2061,05 (28,50)	3,83 (0,11)	1047 (6)
G10 (R+F ₄₀ +M ₃)	22,80 (0,17)	1093,30 (24,72)	3,04 (0,10)	43,58 (1,67)	2490,10 (69,84)	4,19 (0,19)	1057 (6)

For each group, five replicate specimens were tested (n = 5); * denotes the mean and ** the standard deviation.

Figure 2a illustrates the interaction effects on TS, Figure 2b illustrates those on TM and Figure 2c illustrates those on EatB. In each graph, composites without MAPP are represented by red lines, whereas those containing MAPP are represented by green lines.

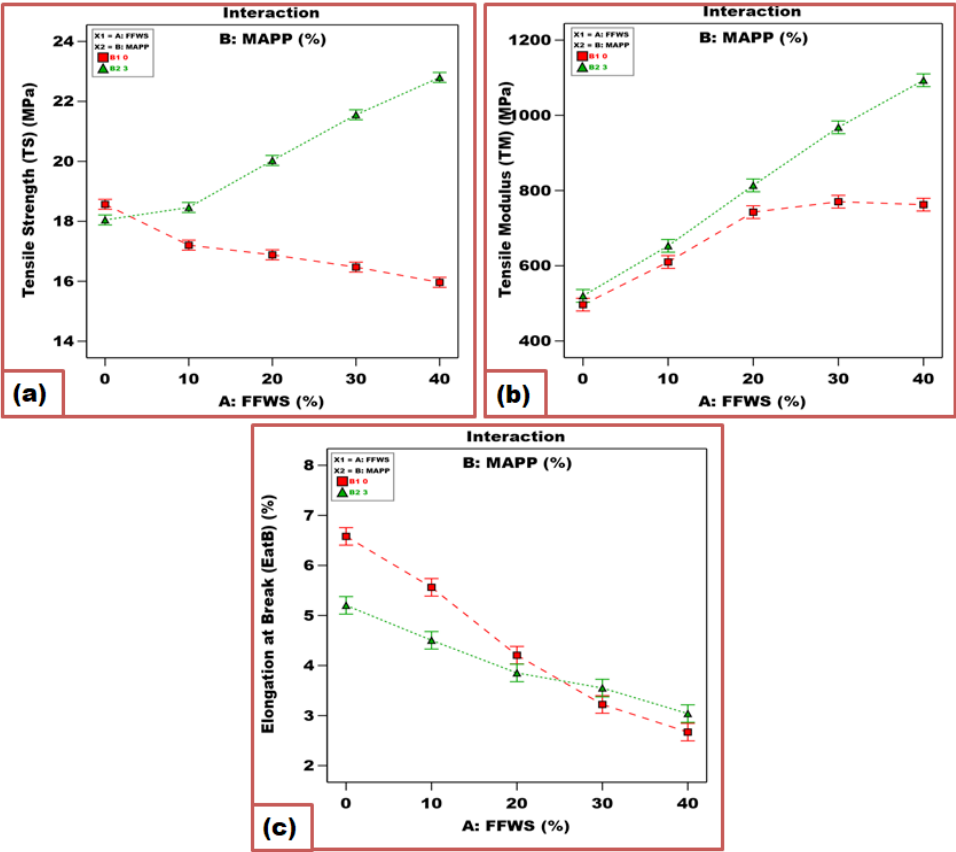


Figure 2: Interaction plots depicting the effects of FFWS content and MAPP on the composites' (a) tensile strength (TS), (b) tensile modulus (TM), and (c) elongation at break (EatB).

Statistical analysis confirmed that both FFWS and MAPP contents had highly significant effects on TS ($p < 0,0001$). Among the factors, MAPP exerted the strongest influence ($F = 1837,46$), while the FFWS×MAPP interaction was also statistically significant ($F = 315,98$; $p < 0,0001$). The interaction plot (Figure 2a) further supported these findings. In the absence of MAPP, TS values decreased progressively from 18,57 MPa (G1, R) to 15,96 MPa (G9, R+F₄₀) as FFWS loading increased, reflecting the detrimental effect of weak interfacial adhesion between the hydrophilic filler and the hydrophobic polypropylene matrix. In contrast, the incorporation of 3 wt % MAPP reversed this trend, with TS values increasing from 18,05 MPa (G2, R+M₃) to 22,80 MPa (G10, R+F₄₀+M₃) across the same FFWS range. SEM observations revealed reduced voids and fiber pull-out in the MAPP-containing composites, indicating improved interfacial adhesion. This improvement may be associated with interactions between the anhydride groups of MAPP and the hydroxyl functionalities of FFWS, which are believed to contribute to enhanced interfacial bonding and stress transfer efficiency. Overall, these results demonstrate that while FFWS alone tends to reduce tensile strength due to poor compatibility, the inclusion of MAPP effectively mitigates this limitation, underscoring the critical role of compatibilizers in developing high-performance WPCs based on recycled polypropylene. Similar results have been reported in the literature (Kim *et al.* 2007, Dányádi *et al.* 2007, Danesh *et al.* 2012, Arsad *et al.* 2013, Mertens *et al.* 2020, Burgada *et al.* 2021).

