

Article

Polypropylene-Based Wood-Plastic Composites from Recovered and Beetle-Infested Wood: Effect of Pre-Damaged Fibers on Mechanical Performance

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Abstract

The increasing scarcity of conventional feedstocks for WPCs requires alternative resources supporting circular material flows in the wood-based bioeconomy. This study investigated thermomechanical pulp (TMP) fibers from fresh, recovered, and beetle-infested spruce as well as fresh beech as reinforcements for polypropylene-based WPCs. Fiber geometry was characterized before and after injection molding, and composite performance was evaluated with and without a maleic-anhydride-grafted polypropylene coupling agent. After injection molding, the aspect ratio ranged from 7.1 to 7.9, with recovered spruce showing the highest value. The addition of 30 wt.-% TMP fibers increased the tensile modulus from 1.4 GPa for neat polypropylene to as much as 4.7 GPa for the coupled WPCs. Compatibilization markedly improved strength, resulting in tensile strengths of up to 54 MPa and flexural strengths of up to 80 MPa, compared with 33 MPa and 36 MPa for neat polypropylene, respectively. Recovered and beetle-infested spruce did not impair composite performance and achieved the highest tensile and flexural strength values. Beech-based WPCs showed lower tensile and flexural performance than spruce-based composites but still reached a technically relevant property level. Overall, recovered and beetle-infested spruce and fresh beech represent viable TMP raw materials for mechanically demanding WPC applications.

Keywords: wood–plastic composites; wood fibers; alternative feedstocks; recovered wood; beetle-infested wood; beech; spruce; mechanical properties

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1. Introduction

According to the National Academy of Science and Engineering in Germany, wood is the most important renewable resource and, together with other renewables, constitutes a key component of a sustainable bioeconomy. Its potential to contribute to the transition from a fossil-based economy to a regenerative one is substantial. However, forest transformation has become imperative, as climate change exerts considerable pressure on existing stands, leading to climate-related damage and calamities and the accumulation of damaged timber. Therefore, monocultures of spruce must be diversified and hardwoods, such as beech, must be increasingly integrated into the forestry ecosystem. Consequently,

the industry will need to adapt to new wood species and properties and reduced qualities resulting from damage events [1,2].

Wood-plastic composites (WPCs) are an established product group within the wood-based materials sector. They are a sustainable and versatile alternative to conventional solutions. Over the past decade, the global WPC market has grown significantly, with current forecasts projecting an average annual growth rate of about 11% [3]. Therefore, securing a stable supply of wood-based raw materials is becoming increasingly critical. Currently, wood flour, primarily sourced from spruce and pine, is the main raw material, as evidenced by reviews of industrial compounds and WPC research [4–9]. However, its availability may become increasingly limited.

There are several potential sources of feedstock for WPC production. Spruce remains a widely used raw material [3], although its availability is increasingly constrained by deforestation and climate-related impacts. However, beetle-infested spruce is becoming more important as a potential feedstock due to the increasing extent of pest-related degradation. Additionally, large quantities of spruce waste wood are available, primarily from construction and post-consumer streams [2]. Climate-resilient hardwoods such as beech could also serve as an alternative feedstock to meet future demand, as they have superior mechanical properties [10]. From the authors' perspective, the utilization of these resources may contribute to broadening the raw material basis for WPC production and support more resource-efficient material strategies. However, these alternative feedstocks exhibit different morphological and chemical properties compared to conventionally used spruce wood flour [11,12].

Previous studies have investigated how such alternative wood sources differ in composition and morphology from conventionally used feedstocks. With regard to particle morphology, Yadama et al. reported that wood flour from beetle-infested spruce contains a higher proportion of fine particles compared to sound wood, most likely due to fiber breakage caused by weathering, fungal colonization, and moisture loss [11]. As highlighted by Hýšek et al., fungal colonization is the primary driver of mechanical degradation, rather than the beetle activity itself. Their study documented a decline of 24% in the modulus of rupture and 32% in the modulus of elasticity over a period of three years [12]. Löwe et al. confirmed that prolonged infestation leads to significant strength losses –14% in tensile strength and –25.6% in compressive strength—with a clear correlation between infestation duration and mechanical decline [13]. In contrast, Künniger et al. demonstrated that wood infested for up to one month still exhibits mechanical properties comparable to healthy wood. After two to three months, however, noticeable reductions in impact and bending strength occur due to fungal colonization, rendering the material increasingly brittle [14]. In summary, recovered and beetle-infested spruce exhibits reduced mechanical properties and tends to yield finer particles compared to freshly cut wood.

As the properties of the composite are highly dependent on the properties of the fiber as well as the polymer, it seems clear that these changes in mechanical performance, particle size distribution, and fiber integrity of the used reinforcement affect the performance of WPCs. Against this background, several studies have examined the use of beetle-infested and recovered industrial wood in WPC production. Yadama et al. demonstrated that extruded WPCs produced with High-Density Polyethylene (HDPE) and wood flour from beetle-infested pine exhibited similar mechanical properties to those of commercial WPCs [11]. Similar findings were reported by Chang and Lam [15,16] as well as by Krause [17]. Hyvärinen et al. demonstrated that blending construction and demolition waste with sound wood flour and processing it into recycled HDPE-based WPCs resulted in only minor reductions in mechanical properties compared to a polypropylene (PP)—wood flour reference. In contrast, construction and demolition waste without sound wood flour led to significant reductions in strength and stiffness [18]. Ge et al. observed significant

losses in mechanical performance when decayed wood was used without modification [19]. Overall, the literature indicates that alternative feedstocks tend to reduce WPC properties, although mitigation strategies can partially compensate for these drawbacks. Nevertheless, some reduction in performance remains inevitable.

Most of the aforementioned studies focused on wood flour with particle sizes below 150 μm (D50), predominantly from spruce and pine, used as a filler rather than a true reinforcement. This can be attributed to the dominance of wood flour in the WPC market, whereas wood fibers are rarely considered [5]. However, using thermo-mechanical pulp wood fibers has been shown to increase tensile properties by up to 20% due to their higher aspect ratio [20]. The physiological differences between wood flour and wood fibers were described in detail by Wiedl et al. [21]. Regarding hardwood alternatives, such as beech, it has been reported that beech yields finer particles than spruce [22–24]. This is also relevant with respect to the potential for higher aspect ratios.

From the authors' perspective, the use of wood fibers instead of wood flour, particularly when derived from alternative raw materials such as recycled or beetle-infested wood, offers a promising strategy to mitigate the mechanical disadvantages caused by wood degradation, as fiber strength and length relative to diameter play crucial roles in composite mechanics. Morphological changes induced by aging may even increase the fiber aspect ratio during thermomechanical pulping and subsequent processing, thereby enhancing the reinforcement efficiency in injection-molded WPCs.

Based on these considerations, the present study investigates the use of thermo-mechanical pulp fibers derived from spruce and beech as reinforcement materials in WPCs. Accordingly, the hypotheses investigated in this work are as follows:

1. Aging processes in wood lead to finer fiber structures during thermo-mechanical pulping and thereby increase the fiber aspect ratio (see Section 3.1).
2. A higher aspect ratio results in significantly improved fiber reinforcement, even in the case of recovered wood fibers (see Section 3.2).
3. There is no significant difference in the mechanical properties of WPCs reinforced with TMP fibers derived from climate-resilient beech and conventional spruce (see Sections 3.1 and 3.2).

2. Materials and Methods

2.1. Materials

A polypropylene homopolymer (HJ120UB) from Borealis (Vienna, Austria) was chosen as the matrix material. The manufacturer specifies an MFR of 75 g/10 min (230 °C/2.16 kg) and a density of 0.905 g/cm³ [25]. Furthermore, the manufacturer assigns the material's basic stabilization and low emissions. A polypropylene copolymer grafted with maleic anhydride (SCONA TPPP 8112 FA) from BYK Additives (Wesel, Germany) was used as a coupling agent (CA) between the PP and the wood fibers (WF), hereafter referred to as MAH-PP [26]. Wood fibers from spruce (*Picea abies*) and beech (*Fagus sylvatica*) were investigated. Fresh spruce and fresh beech wood, as well as beetle-infested spruce wood, were obtained from the forest resources of Rosenheim Technical University of Applied Sciences. The beetle-infested spruce had been affected by bark beetle infestation for several months before processing. After cutting, the logs were stored outdoors for approximately 10 weeks before chipping and refining. The recovered wood fraction was obtained from a European pallet classified as A1 recovered wood. The pallet had been stored outdoors for approximately 5 months before chipping and refining. No detailed information on the previous life of the pallet was available. However, before processing, the material appeared visually clean, with only minor dust contamination and without pronounced weathering, fungal growth, or visible contamination. The fibers were produced by a TMP-

process on a 12-inch laboratory refiner type 12 1CP from Andritz AG (Graz, Austria) in the technical center of the Rosenheim Technical University of Applied Sciences. Within each wood material, the grinding disk and gap were adjusted to achieve high aspect ratios.

2.2. Methods

2.2.1. Production of the Wood-Fiber-Polypropylene Composite

The compounds were produced using an internal mixer. Mixing was performed using a HAAKE PolyLab OS Rheodrive combined with a HAAKE Rheomix OS 3000 with cam rotors (Thermo Fisher Scientific Inc., Waltham, MA, USA). The processing temperature was set to 180 °C and the rotation speed was constantly kept at 20 rpm. After 10 min, a steady torque was reached and the polymer was completely molten. Then, the wood fibers were added to the polymer melt. The mixing was considered complete when the torque and the temperature reached a steady level and the mixing time of all components together reached 10 min. The compound was removed, cooled to room temperature and ground into granules using a Colortronic M103 granulator (Motan Group, Isny, Germany). The wood fibers were dried for three hours at 103 °C. Residual moisture was measured by the gravimetric method using the Halogen-Moisture Analyzer HX204 (Mettler Toledo, Columbus, OH, USA). The result was $2.54 \pm 0.68\%$.

Table 1 presents a comprehensive overview of the material compositions that were the focus of the investigation. The experimental design incorporates neat PP as a reference material, in addition to WPC compounds comprising 30 wt.-% TMP fibers from spruce (fresh, recovered, and beetle-infested) and beech (fresh), each subjected to processing with and without 3 wt.-% CA. A fiber content of 30 wt.-% was selected as a technically relevant and still well-processable loading level for injection-molded PP-based WPCs. The fiber content was kept constant for all wood fiber types in order to isolate the effect of the raw material source and the resulting TMP fiber morphology on the mechanical performance of the composites.