Statistical analysis demonstrated that both FFWS and MAPP contents had highly significant effects on TM ($p < 0,0001$). FFWS was identified as the most influential factor ($F = 424,11$), followed by MAPP ($F = 316,53$), and their interaction was also significant ($F = 60,01$). As shown in the interaction plot (Figure 2b), TM values increased steadily with higher FFWS loading, but the magnitude of this improvement was strongly dependent on the presence of MAPP. In the absence of MAPP, TM increased from 496,65 MPa (G1, R) to 770,34 MPa (G7, R+F₃₀), after which a slight plateau was observed. By contrast, when 3 wt% MAPP was incorporated,

TM values rose more sharply from 519,98 MPa (G2, R+M₃) to 1093,30 MPa (G10, R+F₄₀+M₃). The higher TM values observed in the MAPP-containing composites are consistent with improved interfacial adhesion between FFWS and the polypropylene matrix. SEM observations support this interpretation by showing reduced interfacial voids and improved fiber encapsulation, which may contribute to more efficient stress transfer and increased stiffness. These findings clearly indicate that MAPP not only compensates for interfacial incompatibility but also maximizes the reinforcing effect of FFWS in rPP-based composites. These trends, namely the stiffening imparted by FFWS and its amplification through MAPP compatibilization, are consistent with previous reports on PP or rPP-based wood–plastic composites (Yang *et al.* 2007, Islam *et al.* 2013, Langhorst *et al.* 2018).

Elongation at break (EatB) decreased monotonically with increasing FFWS content. ANOVA indicated a dominant main effect of FFWS ($F = 201,28$; $p < 0,0001$), with significant contributions from MAPP ($F = 29,14$; $p < 0,0001$) and the FFWS $\times$ MAPP interaction ($F = 20,91$, $p < 0,0001$). In the absence of MAPP, EatB declined from 6,58 % for G1 (R) to 2,67 % for G9 (R+F40). Incorporating 3 wt% MAPP reduced ductility at low filler levels (e.g., 5,20 % at 0 % FFWS; 4,50 % at 10 % FFWS) but attenuated the loss at higher loadings, yielding slightly greater values than the uncompatibilized counterparts (3,55 % vs 3,22 % at 30 % FFWS; 3,04 % vs 2,67 % at 40 % FFWS). These trends reflect reduced matrix continuity and chain mobility with increasing lignocellulosic content, while improved interfacial adhesion with MAPP constrains the matrix at low filler contents yet enhances stress transfer at high contents. These findings are consistent with prior reports on wood–plastic composites, which commonly document a reduction in elongation at break with increasing lignocellulosic filler content (Başboğa 2023, Kılıç *et al.* 2023, Atar 2025).

Figure 3a illustrates the interaction effects on FS, and Figure 3b illustrates those on FM. In each plot, composites without MAPP are represented by red lines, whereas those containing 3 wt % MAPP are represented by green lines.

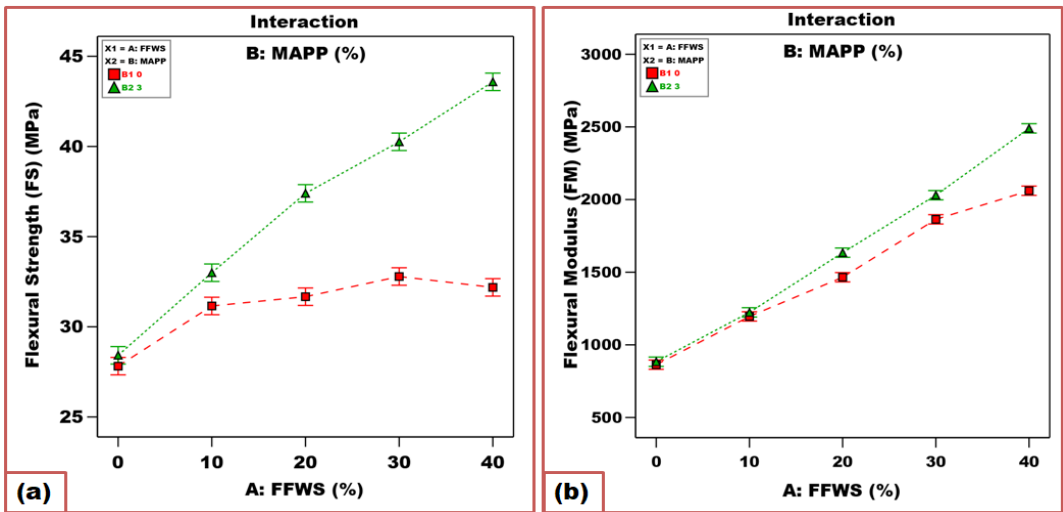


Figure 3: Interaction plots depicting the effects of FFWS content and MAPP on the composites' (a) flexural strength (FS) and (b) flexural modulus (FM).

Statistical analysis showed that FFWS and MAPP contents had highly significant effects on FS ($p < 0,0001$). MAPP exhibited the dominant main effect ($F = 638,76$), FFWS was also substantial ($F = 261,50$), and their interaction was significant (FFWS $\times$ MAPP: $F = 83$; $p < 0,0001$). Consistent with the interaction plot (Figure 3a), FS in MAPP-free composites increased only modestly with FFWS—from 27,82 MPa at 0 wt% to 32,79 MPa at 30 wt%—then declined slightly at 40 wt% (32,12 MPa). With 3 wt% MAPP, FS rose monotonically across 0 wt% - 40 wt% FFWS (28,42 $\rightarrow$ 33,00 $\rightarrow$ 37,40 $\rightarrow$ 40,20 $\rightarrow$ 43,58 MPa), yielding gains of 2,2 %, 5,9 %, 18,1 %, 22,6 %, and 35,7 % over the respective MAPP-free counterparts. The progressive increase in FS observed in the MAPP-containing composites is consistent with improved interfacial adhesion between FFWS and the polymer matrix. SEM images showing reduced fiber pull-out and fewer interfacial defects support this

interpretation. Similar improvements have been associated with anhydride–hydroxyl interactions in previous studies (Leu *et al.* 2012, Ndiaye *et al.* 2013, Jian *et al.* 2022, Nukala *et al.* 2022).

Statistical analysis showed that FFWS and MAPP contents had highly significant effects on FM ($p<0,0001$). MAPP exhibited the largest main effect ($F = 1303,82$), closely followed by FFWS ($F = 1248,91$), and their interaction was also significant ($F = 27,23$; $p<0,0001$). In the interaction plot (Figure 3b), FM increased monotonically with FFWS for both series: without MAPP from 863,89 to 2061,63 MPa ($0 \rightarrow 40$ wt%), and with 3 wt% MAPP from 884,14 to 2490,10 MPa. Relative to the MAPP-free counterparts, MAPP produced modest gains at low filler levels ($\sim +2,3$ % at 0 wt% and 10 wt%) and larger improvements at higher loadings ($+11,5$ % at 20 wt%, $+8,9$ % at 30 wt%, $+20,8$ % at 40 wt%). Mechanistically, this trend is expected: lignocellulosic fibers possess a substantially higher Young’s modulus than the polypropylene matrix; therefore, increasing fiber concentration elevates composite stiffness and necessitates a higher applied stress to achieve a given strain. Compatibilization further enhances fiber-matrix adhesion and stress transfer, steepening the FM-FFWS response. It has been observed that FM values increase similarly with the addition of filler to the PP matrix and the use of MAPP (Çavuş and Mengeloğlu 2020, Kılıç *et al.* 2023).

The interaction plot for notched impact strength (IS) is presented in Figure 4. In the figure, groups without MAPP are shown as red lines, whereas groups with MAPP are shown as green lines.

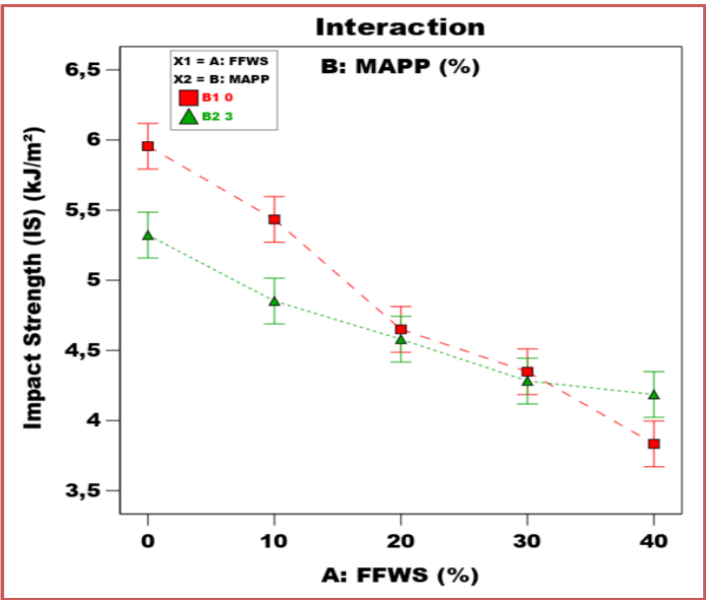


Figure 4: Interaction plot depicting the effects of FFWS content and MAPP on the composites’ notched impact strength (IS).

Statistical analysis showed that FFWS and MAPP contents had highly significant effects on IS ($p < 0,0001$). FFWS was the dominant factor, whereas MAPP had a smaller but significant effect, with a detectable FFWS $\times$ MAPP interaction (see interaction plot in Figure. 4). IS decreased with increasing FFWS for both series: in MAPP-free composites from 5,96 to 3,83 kJ/m² (G1 $\rightarrow$ G9) and, with 3 wt% MAPP, from 5,32 kJ/m² to 4,19 kJ/m² (G2 $\rightarrow$ G10). Relative to the corresponding MAPP-free groups, MAPP produced slight reductions at low–moderate filler levels ($-10,7$ % at 10 wt%, $-1,5$ % at 20 wt%, $-1,6$ % at 30 wt%) but yielded a small recovery at 40 wt% ($+9,4$ %, 4,19 kJ/m² vs 3,83 kJ/m²). These trends reflect the well-known decrease in impact energy with rigid lignocellulosic fillers–due to constrained matrix deformation and stress concentrations–while compatibilization strengthens the interface, limiting debonding-related toughening at low loadings yet partially restoring IS at high filler contents. Consistent with this trend, prior studies report that incorporating lignocellulosic filler into an rPP matrix introduces stress concentrators that promote crack initiation and shift fracture behavior from ductile to brittle, thereby reducing impact strength (Arsad *et al.* 2013, Poletto 2017).

Statistical analysis indicated that FFWS had a strong main effect on composite density ($p<0,0001$), whereas the effects of MAPP and the FFWS $\times$ MAPP interaction were not significant ($p>0,05$). In the interaction plot (Figure 5), density increased nearly linearly with FFWS in both series: from 953 kg/m³ to 1047 kg/m³ without MAPP and from 960 kg/m³ to 1057 kg/m³ with 3 wt% MAPP across 0 wt% - 40 wt% FFWS. The approximately 10 % increase reflects the higher specific gravity of lignocellulosic solids relative to rPP. The small differences associated with MAPP, more evident at 30 wt% - 40 wt% FFWS, likely arise from improved wetting and reduced void content rather than a direct influence on mass density. This trend is consistent with previous WPC studies showing that density rises with lignocellulosic content and is only marginally affected by MAPP or processing variables (Myers *et al.* 1991, Çavuş 2020, Pokhrel *et al.* 2021).