Following the grinding processes, the WPC parts were produced by means of an injection-molding machine from Arburg (Type 270 A, ARBURG GmbH + Co KG, Loßburg, Germany). The injection-molding parameters were kept constant for all compounds. The mold temperature was set to 40 °C. The cylinder temperature profile was 50/180/185/185/190/190 °C from the feeding zone to the nozzle. The injection speed was set to 25.0 cm³/s, and the maximum injection pressure was limited to 2000 bar. Furthermore, the same injection mold with a cold runner was used. The mold contained two cavities: one for a tensile test specimen of Type 527-1B and the other for an impact test specimen of Type 179-1eB. The WPC compounds were dried for three hours at 103 °C. The residual moisture was $0.6\% \pm 0.3\%$.

Table 1. Experimental design; composition of the compounds processed and investigated.

ID	Wood Species	Type	Material Composition		
			WF [wt.-%]	CA [wt.-%]	PP [wt.-%]
PP	-	-	0	0	100
F1_0	Spruce	Fresh wood	30	0	70
F1	Spruce	Fresh wood	30	3	67
F2_0	Spruce	Recovered wood	30	0	70
F2	Spruce	Recovered wood	30	3	67
F3_0	Spruce	Beetle-infested wood	30	0	70
F3	Spruce	Beetle-infested wood	30	3	67
B1_0	Beech	Fresh wood	30	0	70
B1	Beech	Fresh wood	30	3	67

2.2.2. Analysis of Fiber and Composite Properties

The infrared spectra of the different TMP-wood fibers were obtained via Fourier Transform Infrared Spectroscopy with attenuated total reflection (ATR-FTIR), using a Nicolet iN10 equipped with a Smart iTX diamond (Thermo Fisher Scientific Inc., Waltham, MA, USA). The spectra were registered in absorbance mode from 4000 to 700 cm^{-1} at a spectral resolution of 4 cm^{-1} . Measurements were performed on three replicates per wood fiber sample and 16 scans were used.

The wood fibers from different wood types were distributed on an optical scanner (type V850, Seiko Epson Corporation, Tokyo, Japan) to analyze their geometry. The dispersed fibers were scanned and then evaluated using the image analysis software Fiber-Shape 6.2 (IST AG, Vilters, Switzerland), according to ISO 9276. An extraction according to Twisselmann was performed on the PP from the specimen using xylene as the solvent. The remaining fibers were then dried, and their geometry was measured accordingly. A minimum of 7500 fibers after the TMP-process and 10,000 fibers after the injection molding process were analyzed for each wood type.

The tensile test, which was carried out according to ISO 527-2 to determine the tensile modulus and tensile strength of the molded specimens, was performed on a Zwick/Roell type Z020 universal testing machine (ZwickRoell GmbH & Co. KG, Ulm, Germany). The testing speed used to determine the tensile modulus was set to 1 mm/min. Tensile strength was evaluated using a testing speed of 50 mm/min for neat PP and 5 mm/min for WPC samples ($n = 5$). This latter rate has been used in other studies and found to yield reliable results [21,27,28].

The three-point bending test was conducted on a ZwickRoell Z020 universal testing machine (ZwickRoell GmbH & Co. KG, Ulm, Germany) to determine the flexural modulus and flexural strength of the specimens according to ISO 14125. The testing speed used to determine the flexural modulus was 1 mm/min. A testing speed of 2 mm/min was chosen to evaluate the flexural strength ($n = 5$).

The Charpy notched impact strength test was performed according to ISO 179-2 to determine the impact resistance of the notched specimens. The impact test specimens were produced with a type B notch directly during the injection-molding process. For this test, a HIT50P pendulum impact tester (ZwickRoell GmbH & Co. KG, Ulm, Germany) with a pendulum energy of 5 J was used ($n = 10$).

The microscopic images were taken with a Zeiss Smartzoom 5 digital microscope in coaxial bright field. Microsections were prepared with a polishing machine type Mecatech 250 SPC from Presi (Carl Zeiss AG, Oberkochen, Germany). Microsections were prepared from all investigated composite formulations and qualitatively examined for visible voids or air inclusions.

The fiber morphology and composite fracture surface analyses were conducted using a scanning electron microscope (SEM) (Tescan Mira 3, Brünn, Czech Republic). In this investigation, the electron acceleration voltage was set to 10 kV.

Utilizing differential scanning calorimetry (DSC) according to DIN EN ISO 11357-3, the injection-molded WPCs were examined with regard to their crystallization behavior, influenced by the differing fiber types ($n = 3$). The experimental tests were carried out from 25 °C to 200 °C with a heating/cooling rate of 10 K/min and under a nitrogen atmosphere with a flow rate of 60 mL/min using a DSC3+ from Mettler Toledo (Mettler Toledo International Inc., Columbus, USA). Both heating curves were analyzed and the degree of crystallinity χ of the PP phase was determined according to the following Equation (1) [29]:

$$\chi = \frac{\Delta H_f(\text{sample})}{\Delta H_c(\text{PP})} \cdot \frac{100}{w} \quad (1)$$

where ΔH_f is the enthalpy of fusion measured from DSC, ΔH_c is the theoretical enthalpy of fusion of 100% crystalline PP (207 J/g) and w is the weight fraction of PP in the particular sample [30].

The density was determined according to ISO 1183-1 using the immersion method and ethanol as immersion liquid ($n = 3$).

2.2.3. Statistical Evaluation

The normality of each group was assessed using the Shapiro–Wilk test, and the homogeneity of variances was verified using Levene’s test. If both assumptions were met, a one-way ANOVA was performed to detect differences between the groups, followed by a Tukey’s HSD post-hoc test for pairwise comparisons. When the variances were inhomogeneous and due to the small sample size, a non-parametric Kruskal–Wallis ANOVA with Dunn–Bonferroni correction was applied to compare the median values of the different groups. All statistical analyses were performed with a significance level of 5%. The results are presented as scatter plots, with each data point shown individually and the median (D50) indicated by a horizontal line. Unless explicitly stated otherwise, numerical values reported in the text refer to the median of the respective group; individual values, minima, and maxima are specified as such where discussed.

3. Results

3.1. Fiber Properties

3.1.1. Fiber Morphology

Macroscopic and microscopic fiber morphology revealed distinct differences between the investigated wood sources (Figure 1). Fresh spruce TMP fibers (a) appeared as comparatively long and coarse fiber bundles with an extended, strand-like morphology. Recovered wood (b) and beetle-infested spruce (c) showed slightly darker and more muted color tones compared with fresh spruce. In addition, these materials appeared somewhat finer and less dominated by coarse bundles, indicating a stronger degree of fiber separation during TMP refining. Fresh beech TMP fibers (d) exhibited a more compact and shorter fiber-bundle morphology, which is consistent with the generally shorter fiber elements and lower length-to-diameter ratios of beech wood cells compared with spruce tracheids.

The SEM micrographs further support these macroscopic observations. Fresh spruce fibers showed comparatively coarse fiber bundles, partly consisting of several associated tracheids. In contrast, the recovered wood and beetle-infested spruce fibers exhibited a higher degree of bundle separation, with smaller fiber bundles and a higher proportion of individual fiber elements. These observations indicate that lateral splitting and fibrillation occurred during TMP refining, leading to a reduction in effective fiber width. The beech TMP fibers also showed visible fiber bundles and cell-wall openings, but the observed structures appeared more compact and less elongated than the spruce-based fiber elements. This morphology is consistent with the lower aspect ratios later determined for the beech-based fiber fraction.

Visible lumina and cell-wall openings were observed in all investigated wood fiber fragments, although their frequency and appearance differed between the fiber types. The beetle-infested spruce fibers showed particularly pronounced cell-wall openings and fissures. These features may be related to biological pre-damage of the wood material [31] and subsequent mechanical opening during TMP refining. Similar morphology-related effects have been reported for treated lignocellulosic fibers, where the removal of non-cellulosic surface constituents promoted fiber bundle fibrillation, reduced fiber diameter, and thereby increased the aspect ratio [32]. Although the treatment route and fiber type

differ from the present TMP wood fibers, these findings support the general interpretation that fibrillation, bundle separation, and lateral splitting can reduce effective fiber width and contribute to higher aspect ratios.