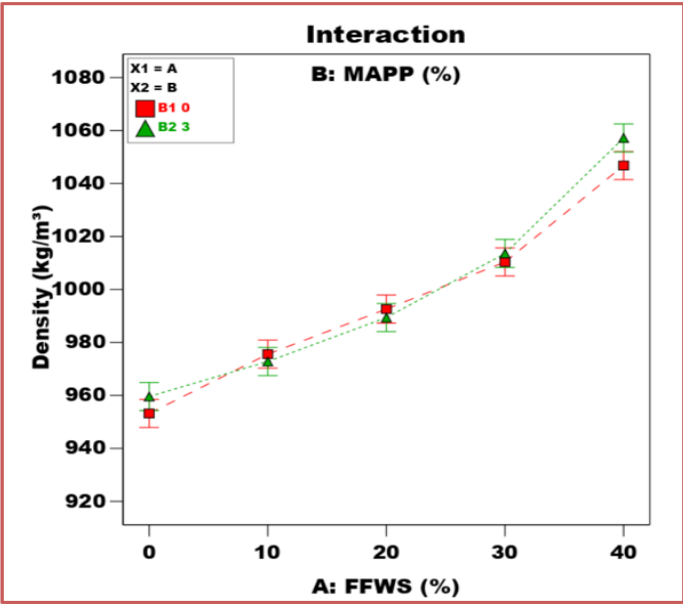


Figure 5: Interaction plot depicting the effects of FFWS content and MAPP on the composites’ density values.

Figure 6 presents the water absorption (WA) of FFWS-filled rPP composites at 2 h, 24 h, 48 h, 72 h, 168 h, 336 h, 504 h, and 672 h. Because the water absorption of neat rPP is considered zero in this study, data for the unfilled rPP are not shown. In the bar chart, shaded bars indicate groups with 3 wt% MAPP, whereas open bars indicate MAPP-free groups.

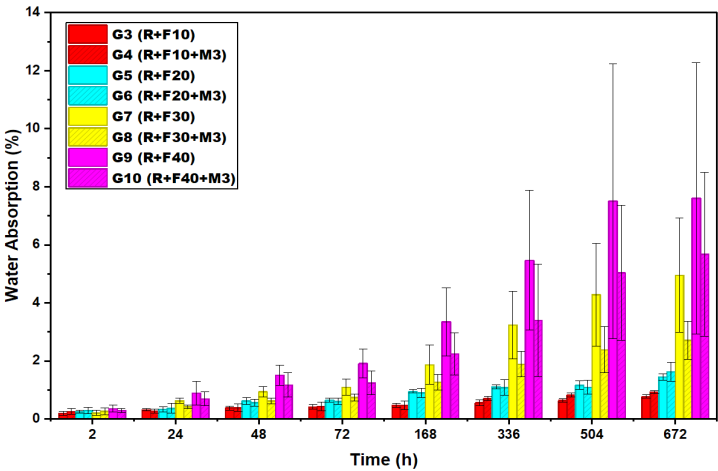


Figure 6: Water absorption of FFWS-reinforced rPP composites over 28 days of immersion (2 h - 672 h).

Statistical analysis based on a factorial ANOVA model revealed that water absorption was significantly affected by FFWS content ($p < 0,0001$), immersion time ($p < 0,0001$), and MAPP addition ($p < 0,0001$). In addition, a significant interaction between FFWS content and immersion time was observed ($p = 0,0014$), indicating that the influence of filler loading on water uptake became more pronounced with prolonged exposure. The overall model was highly significant ($F = 8,68$; $p < 0,0001$), while the lack-of-fit was not significant ($p = 0,4592$), confirming the adequacy of the selected model. As illustrated in Figure 6, water absorption increased monotonically with immersion time for all formulations, and higher FFWS contents resulted in greater uptake at any given time point. The presence of MAPP led to statistically significant reductions in water absorption, particularly at higher FFWS levels and longer immersion times, consistent with improved interfacial encapsulation and reduced void content. These findings align with previous studies on PP-based WPCs, where water absorption increases with lignocellulosic filler content and immersion time, while maleic anhydride-based compatibilizers provide moderate to significant reductions through improved fiber encapsulation and reduced interfacial voids (López *et al.* 2012, Islam *et al.* 2013, Kumar *et al.* 2019, Vallejos *et al.* 2023, Kılıç *et al.* 2024).

The specimens containing 20, 30, and 40 wt% filler, both with and without MAPP, were evaluated against white-rot (*Trametes versicolor*; TV) and brown-rot (*Coniophora puteana*; CP) fungi. The resulting mass loss values are detailed in Table 3 (mean $\pm$ standard deviation, $n = 5$). These data are also visualized in Figure 7 as bar charts to facilitate comparison of composite performance with reference wood samples (Oriental beech (*Fagus orientalis* Lipsky) and scots pine (*Pinus sylvestris* L.) and between the two fungal species.

Table 3: Mass loss (%) of WPC specimens and reference wood samples after fungal decay exposure.

Fungus Type	Group Code	Mass loss (%)
<i>Trametes versicolor</i>	G1(R)	0
	G5 (R+F ₂₀)	*0,51 **(0,19)
	G6 (R+F ₂₀ +M ₃)	0,61 (0,39)
	G7 (R+F ₃₀)	0,91 (0,34)
	G8 (R+F ₃₀ +M ₃)	0,74 (0,18)
	G9 (R+F ₄₀)	1,80 (0,50)
	G10 (R+F ₄₀ +M ₃)	1,26 (0,42)
	Beech (control)	76,73 (6,15)
	Scots pine (control)	31,48 (1,62)
<i>Coniophora puteana</i>	G1(R)	0
	G5 (R+F ₂₀)	1,43 (1,67)
	G6 (R+F ₂₀ +M ₃)	0,68 (0,23)
	G7 (R+F ₃₀)	1,38 (0,35)
	G8 (R+F ₃₀ +M ₃)	0,65 (0,46)
	G9 (R+F ₄₀)	1,73 (0,52)
	G10 (R+F ₄₀ +M ₃)	1,59 (0,70)
	Beech (control)	19,40 (6,75)
	Scots pine control)	15,86 (9,94)

For each group, five replicate specimens were tested ($n = 5$); * denotes the mean and ** the standard deviation.

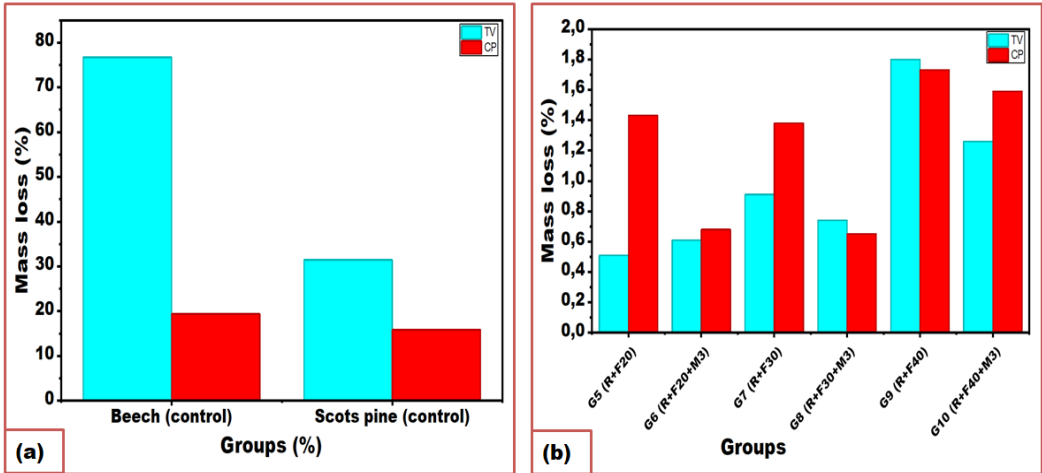


Figure 7: Mass loss (%) of (a) reference wood specimens (Beech and Scots pine) and (b) rPP composites reinforced with FFWS at different filler loadings, with and without MAPP, after exposure to white-rot (*Trametes versicolor*; TV) and brown-rot (*Coniophora puteana*; CP) fungi.

Statistical analysis indicated a significant model in which FFWS and MAPP showed significant main effects ($p<0,05$), whereas decay type (*Trametes versicolor* vs *Coniophora puteana*) and all interaction terms were not significant ($p>0,05$). As summarized in Table 3, mass loss increased with FFWS irrespective of the fungus. Under *Trametes versicolor*, values were 0 % for G1 and rose to 0,51 % (G5, 20 wt% FFWS), 0,91 % (G7, 30 wt%), and 1,80 % (G9, 40 wt%); adding 3 wt% MAPP reduced the loss at higher filler levels, yielding 0,74 % at 30 wt% (G8) and 1,26 % at 40 wt% (G10), while a slight increase was observed at 20 wt% (0,61 %, G6). Under *Coniophora puteana*, MAPP consistently lowered mass loss relative to the MAPP-free counterparts (1,43 % to 0,68 % at 20 wt%, 1,38 % to 0,65 % at 30 wt%, 1,73 % to 1,59 % at 40 wt%). Across all composite formulations, losses remained below 2 %, in sharp contrast to the reference woods, which showed severe degradation (beech: 76,73 % under *Trametes versicolor* and 19,40 % under *Coniophora puteana*; Scots pine: 31,48 % and 15,86 %, respectively). These results indicate that rPP confers high intrinsic decay resistance; increasing the lignocellulosic fraction modestly elevates susceptibility, and MAPP improves encapsulation and limits fungal ingress at moderate to high filler contents.

Compared with solid wood, wood–plastic composites (WPCs) generally exhibit greater resistance to fungal attack because lignocellulosic particles are embedded within a thermoplastic matrix, which reduces water uptake and creates a physical barrier to hyphal penetration (Naumann *et al.* 2012a, Naumann *et al.* 2012b, Catto *et al.* 2016, Cesarino *et al.* 2019, Schirp and Wolcott 2005). Consistent with this mechanism, increasing filler loading tends to raise mass loss, since a higher lignocellulosic fraction provides more digestible substrate and favors moisture retention that facilitates decay (Schirp and Wolcott 2005, Klyosov 2007). The biological degradation of WPCs depends on several factors, including fiber content and chemistry, the biodegradability of the reinforcement, and the quality of the fiber–matrix interphase, and numerous studies reports increasing mass loss with increasing wood content (Mankowski and Morrell 2000, Kartal *et al.* 2013, Candelier *et al.* 2019, Cesarino *et al.* 2019). In addition, compatibilizing agents can lower water absorption and thereby reduce susceptibility to microbial deterioration (Klyosov 2007).