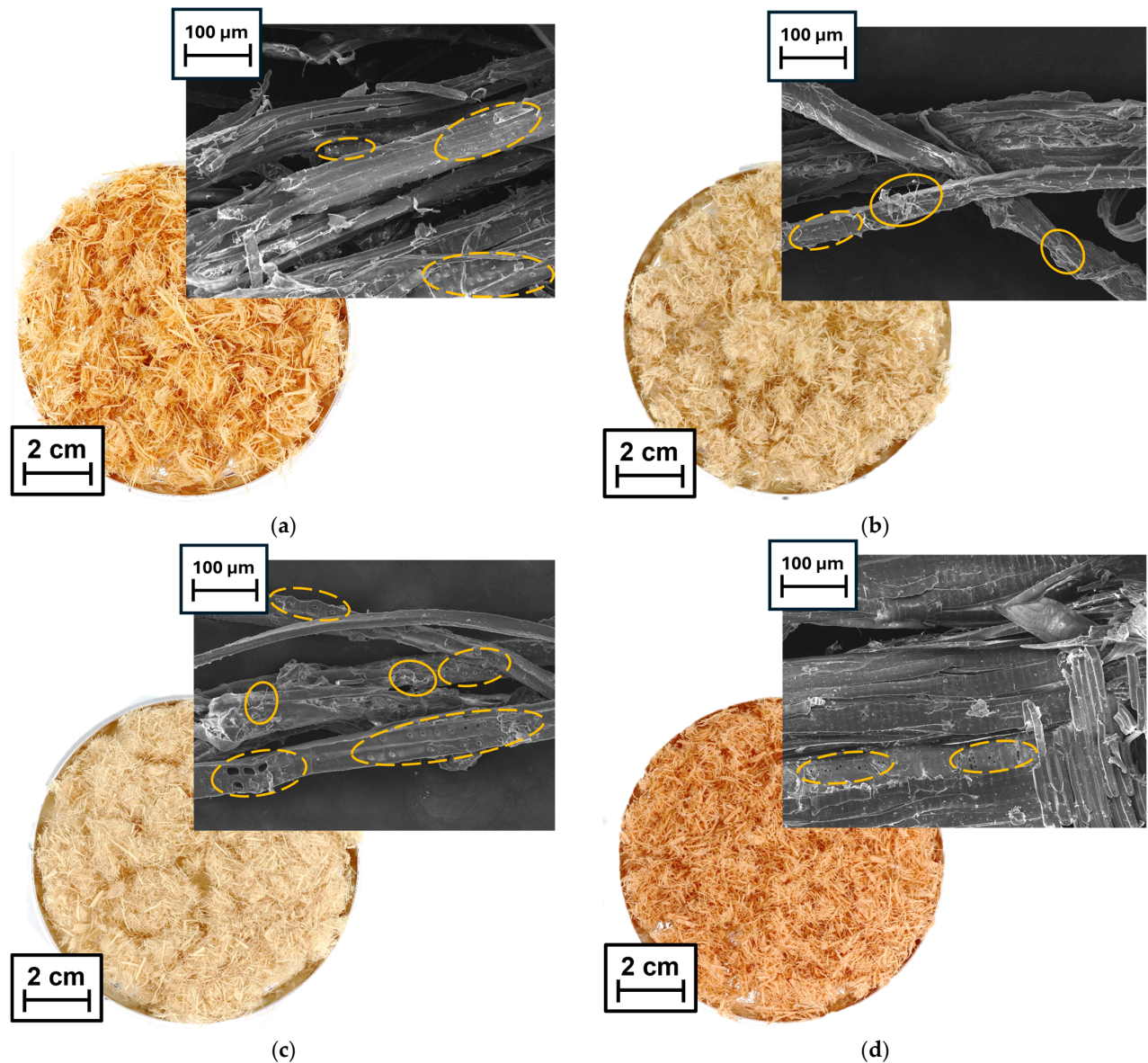


Figure 1. Macroscopic appearance and SEM micrographs of TMP fibers after thermomechanical pulping and before injection molding: (a) fresh spruce, (b) recovered wood, (c) beetle-infested spruce, and (d) fresh beech. Dashed orange ellipses indicate selected visible pits, damaged and undamaged (---), while solid orange ellipses indicate selected regions of fibrillation and lateral splitting (—).

3.1.2. Chemical Composition

ATR-FTIR spectroscopy was used to determine if any chemical changes occurred to the spruce wood fibers as a result of aging and to see if there are any significant chemical differences between spruce and beech wood. The spectra of fresh, recovered, and beetle-infested spruce wood are shown in Figure 2a. The three most prominent peaks are: a strong, broad O-H stretching absorption band between 3000 and 3700 cm^{-1} [33]; a C-H stretching absorption band between 2800 and 3000 cm^{-1} [11]; and a strong band at 1029 cm^{-1} indicating C-O stretching vibration in cellulose and hemicellulose, as well as C=O stretching vibration in cellulose, hemicellulose and lignin [34]. According to Pandey [35], an absorption band at 1029 cm^{-1} is also associated with both a C-H deformation in guaiacyl, as an aromatic component of lignin, and a C-O deformation in a primary alcohol.

While the peak positions are identical, differences are observed in the intensities. Fresh and recovered spruce show the highest level of absorption. Beetle attacks, especially the introduced fungi, induce degradation of the cellulose, hemicellulose, and lignin components [11,12]. In comparison with fresh spruce, the peak area of the CO stretching vibrations in cellulose, hemicellulose and lignin at 1029 cm^{-1} of beetle-infested spruce decreased by 29%. This change can be attributed to the degradation of the C-O group in beetle-infested spruce. The peak area of the O-H stretching (3000–3700 cm^{-1}) and C-H stretching (2800–3000 cm^{-1}) absorption bands of beetle-infested spruce decreased by 25% and 54%, respectively, compared to fresh spruce. This finding signifies quantitative changes in the composition of fresh and beetle-infested wood, consequent to the degradation of its cellulose, hemicellulose and lignin components. The degradation was also observed in the SEM analysis. As illustrated in Figure 1c, cracks are evident widening the pits of beetle-infested spruce wood fibers.

The chemical composition of spruce and beech wood is not identical, but similar (Figure 2b). The functional group region (1800 cm^{-1} to 4000 cm^{-1}) of their ATR-FTIR spectra shows two prominent peaks (at 2800–3000 cm^{-1} and 3000–3700 cm^{-1}) with almost equivalent intensities, whereas the fingerprint region (700 cm^{-1} to 1800 cm^{-1}) shows differences in the intensities of the absorption bands. The spectra of fresh spruce wood differ from those of fresh beech wood by less intense bands at 1729 cm^{-1} (xylans) and at 1234 cm^{-1} (syringyl rings) [36]. The stronger absorption band at 1506 cm^{-1} indicates aromatic skeletal vibrations in lignin, as well as C=C stretching of the aromatic ring in guaiacyl [34].

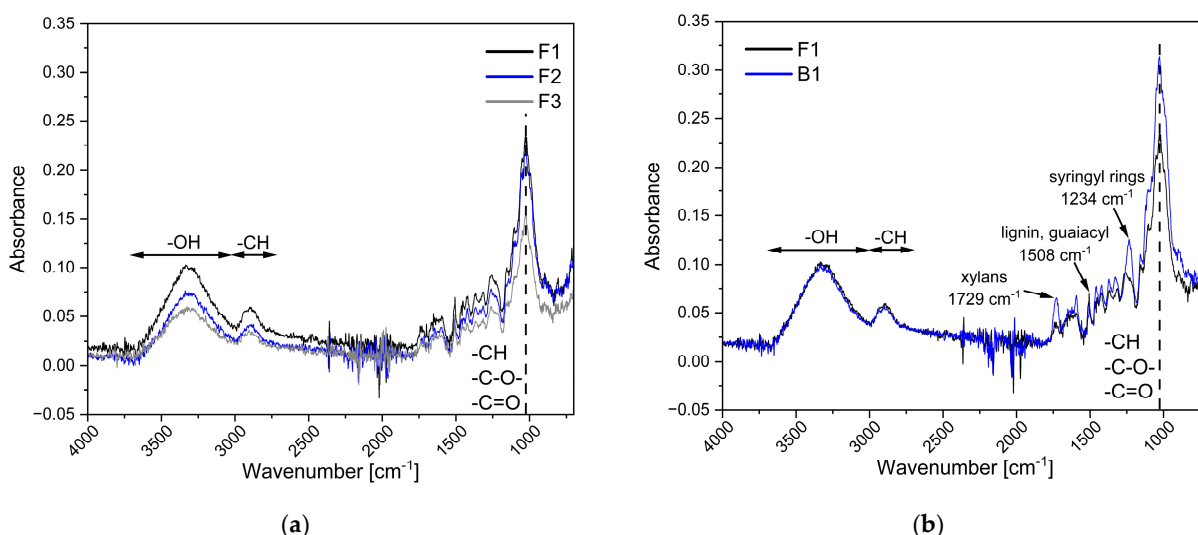
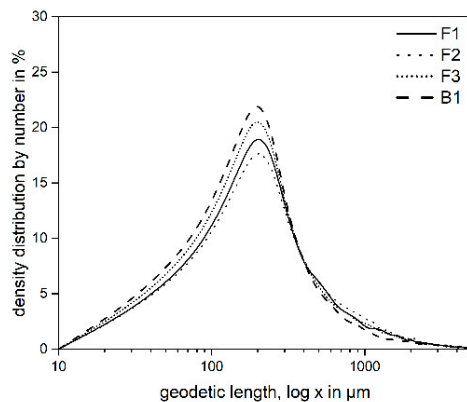


Figure 2. ATR-FTIR absorption spectra of (a) fresh spruce (F1), recovered spruce (F2) and beetle-infested spruce (F3) and (b) fresh spruce (F1) and fresh beech (B1).

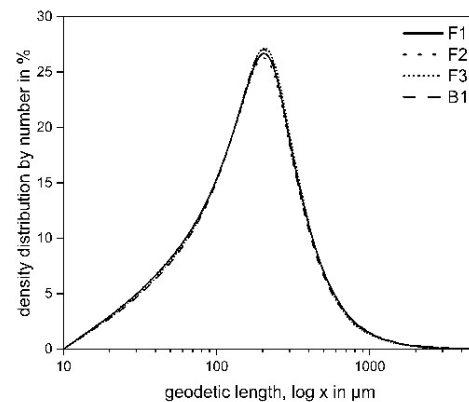
The FTIR spectra indicate qualitative differences between the investigated wood fiber types. These differences may be related to variations in the chemical composition of the wood species and raw material conditions. Literature reports that spruce and beech differ in their relative contents of cellulose, hemicellulose, lignin, and extractives, with spruce generally showing a higher lignin content than beech [37]. However, a detailed quantitative analysis of cellulose, hemicellulose, lignin, or extractive contents was not part of the present study. Therefore, the FTIR results are interpreted as qualitative indications of compositional differences rather than as a quantitative assessment of the chemical composition.

3.1.3. Fiber Geometry

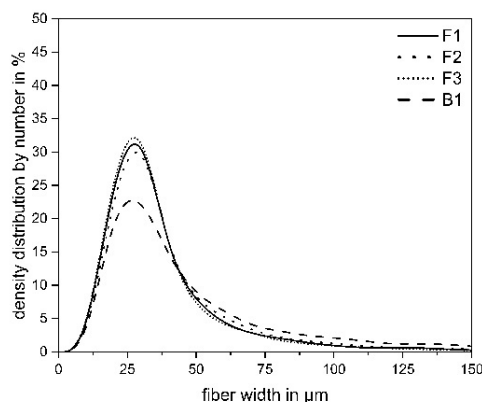
The fiber morphology was also analyzed using software before compounding (directly after TMP processing) and after injection molding to assess fiber attrition between the different fiber types. Figure 3 shows the distributions of fiber length (Figure 3a,b), fiber width (Figure 3c,d), and aspect ratio (L/D) (Figure 3e,f) for spruce (fresh, recovered, and beetle-infested) and beech (fresh).