Thermal stability of the composites was assessed by thermogravimetric analysis and derivative thermogravimetry (TGA and DTGA). The TGA and DTGA curves for G1 (R), G5 (R+F₂₀), G6 (R+F₂₀+M₃), G9 (R+F₄₀), and G10 (R+F₄₀+M₃) are shown in Figure 8a and Figure 8b, respectively. Table 4 summarizes the degradation onset temperature (T_{onset}), endset temperature (T_{endset}), and the corresponding mass losses at T_{onset} , across the main degradation interval ($T_{onset}-T_{endset}$), and at 700 °C.

Table 4: Thermogravimetric Degradation Parameters of the Composite Formulations.

ID	T _{onset} (°C)	T _{endset} (°C)	Mass Loss		
			At T _{onset} (%)	At T _{onset} - T _{endset} (%)	At 700 °C (%)
G1(R)	286,1	516,8	1,3	92,7	6,0
G5 (R+F ₂₀)	255,0	539,9	2,1	91,4	6,6
G6 (R+F ₂₀ +M ₃)	253,3	587,4	1,8	92,3	5,9
G9 (R+F ₄₀)	252,8	556,6	5,5	92,2	2,3
G10 (R+F ₄₀ +M ₃)	221,4	825,5	2,8	92,0	5,0

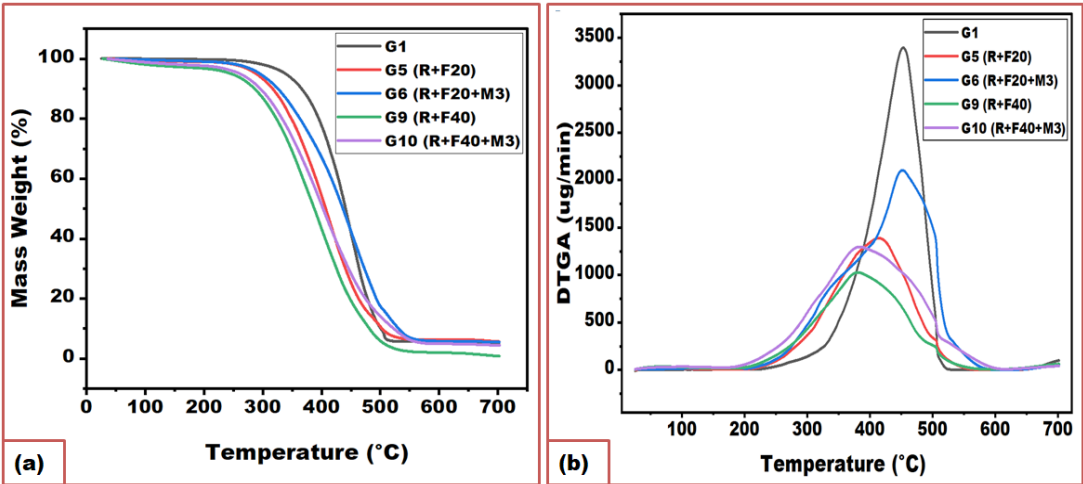


Figure 8: Thermogravimetric and Derivative Thermogravimetric Profiles of the Composites: (a) TGA curves; (b) DTGA curves.

The TGA curves of all composites exhibit multiple mass loss stages. The initial stage, commencing at room temperature and concluding at T_{onset}, is typically associated with moisture loss in the composites, a finding consistent with prior studies (Nukala *et al.* 2022, Silveira *et al.* 2023). Increasing FFWS reduces Tonset, lowering it from 286,1 °C for G1 (R) to 255,0 °C for G5 (R+F₂₀) and 252,8 °C for G9 (R+F₄₀). At equivalent filler levels, formulations containing MAPP demonstrate a further decrease, with Tonset values of 253,3 °C for G6 (R+F₂₀+M₃) and 221,4 °C for G10 (R+F₄₀+M₃). Similar studies on wood-plastic composites (WPCs) have reported a decline in initial degradation temperatures upon the addition of filler to the PP matrix (Wu *et al.* 2021, Başboğa 2023). At higher temperatures, the degradation window expands, with T_{endset} increasing from 516,8 °C (G1) to 539,9 °C (G5), 556,6 °C (G9), 587,4 °C (G6), and 825,5 °C (G10), likely attributable to components such as cellulose, hemicellulose, and lignin from the FFWS filler. It is well-established that cellulose decomposes between 275 °C - 350 °C, hemicellulose between 150 °C - 350 °C, and lignin between 350 °C - 500 °C (Eroğlu *et al.* 2023). Chen *et al.* (2020) reported that lignin begins degradation at approximately the same temperature as hemicellulose but continues to exhibit mass loss up to 800 °C, while other studies have noted that these components enhance the thermal decomposition temperature in WPCs (Kim *et al.* 2004, Jeske *et al.* 2012). In the DTGA profiles, the intensity of the primary PP peak decreases and shifts slightly with increasing FFWS, consistent with a reduced degradation rate due to the dispersed lignocellulosic phase. Overall, FFWS diminishes the initial thermal stability, whereas MAPP at higher filler contents yields a broader and more gradual high-temperature decomposition profile.