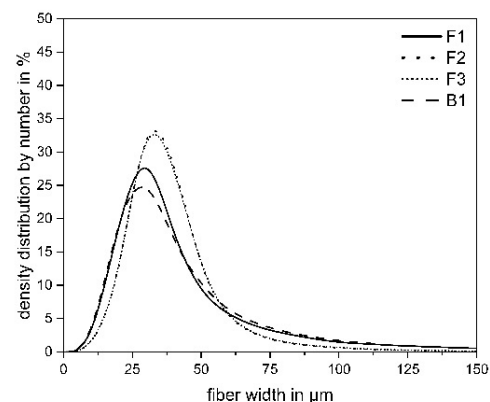
(a)



(b)



(c)



(d)

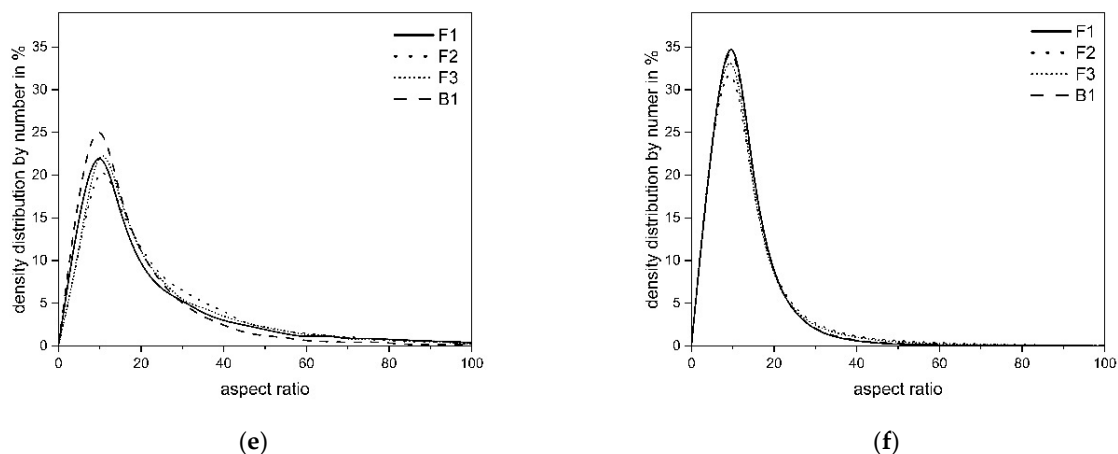


Figure 3. Number-weighted distributions of TMP fiber morphology after TMP-process (a,c,e) and after injection molding (b,d,f): Fiber length (a,b), fiber width (c,d) and aspect ratio (e,f); (F1: fresh spruce, F2: recovered spruce, F3: beetle-infested spruce, B1: fresh beech).

Before Processing (TMP State)

ANOVA with Tukey's HSD was performed on the number-weighted mean fiber length, confirming significant differences between almost all groups. Before processing, the fiber length distributions (Figure 3a) ranged mainly from 100 to 2000 μm , with a pronounced peak around 200 μm . Among the spruce-based variants, fresh spruce, recovered wood, and beetle-infested spruce showed largely overlapping length distributions. With respect to the central part of the distribution, recovered wood exhibited the highest D50 fiber length, whereas beech showed the lowest D50 value. In contrast, the D90 values revealed that beech still contained a small fraction of comparatively long fibers, indicating a broader upper tail of the fiber-length distribution. Thus, the differences between the wood fiber types were not reflected uniformly across the entire length distribution, but depended on the considered distribution range (Table 2). Statistical analyses showed that the fiber lengths of recovered wood and beetle-infested spruce were statistically indistinguishable ($p > 0.05$), while all other group comparisons were significant.

Fiber width distributions (Figure 3c) revealed only minor differences between spruce types. More pronounced differences were visible between spruce and beech: spruce fibers contained significantly more fine fractions and virtually little to no coarse fibers with diameters above 100 μm , which were still present in fresh spruce. In the TMP state, fresh and recovered spruce did not differ significantly in mean width ($p > 0.05$), while all other between-group comparisons were significant.

The shift toward finer fiber structures directly translated into higher aspect ratios (Figure 3e) for the spruce-based materials, particularly for recovered wood and beetle-infested spruce. These two materials remained statistically indistinguishable from each other ($p > 0.05$), but showed significantly higher aspect ratios than fresh spruce and beech. This indicates that the recovered and beetle-infested wood sources promoted a stronger separation of fiber bundles and finer fiber structures during TMP processing. These findings are consistent with the observations of Yadama et al. [11], who reported that recovered and insect-infested wood tends to yield finer particles due to additional mechanical degradation during processing. In comparison, beech TMP fibers showed the lowest aspect ratios in the central part of the distribution, which can be related to the intrinsically lower length-to-diameter ratios of beech wood cells compared with spruce tracheids reported by Blechschmidt [24].

After Injection Molding

After injection molding, all feedstocks showed a pronounced reduction in fiber length and fiber width compared to the TMP state, indicating that compounding and injection molding induced further fiber attrition and secondary thermomechanical defibrillation. To quantify this processing-induced fiber shortening, the D50 and D90 fiber lengths before and after injection molding were compared (Table 2). Based on the D50 values, the fiber length reduction ranged from 24% for beech to 43% for recovered wood. The upper part of the length distribution was affected even more strongly, with D90 reductions between 60% and 71%. Thus, fibers longer than 1 mm were largely shortened during processing, and the length distributions shifted toward a dominant range of approximately 200–300 μm (Figure 3b). After injection molding, no significant differences in fiber length were found between the investigated TMP fiber types.

The reduction in fiber width followed a different trend (Figure 3d). Recovered wood and beetle-infested spruce retained the lowest fiber widths after processing, whereas fresh spruce and beech showed broader width distributions and a higher proportion of larger fiber elements. Consequently, the differences in aspect ratio after injection molding were not primarily caused by longer median fiber lengths, but rather by differences in fiber width, bundle separation, and fibrillation. This resulted in higher aspect ratios for recovered wood and beetle-infested spruce compared to fresh spruce and beech, particularly in the upper part of the aspect-ratio distribution (Figure 3f, Table 3). These findings indicate that degradation-related splitting enhances the fineness of the fiber population in F2 and F3, which translates into improved reinforcement potential (high L/D) even after thermoplastic processing.

For fresh spruce, the comparison between F1_0 and F1 indicated that the measured fiber geometry, specifically the aspect ratio, was not significantly affected by the presence of the coupling agent; however, this assessment was limited to this material pair. Nevertheless, the coupled fresh spruce composite showed a tendency toward longer residual fibers after processing, indicating that the CA may influence processing-induced fiber attrition in TMP-reinforced WPCs. This observation contrasts with reports on glass-fiber-reinforced thermoplastics, where improved coupling was associated with reduced weight-average residual fiber length [38]. However, the damage mechanisms of brittle, homogeneous glass fibers cannot be directly transferred to heterogeneous TMP wood fibers. Since this effect was evaluated only for fresh spruce, it remains unclear whether the observed tendency represents a singularity or a systematic effect of compatibilization. Future work should therefore systematically investigate coupled and uncoupled variants of all TMP fiber types.

Consequently, the first hypothesis is supported with respect to the formation of finer fiber structures and higher aspect ratios in recovered wood and beetle-infested spruce. This effect was evident directly after the TMP process and remained observable after injection molding, indicating that the altered fiber morphology persisted throughout subsequent processing steps. Regarding the third hypothesis, significant differences in fiber geometry were observed between beech and conventional spruce.

Table 2. Quantification of fiber length reduction from the TMP state to the injection-molded state based on D50 and D90 values.

ID	Wood Species	Type	After TMP- Process	After Injec- tion Mold- ing	Length Re- duction of D50	After TMP- Process	After Injec- tion Mold- ing	Length Re- duction of D90
			D50 [μm]	D50 [μm]	[%]	D90 [μm]	D90 [μm]	[%]
F1	Spruce	Fresh wood	390	315	20	2750	1125	59
F1_0	Spruce	Fresh wood	390	235	40	2750	870	68
F2_0	Spruce	Recovered wood	420	240	43	2350	950	60
F3_0	Spruce	Beetle-infested wood	340	230	32	2230	870	61
B1_0	Beech	Fresh wood	310	235	24	3290	965	71

Table 3. Aspect ratios and origin of utilized wood fibers after TMP process and after injection molding process (D10/D50/D90).

ID	Wood Species	Type	After TMP-Process			After Injection Molding		
			D10 [-]	D50 [-]	D90 [-]	D10 [-]	D50 [-]	D90 [-]
F1	Spruce	Fresh wood	4.2	12.6	56.5	3.6	7.1	16.2
F1_0	Spruce	Fresh wood	4.2	12.6	56.5	3.7	7.6	18.3
F2_0	Spruce	Recovered wood	4.8	15.0	50.4	3.7	7.9	23.4
F3_0	Spruce	Beetle-infested wood	4.9	13.6	50.2	3.7	7.6	21.4
B1_0	Beech	Fresh wood	4.0	10.7	34.1	3.7	7.6	18.7

3.2. WPC Properties

3.2.1. Tensile Properties

The tensile modulus of neat PP was measured as 1.4 GPa, whereas all WPC systems reached values between 3.4 and 4.7 GPa depending on the wood source, see Figure 4a. This increase is explained by the load transfer from the ductile matrix to the stiffer TMP fibers. In fiber-reinforced composites, stiffness is governed by the fiber volume fraction, the fiber aspect ratio, and the efficiency of stress transfer across the fiber–matrix interface. The rough and fibrillated morphology of TMP fibers promotes mechanical interlocking and form-fit adhesion, resulting in effective stress transfer. Statistical analyses (one-way ANOVA, Tukey HSD) confirmed significant differences between neat PP and the wood-filled compounds. The addition of the CA resulted in significantly higher modulus values for recovered and beetle-infested spruce (+10%), which was also shown for wood flour [39,40]. Within spruce, recovered wood yielded a significantly higher modulus compared to both fresh and beetle-infested spruce. Beech-based WPCs exhibited significantly lower stiffness than recovered and beetle-infested spruce, but did not differ from fresh spruce—as also shown by Rafighia et al. in the investigation of sawdust [41]. This outcome is of interest, as it demonstrates that, despite the fact that raw beech wood possesses a higher intrinsic modulus of elasticity (14 GPa) than spruce (11 GPa) [10], the composite stiffness is determined primarily by interfacial load transfer and fiber morphology rather than the bulk properties of the source wood. Furthermore, the tensile modulus of beetle-infested spruce TMP-fibers exceeds the values from literature using wood flour at a higher concentration level (58 wt.-% vs. 30 wt.-%) [11].

For tensile strength, neat PP exhibited around 33 MPa. Without the CA, all WPC systems remained at this level, which does not indicate a fiber-reinforcing effect.