Figure 9 presents differential scanning calorimetry (DSC) heat-flow curves as a function of temperature for rPP composites at different FFWS loadings. The first-heating (melting) profiles for G1 (R), G5 (R+F₂₀), G6

(R+F₂₀+M₃), G9 (R+F₄₀), and G10 (R+F₄₀+M₃) are shown in Figure 9a, and the subsequent cooling (crystallization) profiles are shown in Figure 9b.

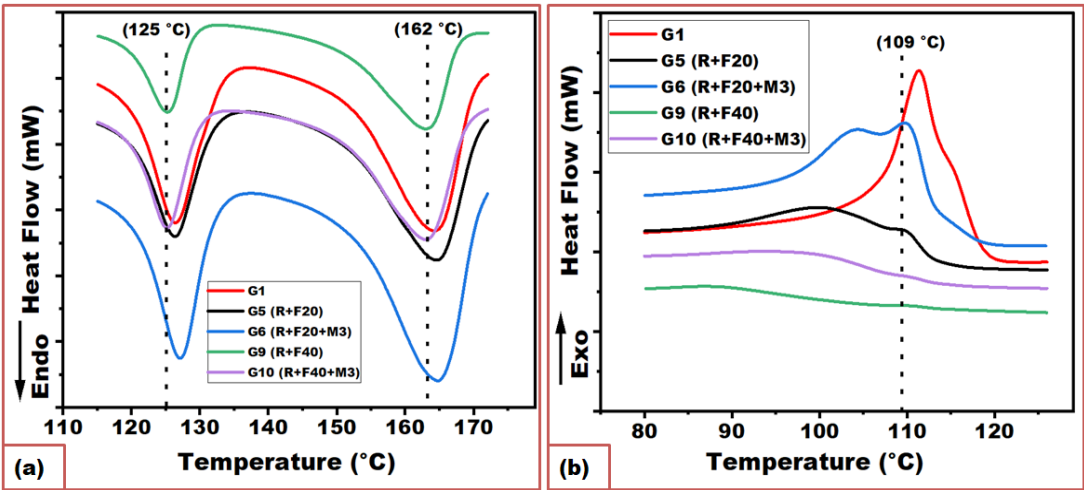


Figure 9: DSC thermograms of rPP/FFWS composites: (a) first heating cycle; (b) first cooling cycle.

The first-heating thermograms display two endothermic features: a smaller peak at about 125 °C and the principal PP melting peak at 160 °C - 163 °C. The peak at 125 °C is indicative of HDPE melting and demonstrates that the recycled PP feedstock contains a minor PP/HDPE blend, which is a common outcome of post-consumer recycling streams (for example, HDPE bottle caps mixed with PP). Similar results have been reported by others (Brachet *et al.* 2008, Fang *et al.* 2013, Chiou and Lin 2023). Consistent with increasing FFWS content, the main PP melting endotherm becomes broader and shifts to slightly lower temperature (G1 → G5 → G9), reflecting reduced crystal perfection and constrained chain mobility. At the same filler levels, the MAPP-containing formulations (G6 vs G5; G10 vs G9) show a partial recovery in melting temperature and peak sharpness, consistent with improved interfacial compatibility. On cooling (Figure 9b), a single crystallization exotherm appears near 109 °C - 112 °C; its peak temperature and intensity decrease with increasing FFWS, whereas 20 wt% FFWS with MAPP (G6) crystallizes at a slightly higher temperature than its uncompatibilized counterpart (G5), suggesting partial restoration of nucleation and crystallization rate. Overall, the DSC curves indicate that (i) the matrix is PP-rich with a detectable HDPE fraction and (ii) FFWS lowers melting and crystallization temperatures while MAPP mitigates these effects at moderate loading and, to a lesser extent, at high loading.

Figure 10 presents the fracture surface morphologies of the composites. Parts (a), (b), (c), and (d) correspond to SEM micrographs of G5 (R+F₂₀), G6 (R+F₂₀+M₃), G9 (R+F₄₀), and G10 (R+F₄₀+M₃), respectively. Distinct morphological features are highlighted by arrows: fiber pull-out cavities, interfacial debonding, and unwetted fiber bundles in the non-compatible systems (a, c); and, in contrast, encapsulated fibers, polymer matrix ligaments, and reduced void formation in the MAPP-treated composites (b, d). These observations confirm the improved interfacial adhesion and more effective stress transfer imparted by the coupling agent.

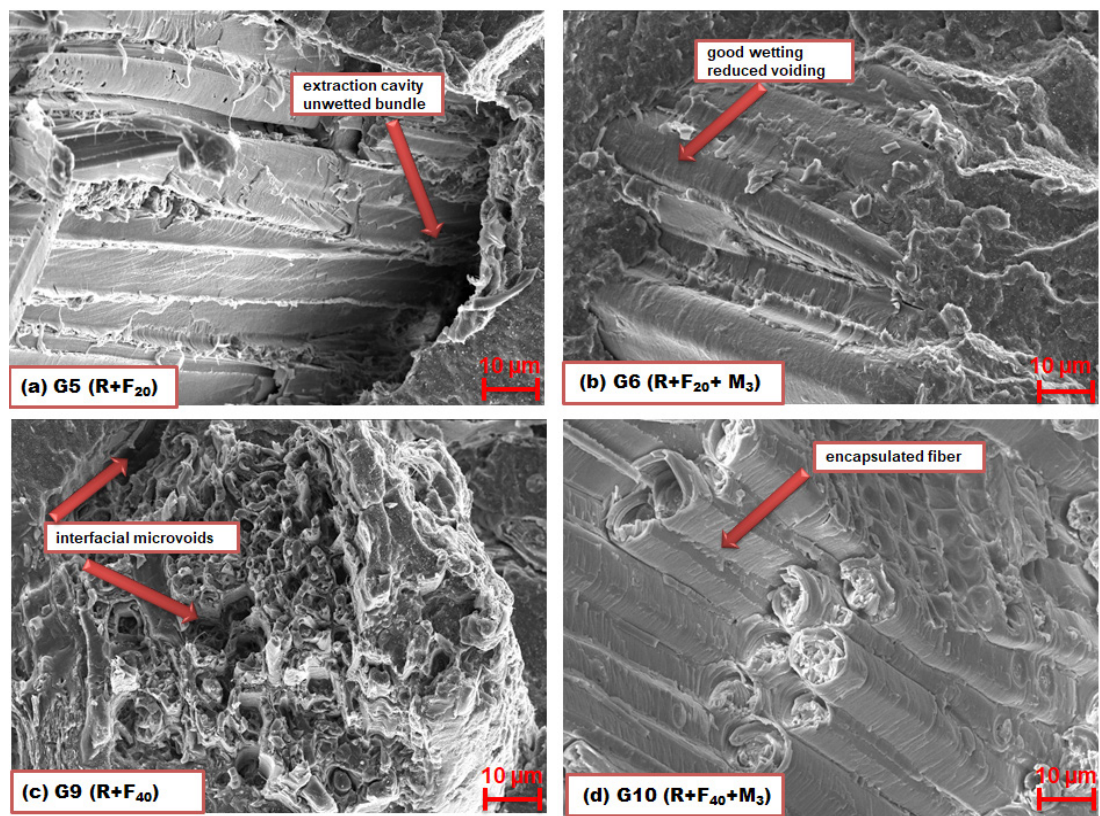


Figure 10: Representative SEM micrographs (500×) of fracture surfaces of rPP/FFWS composites: (a) G5 (R+F₂₀), (b) G6 (R+F₂₀+M₃), (c) G9 (R+F₄₀), and (d) G10 (R+F₄₀+M₃).

SEM examination (500×) of the fracture surfaces highlights the role of MAPP in improving interfacial bonding. The MAPP-free samples G5 (R+F₂₀) and G9 (R+F₄₀) exhibit prominent extraction cavities, unwetted bundles, interfacial microvoids, and long fiber pull-out marks, indicative of poor wetting and a debonding-controlled failure mode. The presence of voids and gaps at the interface between the recycled polypropylene matrix and wood fibers under weak adhesion has likewise been documented by others (Gulitah and Liew 2019, Çavuş and Mengeloğlu 2020, Burgada *et al.* 2021). In contrast, the MAPP-containing samples G6 (R+F₂₀+M₃) and G10 (R+F₄₀+M₃) show polymer sheaths around fibers, encapsulation with continuous interfaces, fewer voids, and shorter pull-out lengths; these features are consistent with stronger fiber–matrix adhesion and a more cohesive fracture mode. SEM evidence for adhesion improvement upon adding MAPP to PP-cellulosic WPCs has also been reported (Renner *et al.* 2009, Burgada *et al.* 2021, Birinci and Kaymakçı 2023, Kılıç *et al.* 2024). These microstructural observations are in line with the measured enhancements in mechanical properties (e.g., tensile and flexural strength) for the MAPP-containing composites.

CONCLUSIONS

This study systematically evaluated wood–plastic composites (WPCs) manufactured from heterogeneous furniture-factory waste sawdust (FFWS), recycled polypropylene (rPP), and maleic anhydride-grafted polypropylene (MAPP). The incorporation of FFWS at varying loadings (0 wt% – 40 wt%) significantly influences the mechanical, physical, thermal, and biological properties of the composites. Notably, FFWS increases tensile and flexural moduli but compromises tensile strength, elongation at break, and impact strength in the absence of MAPP, reflecting weak interfacial adhesion between the hydrophilic filler and hydrophobic

matrix. The addition of 3 wt% MAPP markedly enhances tensile strength (by up to 42,9 % at 40 wt% FFWS), flexural strength (by up to 35,7 %), and moduli, driven by improved interfacial bonding, as evidenced by SEM observations of reduced voids and fiber pull-out. Water absorption rises with FFWS content and immersion duration, with MAPP providing minor reductions through improved encapsulation. The composites exhibit exceptional biological durability, with mass losses below 2 % under both white-rot and brown-rot fungal exposure, underscoring the protective role of the rPP matrix. Thermogravimetric analysis indicates reduced initial thermal stability with increasing FFWS, while MAPP extends the degradation window. Differential scanning calorimetry reveals a PP-rich matrix with a minor HDPE fraction, where FFWS lowers melting and crystallization temperatures, partially mitigated by MAPP.

Overall, the findings demonstrate that heterogeneous furniture-factory waste sawdust can be successfully incorporated into rPP-based WPCs and that MAPP compatibilization plays a key role in improving composite performance.

This study addresses an existing knowledge gap by providing a comprehensive characterization of FFWS/rPP composites produced from real industrial waste streams and contributes to a better understanding of the relationships between composition, interfacial adhesion, and composite properties. Future research should focus on evaluating the long-term durability and weathering performance of FFWS/rPP composites under outdoor exposure conditions.

Authorship contributions

İ.K: Conceptualisation, data curation, formal analysis, investigation, methodology, project management, resources, software, verification, visualization, writing – original draft, writing – review and editing.

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Conflict of interest

The author declares that there is no conflict of interest regarding the publication of this work.

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