In contrast, with the CA, the tensile strength increased significantly, reaching values up to 46–54 MPa depending on the wood source, see Figure 4b. This pronounced increase

in tensile strength is consistent with the SEM observations of selected fracture surfaces shown in Figure 5. As a representative example, the recovered wood composite was compared with and without coupling agent. In the uncoupled composite, numerous fiber pull-outs were observed, particularly pull-outs of individual fibers. This indicates that the TMP fibers were present as finely separated fiber elements, but that interfacial stress transfer between the fibers and the PP matrix was limited in the absence of the CA. In contrast, the coupled composite showed fewer clearly detached fibers, more frequent fiber breakage, and more pronounced matrix coverage of the fibers. These fracture-surface features qualitatively support the interpretation that the CA improved fiber–matrix interaction and interfacial stress transfer. Since the SEM comparison was performed on selected recovered wood specimens, the observations are not interpreted as a quantitative proof for all formulations. However, the systematic increase in tensile strength for all coupled WPC systems suggests that the same general coupling-related mechanism contributed to the improved mechanical performance across the investigated wood fiber types. Tukey HSD post-hoc comparisons confirmed that recovered spruce achieved the highest strength next to beetle-infested spruce, significantly higher than fresh and beetle-infested spruce. These results confirm the state of the art about similar tensile properties [11,15–17] and even exceed the values of fresh spruce wood fibers. The achieved mechanics of beech provided reinforcement at the same level as fresh-cut spruce, despite its higher intrinsic wood strength (135 MPa vs. 95 MPa [10]) as already mentioned for the tensile modulus, also validated by Rafighia et al. [41].

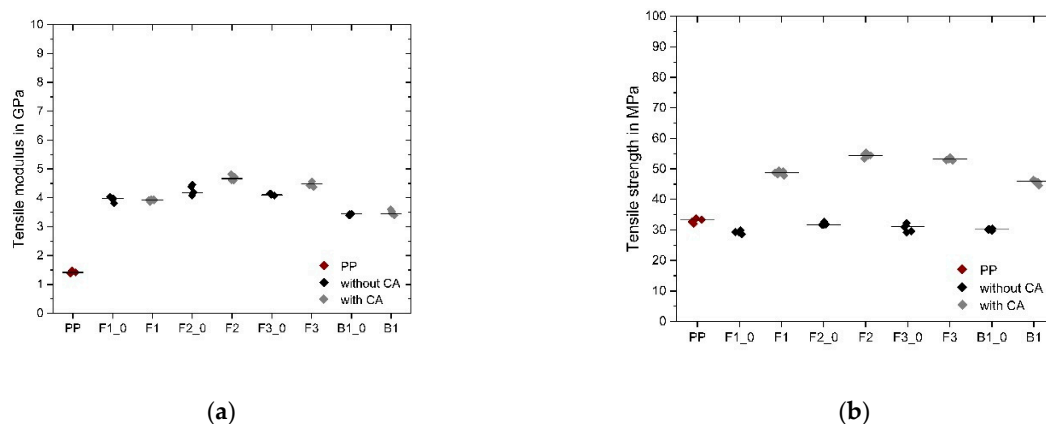


Figure 4. (a) tensile modulus and (b) tensile strength of neat PP and WPC compounds containing 30 wt.-% TMP fibers from spruce (F1: fresh, F2: recovered, F3: beetle-infested) and fresh beech (B1), without (X₀) and with CA (X). The horizontal line represents the median value.

Although the higher aspect ratios of the recovered wood and beetle-infested spruce fibers are consistent with their improved tensile reinforcement, the mechanical behavior cannot be attributed to fiber length or aspect ratio alone. After injection molding, the fiber length distributions of the different TMP fiber types largely converged. Therefore, the remaining differences in aspect ratio were mainly related to differences in fiber width, lateral splitting, fibrillation, and bundle separation rather than to longer fibers alone. The processing-induced lateral splitting and fibrillation may increase the accessible fiber surface area and provide a morphological potential for improved mechanical interlocking and stress transfer with the PP matrix. However, this potential does not appear to be fully effective in the non-compatible systems, as the uncoupled WPC formulations did not show a pronounced and systematic increase in tensile strength despite differences in fiber

morphology. At the same time, the strong increase in tensile strength after addition of the coupling agent demonstrates that interfacial stress transfer is a decisive factor.

The selected processing temperatures of 180–190 °C were below the temperature range in which relevant thermal degradation of recovered wood has been reported to start. Baris et al. showed in thermogravimetric investigations of recovered wood that pronounced decomposition begins only at substantially higher temperatures, close to or slightly below 250 °C. Therefore, differences in thermal stability are not expected to be the primary factor governing the mechanical differences observed under the processing conditions used in this work [42]. Thus, the differences between the wood fiber types are interpreted as the combined result of fiber geometry, fibrillation and the resulting accessible surface area, together with sufficient fiber–matrix interaction provided by the coupling agent, and possibly local fiber orientation and dispersion effects.

Microsections were prepared from all investigated composite formulations and allowed a qualitative assessment of local fiber arrangement, bundle structure, and fiber orientation in the examined sections, see Figure 6. Since all compounds were processed using the same injection mold and identical injection-molding parameters, orientation-related differences were minimized as far as possible. Nevertheless, local differences in fiber orientation cannot be excluded, particularly because the investigated wood fiber types differed in fiber geometry, fibrillation, and bundle structure. The differences in fiber size can also be seen in the microsection visualized in Figure 6. As illustrated in Figure 6a, the fibers and bundles in the cross-section of the WPC component with fresh spruce wood fibers are significantly coarser than those depicted in Figure 6b—recovered spruce wood. These aspects are further reflected in the impact behavior, where the coupled systems showed higher breaking forces but also increased scatter, indicating a stronger sensitivity to local microstructural heterogeneities.

This indicates that despite differences in intrinsic strength due to wood type (beech vs. spruce) and history (fresh vs. recovered vs. beetle-infested), factors such as fiber aspect ratio and interfacial compatibility dominate composite performance. The tensile strength achieved with recovered spruce TMP-fibers exceeds the values from a previous study using TMP-fibers, as summarized by Mertens et al. [20].

Overall, the results demonstrate that tensile stiffness and strength in WPCs are significantly enhanced compared to neat PP. The CA is essential for improving tensile strength and also contributes to increased stiffness. Among the investigated feedstocks, recovered spruce shows the highest reinforcement potential, whereas beetle infestation does not negatively affect mechanical performance. These results confirm earlier reports on wood flour as filler by Krause [17], Chang and Lam [15,16], and Yadama [11], showing that beetle-infested and recovered wood do not impair WPC performance. Moreover, the use of TMP fibers leads to a further enhancement of the mechanical properties due to their favorable fiber morphology, including high aspect ratio, fibrillation, and increased accessible fiber surface area, provided that sufficient fiber–matrix interaction is achieved.

With regard to the tensile properties, hypothesis 2 can therefore be confirmed: a higher aspect ratio results in significantly improved fiber reinforcement, even in the case of recovered wood fibers. Hypothesis 3, however, must be rejected with respect to tensile properties, as a significant difference can be observed between climate-resilient beech and conventional spruce. From a technical perspective, beech can be considered a viable alternative feedstock; however, its composites do not achieve the same performance as spruce-based composites, despite the higher intrinsic mechanical properties of beech wood.

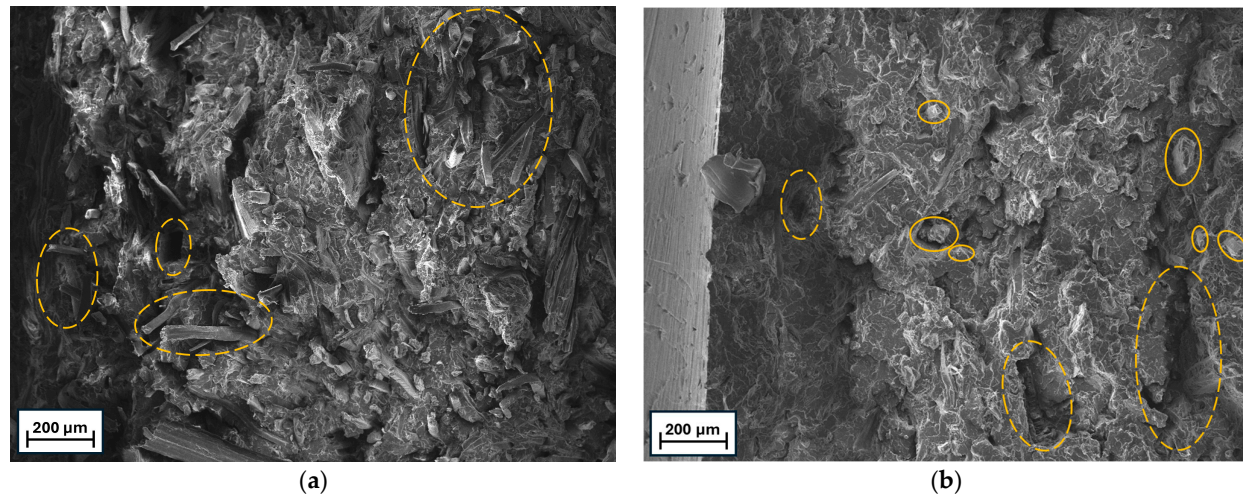


Figure 5. SEM micrographs of fracture surfaces of notched Charpy impact specimens based on recovered wood TMP fibers: (a) without CA and (b) with CA. Selected examples of fiber breakage are marked by solid orange ellipses (—), whereas selected fiber pull-outs are indicated by dashed orange ellipses (---). The marked features are intended as qualitative examples of the observed fracture morphology.

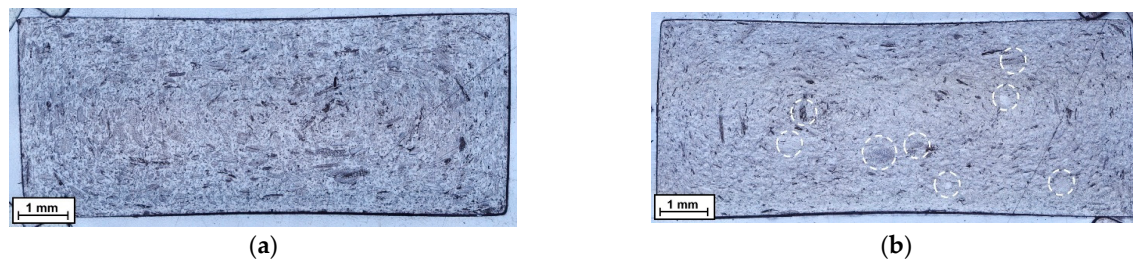


Figure 6. Reflected light microscopy of the microsection of (a) fresh wood–spruce and (b) recovered wood–spruce; the micrographs reveal pronounced fiber bundling in sample (a), whereas sample (b) shows reduced fiber bundling with only a few visible fiber bundles, highlighted by dashed circles.

3.2.2. Flexural Properties

Flexural modulus of neat PP was measured at 1.3 GPa, while all WPC systems ranged between 3.2 and 4.0 GPa, see Figure 7a. Similar to tensile modulus, this enhancement results from efficient stress transfer from the ductile matrix to the stiffer fiber network under bending loads. ANOVA and Tukey HSD confirmed significantly higher values for all wood-filled systems compared to neat PP. Within the WPCs, the only significant differences were detected between fresh and recovered spruce as well as between fresh spruce and fresh beech, irrespective of condition or CA. Beech showed slightly lower values (~3.2 GPa) compared to spruce (~3.8 GPa), consistent with the tensile modulus results, but differences were minor. Overall, stiffness in bending was maintained across all feedstocks, indicating that ageing and beetle infestation did not reduce reinforcement efficiency.

Figure 7b shows the flexural strength measured for all test specimens. Neat PP was measured as 36 MPa. In the absence of the CA, all WPC systems remained close to this level (51–55 MPa), whereas with the CA, strength increased substantially to 77–81 MPa for spruce and 72 MPa for beech. This pronounced increase indicates that the CA improved interfacial stress transfer, enabling more effective load transfer from the PP matrix to the TMP fiber network. This interpretation is supported qualitatively by the SEM fracture-surface observations of recovered pallet wood specimens shown in Figure 5. The systematic increase in flexural strength for all coupled WPC systems indicates that this

coupling-related improvement in interfacial stress transfer was relevant across the investigated fiber types. The improved interfacial stress transfer is also reflected in the higher elongation at break, with values $\geq 3.4\%$ with CA and $\leq 2.9\%$ without CA. Statistical analyses confirmed these differences as highly significant. Within spruce, recovered and beetle-infested wood yielded slightly higher values than fresh wood, while no significant deterioration was observed between ageing or infestation. Beech-based WPCs with CA exhibited somewhat lower flexural strength than spruce, despite the higher intrinsic strength of beech wood (120 MPa vs. 80 MPa [10]). The findings of this study are consistent with the results of the tensile tests and the fiber geometry analyses, as the F2 and F3 samples exhibited the highest aspect ratios in the composite.

In summary, the results indicate that WPCs containing the CA exhibit significantly improved flexural properties compared to neat PP. Furthermore, recovered and beetle-infested spruce performed at least comparably to fresh spruce, supporting the assumption that aging processes promote finer fiber structures during thermo-mechanical pulping and thereby increase the fiber aspect ratio (hypothesis 1). In contrast, the hypothesis 3 that TMP fibers derived from climate-resilient beech and conventional spruce provide equivalent mechanical performance was rejected, as beech showed slightly lower reinforcement efficiency in bending despite representing a viable alternative feedstock for technical WPC applications.

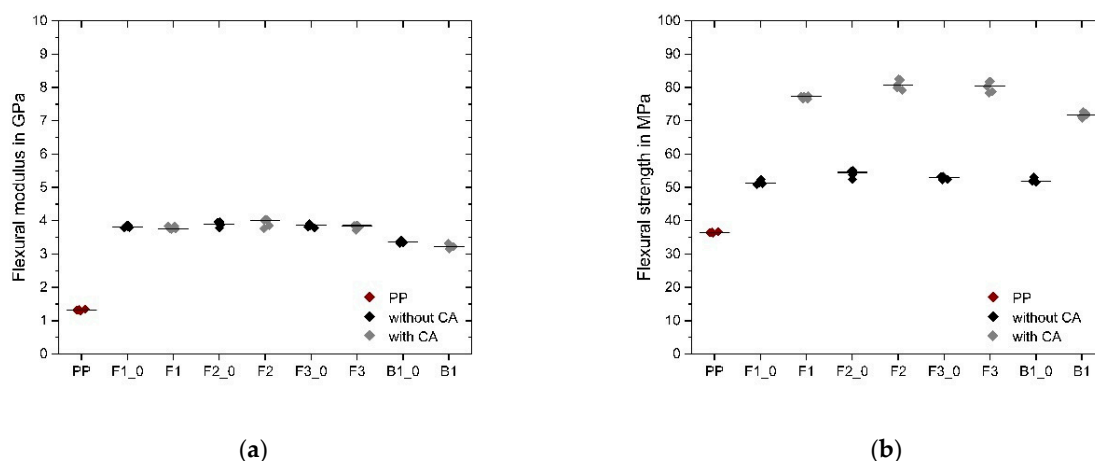


Figure 7. (a) flexural modulus and (b) flexural strength of virgin PP and WPC compounds containing 30 wt.-% TMP fibers from spruce (F1: fresh, F2: recovered, F3: beetle-infested) and fresh beech (B1), without (X_0) and with CA (X). The horizontal line represents the median value.

3.2.3. Impact Properties

Figure 8a displays the breaking force measured for the entire set of test specimens. The breaking force of neat PP was measured at 187 N. With CA, all WPCs showed significantly higher values between 250 and 264 N, while without CA, the breaking force remained close to the neat PP level. The presence of the CA, which strengthens fiber–matrix adhesion, improves stiffness and therefore increases the force required to initiate the break. It can also be seen that the breaking forces achieved scatter more in samples with CA. Statistical analyses showed no differences between the different wood types. Among the spruce and beech variants, no clear trend was observed between fresh, recovered, and beetle-infested wood, as the values overlapped within experimental scatter. Beech-based WPCs in general exhibited breaking forces comparable to spruce, demonstrating that beech represents an alternative feedstock without mechanical disadvantages in this property.

The notched impact strength of neat PP showed a median value of 3.52 kJ/m² (see Figure 8b). The median impact strengths of the WPC systems were generally lower, independent of wood source, reflecting the reduced plastic deformation capacity of the PP matrix after incorporation of the lignocellulosic phase. The uncoupled compounds exhibited rather uniform median impact strengths between approximately 2.26 and 2.36 kJ/m². In contrast, the addition of CA increased the median impact strength of the wood-based compounds and led to a broader scatter of the measured values. Importantly, the scatter plot shows that individual specimens of the coupled F2 and F3 compounds reached or exceeded the impact strength of neat PP, with maximum values up to 3.74 kJ/m², while the highest individual value of 4.10 kJ/m² was observed for B1. This indicates that effective fiber–matrix adhesion can locally enhance energy absorption beyond that of neat PP; however, this effect was not uniformly achieved across all specimens. Statistically, no significant differences were found among the coupled spruce-based compounds F1, F2, and F3, despite their different raw material states. Comparable findings have been reported for WPCs based on wood flour with different particle sizes, where no significant differences in impact strength were observed [27,43]. The reduction in impact strength compared with neat PP is consistent with the established behavior of short-fiber-reinforced thermoplastics, where the lignocellulosic phase restricts plastic deformation of the matrix and promotes earlier crack initiation under dynamic loading, as previously shown for TMP spruce fibers [28]. At the same time, the CA improves stress transfer across the fiber–matrix interface and therefore increases the force required to initiate and propagate fracture. This is also supported by the higher breaking force and the increased deflection at fracture (+40%), defined here as the specimen deflection recorded during the instrumented Charpy impact test until fracture occurred, which is consistent with the higher elongation at break observed in tensile and flexural testing. These results align with the investigations of Obermeier et al. on fresh spruce TMP fibers [28]. However, the coupled compounds also exhibited markedly different scatter behavior. While the uncoupled variants showed comparatively narrow distributions, the coupled formulations F2, F3, and B1 revealed substantially higher standard deviations. This indicates that interfacial strengthening by the CA does not necessarily result in a uniform fracture process. Rather, the improved adhesion appears to shift the failure behavior towards a stronger sensitivity to local structural inhomogeneities. Consequently, variations in both breaking force and deflection distance contribute to the increased scatter in impact strength.

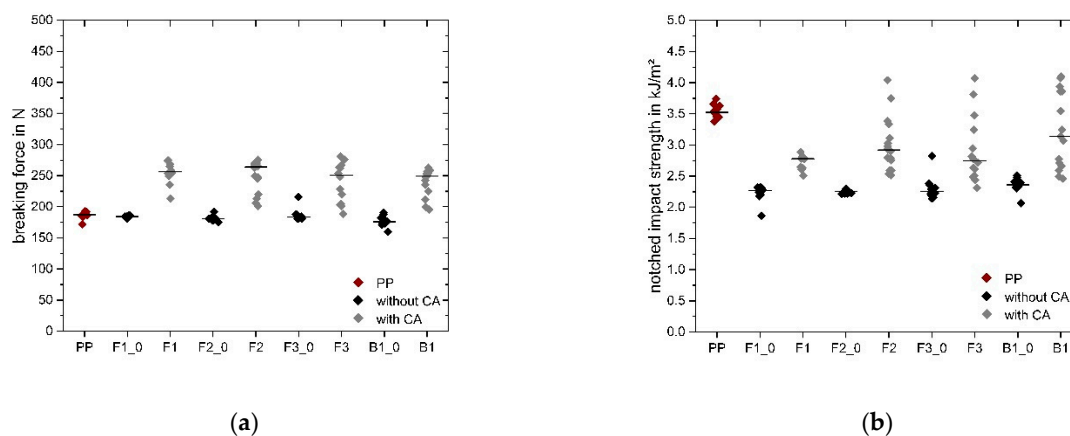


Figure 8. (a) breaking force and (b) and impact strength (right) of virgin PP and WPC compounds containing 30 wt.-% TMP fibers from spruce (F1: fresh, F2: recovered, F3: beetle-infested) and fresh beech (B1), without (X₀) and with CA (X). The horizontal line represents the median value.

A closer inspection of the mechanical response suggests that several coupled specimens reached a comparable force level, whereas the subsequent crack propagation and energy dissipation differed considerably. This interpretation is consistent with the fracture surface observations, which did not reveal a uniform failure mode. This is exemplified by the SEM fracture-surface observations shown in Figure 9a,b, which compare two notched Charpy impact specimens from the same coupled recovered wood TMP composite formulation (F2). The SEM fracture-surface observations of two selected F2 specimens further support this interpretation qualitatively. The specimen with the lower notched impact strength showed a fracture morphology with more pronounced fiber bundle pull-out and locally detached fiber structures, indicating that crack propagation was more strongly governed by debonding and pull-out processes, see Figure 9a. In contrast, the specimen with the higher notched impact strength exhibited a more compact fracture morphology, with less evident pull-out and more pronounced matrix-covered fiber regions, see Figure 9b. These features suggest that local differences in fiber embedding, bundle separation, and fiber–matrix interaction affected the energy dissipation during impact loading. However, the SEM observations are interpreted as selected qualitative examples and do not represent a quantitative correlation between fracture morphology and impact strength. In addition, the minimum deflection distance of the coupled specimens was comparable to that of the uncoupled materials, whereas the maximum deflection distance was substantially higher. These findings indicate that the coupled systems are more sensitive to local microstructural heterogeneities, which affect crack propagation after peak load has been reached.

By contrast, the uncoupled compounds exhibit consistently lower but more reproducible impact strengths, which is in line with a generally weak and comparatively uniform fiber–matrix adhesion. The CA therefore improves the average impact performance, but at the same time increases the sensitivity of fracture to local structural variations.

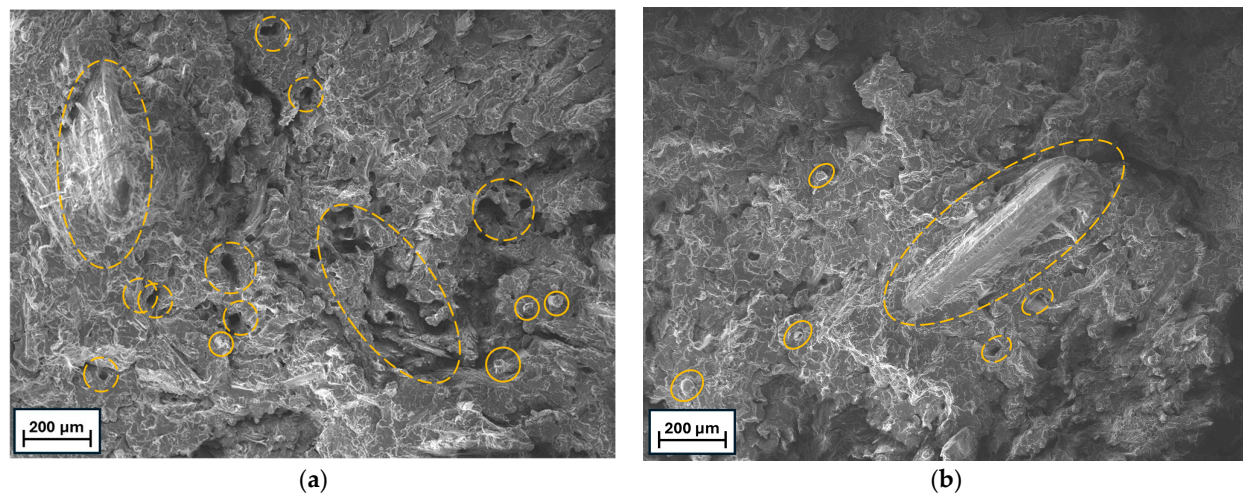


Figure 9. SEM micrographs of fracture surfaces of two notched Charpy impact specimens from the same coupled recovered pallet wood TMP composite formulation (F2): (a) specimen 6 with a notched impact strength of 2.59 kJ/m² and (b) specimen 8 with a notched impact strength of 4.04 kJ/m². Solid orange ellipses indicate selected fiber breakages, whereas dashed orange ellipses indicate selected fiber pull-outs. The selected fracture surfaces illustrate local differences in fiber bundle pull-out, fiber embedding, matrix coverage, and fracture morphology and are used as qualitative examples to support the discussion of the observed scatter in impact behavior.

Furthermore, differences in density, see Figure A1, and crystallinity, see Figure A2, are unlikely to account for the observed variations in breaking force and impact strength.

The median densities of all WPC compounds ranged from 1.007 g/cm³ to 1.011 g/cm³, whereas neat PP showed a lower density of 0.912 g/cm³, consistent with the incorporation of 30 wt.% wood fibers. No consistent and significant density differences were found among the WPC variants, irrespective of wood source or the presence of CA. These findings align with the literature [14,17]. This interpretation is supported by the highly consistent part weights, which varied by less than 0.5% across all WPC formulations, indicating stable processing conditions and good reproducibility during injection molding. In addition, the qualitative examination of the microsections showed no visible voids or air inclusions. However, this qualitative assessment does not represent a complete three-dimensional void characterization of the entire specimen volume. A similarly uniform picture was obtained for the degree of crystallinity. In the first heating run, median crystallinity values ranged from approximately 39 to 46%, while in the second heating run they ranged from approximately 45 to 51%. No systematic differences were observed between coupled and uncoupled compounds, nor between the different wood sources and wood conditions. Moreover, all crystallinity values measured for the WPC compounds remained within the scatter band obtained from ten repeated measurements on a single specimen. Accordingly, differences in density or in the ratio of crystalline to amorphous phases cannot explain the observed mechanical differences.

A similarly uniform picture was obtained for the degree of crystallinity of the PP phase. In general, the crystallinity of polypropylene can influence the mechanical behavior of PP-based composites, since a higher crystalline fraction may contribute to stiffness and strength, while also affecting deformation and impact behavior. In the present study, however, the measured crystallinity values did not show a systematic trend corresponding to the observed differences in tensile, flexural, or impact properties. In the first heating run, median crystallinity values ranged from approximately 39 to 46%, while in the second heating run they ranged from approximately 45 to 51%. No consistent differences were observed between coupled and uncoupled compounds, nor between the different wood sources and wood conditions. Moreover, all crystallinity values measured for the WPC compounds remained within the scatter band obtained from ten repeated measurements on a single specimen. Accordingly, differences in density or in the ratio of crystalline to amorphous PP phases are not considered the primary factors governing the observed mechanical differences. Instead, the results indicate that fiber morphology, fibrillation, fiber–matrix interaction, and local structural heterogeneity play a more dominant role under the applied processing conditions.

A possible explanation for the increased scatter observed in B1, F2, and F3 is a stronger process-induced modification of fiber geometry, compared with F1, best seen in the area equivalent diameter of the measured particles. The distribution of F1 exhibited near-identical characteristics, in contrast to those observed in the distributions of the remaining wood types and qualities, which demonstrated pronounced divergence in the regions of higher diameters, see Figure 10a vs. Figure 10b–d. Besides fiber shortening, lateral splitting or fibrillation occurs, which increases the accessible fiber surface area. In such a case, the effective ratio between CA and available fiber surface may change locally, and the time available during processing may not be sufficient to establish a uniformly developed interphase on all newly generated surfaces. This might contribute to local variations in fiber–matrix adhesion and thus to the more heterogeneous impact response of these compounds. A similar relationship between fiber fibrillation, loose fiber ends, fracture morphology, and crack propagation was reported by Yadav et al. for treated bagasse-fiber composites. Although the fiber type and matrix differ from the present PP-based TMP-WPCs, these findings support the general interpretation that highly fibrillated lignocellulosic fiber structures can increase the sensitivity of impact fracture to local morphology [32].

On the level of feedstock comparison, the generally similar breaking force and impact strength values obtained for spruce- and beech-based compounds indicate that intrinsic wood-species-related differences are not the dominant factor governing these properties. Although measurable differences in fiber geometry were observed between the investigated feedstocks, these did not translate into correspondingly distinct values of breaking force or impact strength. This suggests that the overall mechanical response is controlled by a combination of interfacial adhesion, fiber geometry, fiber orientation, and local structural inhomogeneities rather than by wood species alone.

With respect to impact strength, hypothesis 2 is rejected, as no statistically significant differences were found among the coupled spruce-based compounds F1, F2, and F3, despite their different raw material states. Hypothesis 3, on the other hand, can be accepted, as no significant differences in impact strength were observed between beech- and conventionally spruce-based WPCs. Nevertheless, recovered spruce, beetle-infested spruce, and fresh beech-based WPCs generally reached a property level comparable to that of fresh spruce, indicating that these raw materials are suitable for WPC production. Furthermore, the measured impact strength exceeds the values reported for comparable WPCs manufactured with wood flour instead of fibers [44,45].

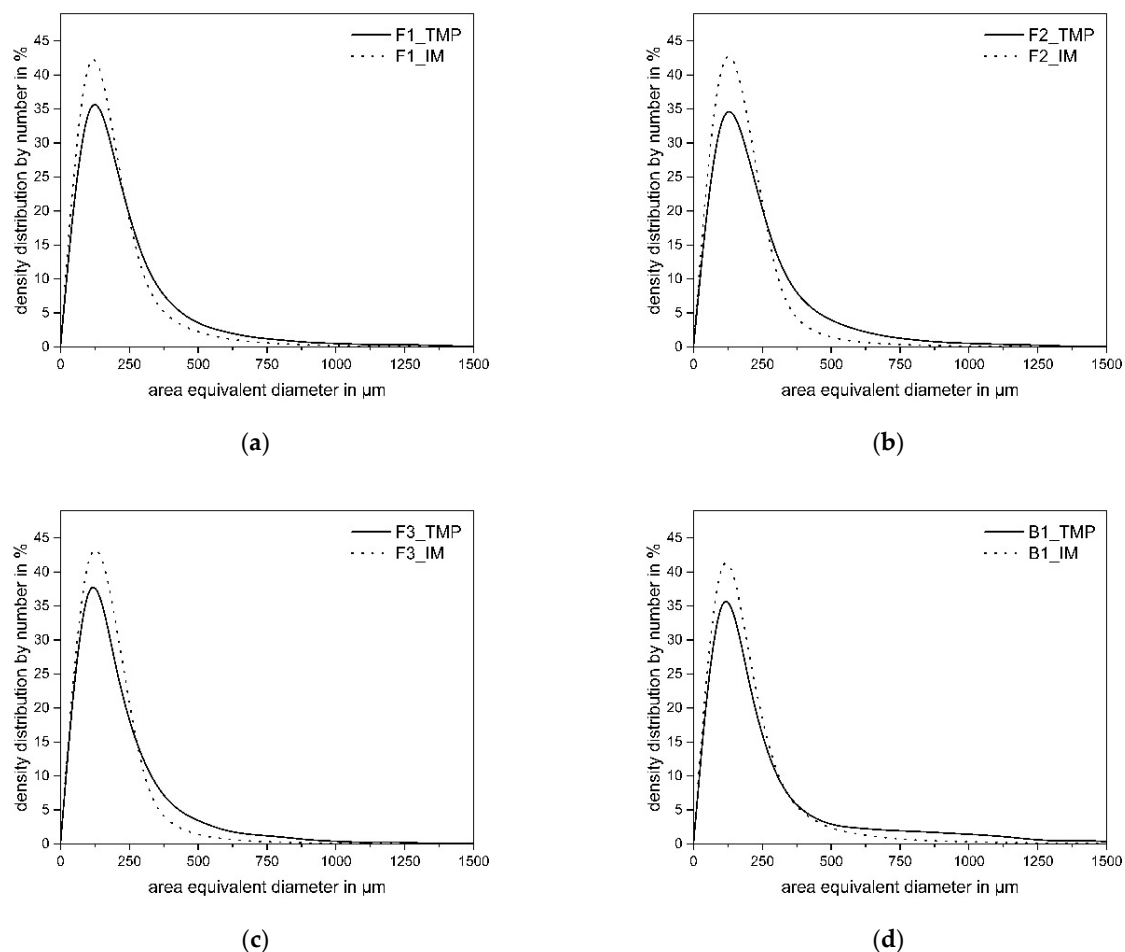


Figure 10. Number-weighted distributions of area-equivalent diameter of TMP fiber morphology after TMP process (X_TMP) and after injection molding without CA (X_IM); (a) F1: spruce–fresh wood; (b) F2: spruce–recovered wood; (c) F3: spruce–beetle-infested and (d) B1: beech–fresh wood.

This study demonstrated that TMP fibers from fresh, recovered, and beetle-infested spruce as well as from fresh beech wood can be successfully processed into WPCs, reaching mechanical performance levels comparable to each other. Table 4 summarizes the key mechanical properties of all investigated WPC compounds and highlights the overall performance differences between spruce- and beech-based systems. The results should be interpreted within the boundaries of the present experimental design, which was based on PP-based WPCs containing 30 wt.% TMP fibers processed under constant conditions. This approach allowed the influence of raw material source and resulting TMP fiber morphology to be isolated. The transferability of the observed morphology–property relationships to other fiber contents or processing conditions should be investigated in future studies.

Table 4. Overview of the key mechanical properties of the investigated WPC compounds with CA and the neat PP reference.

Property *	Poly-Propylene PP	Spruce			Beech
		Fresh F1	Recovered F2	Beetle-Infested F3	Fresh B1
Tensile modulus [GPa]	1.42 ^a	3.92 ^b	4.67 ^c	4.48 ^d	3.46 ^e
Tensile strength [MPa]	33.3 ^a	48.8 ^b	54.4 ^c	53.2 ^c	46.1 ^{bd}
T-Elongation at break [%]	7.6 ^a	3.24 ^b	3.38 ^{bc}	3.46 ^{bc}	3.40 ^c
Flexural modulus [GPa]	1.32 ^a	3.76 ^b	4.00 ^b	3.85 ^b	3.22 ^c
Flexural strength [MPa]	36.5 ^a	77.4 ^b	80.7 ^c	80.4 ^c	71.8 ^d
F-Elongation at break [%]	n.b.	3.45 ^a	3.64 ^b	3.82 ^c	4.16 ^d
Notched impact strength [kJ/m ²]	3.52 ^a	2.78 ^{ab}	2.92 ^{ac}	2.74 ^{acd}	3.14 ^{acd}
Max. Force during impact [N]	187.3 ^a	256.9 ^b	264.0 ^b	251.3 ^b	249.6 ^b
Density [kg/m ³]	0.911 ^a	1.008 ^b	1.007 ^b	1.008 ^b	1.011 ^b

* Values are reported as D50 values. Different superscripted letters within one column indicate significant differences between groups at $p < 0.05$. Statistical comparisons were performed using non-parametric tests.

4. Conclusions

This study demonstrated that TMP fibers from fresh, recovered, and beetle-infested spruce as well as from fresh beech wood can be successfully processed into WPCs, reaching mechanical performance levels comparable to each other, see Table 4. Within the scope of this work, three hypotheses were evaluated, which are summarized below.

In terms of fiber properties and hypothesis 1 (Section 3.1), IR spectroscopy indicated chemical differences associated with the investigated wood raw materials. The different spruce fibers showed broadly comparable length distributions in the TMP state, while beech fibers exhibited lower median fiber lengths. After processing, fiber lengths decreased for all feedstocks and largely converged, indicating pronounced processing-induced fiber attrition. However, recovered wood and beetle-infested spruce retained finer fiber widths and more fibrillated structures, resulting in favorable aspect-ratio distributions compared with fresh spruce and beech. Thus, hypothesis 1 is supported in the sense that recovered and beetle-infested wood sources promoted finer TMP fiber structures with higher aspect ratios.

With respect to hypothesis 2, all fiber-reinforced samples showed significantly improved tensile and flexural properties compared to neat PP, with recovered and beetle-infested spruce providing the highest reinforcement. The CA was crucial for strength enhancement, while stiffness increased in all filled systems. Although the favorable aspect-ratio distributions of recovered wood and beetle-infested spruce are consistent with their

high tensile and flexural performance, the mechanical behavior cannot be attributed to aspect ratio alone. Instead, the reinforcing effect is interpreted as the result of combined morphology-related effects, including lateral splitting, fibrillation, bundle separation, and accessible fiber surface area, together with fiber–matrix interaction. The pronounced increase in tensile and flexural strength after addition of the coupling agent further demonstrates that interfacial stress transfer is a decisive factor for the performance of the investigated WPCs. For impact strength, uncoupled systems performed below neat PP, whereas compatibilization significantly improved results but increased scatter. This scatter may be related to the high sensitivity of notched impact fracture to local microstructural heterogeneity, particularly in systems with strongly fibrillated TMP fibers and adhesion-controlled failure behavior. Overall, hypothesis 2 is partially supported: tensile and flexural improvements are associated with favorable fiber morphology and effective fiber–matrix interaction, whereas impact behavior is additionally governed by local fracture processes and microstructural heterogeneity.

Hypothesis 3 shows a property-dependent outcome. It is rejected for tensile and flexural properties, as beech-based WPCs exhibited significantly lower reinforcement efficiency compared to spruce-based composites, despite beech wood's higher intrinsic strength. This indicates that composite performance is primarily governed by processed fiber morphology, fibrillation, and fiber–matrix interaction rather than bulk wood properties, although beech remains a technically viable feedstock. In contrast, hypothesis 3 is accepted for impact strength, as no significant differences were observed between beech- and spruce-based WPCs. While compatibilization improved impact performance across all systems, it also increased scatter due to a more heterogeneous, adhesion-controlled failure behavior.

Overall, the results indicate that recovered pallet wood, beetle-infested spruce, and fresh beech can be considered suitable TMP raw materials for PP-based WPC production. Recovered wood and beetle-infested spruce achieved mechanical properties comparable to or higher than those of fresh spruce-based WPCs and therefore offer promising opportunities for the sustainable utilization of alternative wood resources in mechanically demanding WPC applications.

Author Contributions: Conceptualization and methodology, S.W., M.S., F.O., P.K. and M.L.; software, formal analysis, investigation, data curation, writing—original draft preparation and visualization, S.W. and M.S.; validation and writing—review and editing, S.W., M.S., F.O., U.O.U., P.K. and M.L.; resources and supervision, P.K. and M.L.; project administration, S.W.; funding acquisition, S.W. and P.K. All authors have read and agreed to the published version of the manuscript.

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Abbreviations

The following abbreviations are used in this manuscript:

WPC	Wood-Plastic-Composite
TMP	Thermomechanical Pulp
HDPE	High-Density Polyethylene
PP	Polypropylene
CA	Coupling Agent
WF	Wood Fiber
DSC	Differential Scanning Calorimetry
SEM	Scanning Electron Microscope

Appendix A

Appendix A.1. Density Measurements

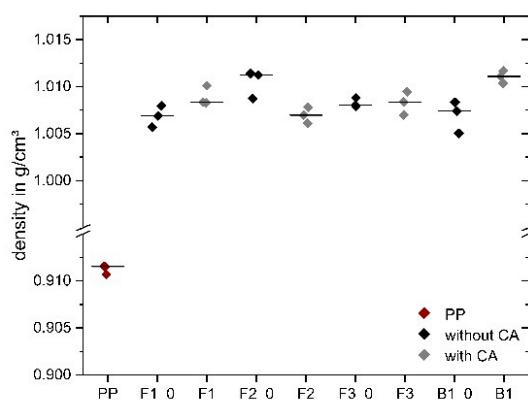


Figure A1. Density of neat PP and WPC compounds containing 30 wt.-% TMP fibers from spruce (F1: fresh, F2: recovered, F3: beetle-infested) and fresh beech (B1), without (X_0) and with CA. The horizontal line represents the median value.

Appendix A.2. Crystallinity Measurements

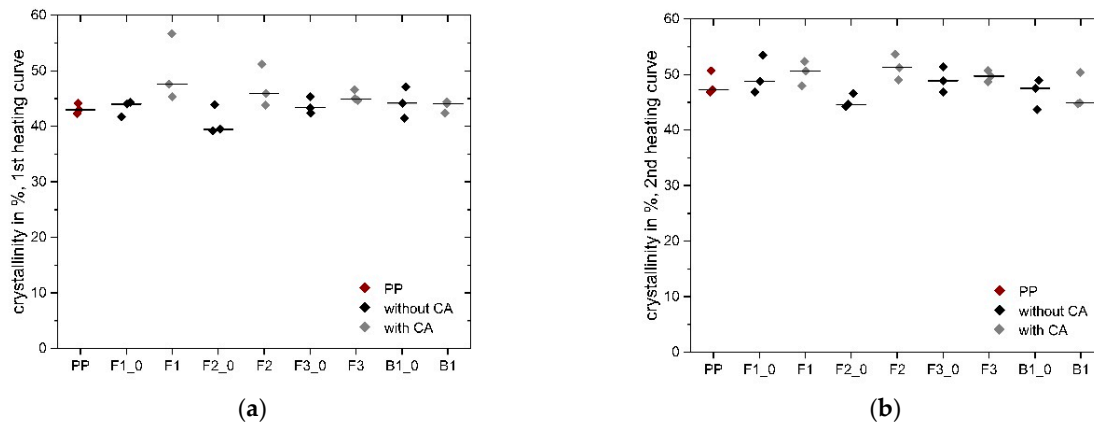


Figure A2. Crystallinity of neat PP and WPC compounds containing 30 wt.-% TMP fibers from spruce (F1: fresh, F2: recovered, F3: beetle-infested) and fresh beech (B1), without (X_0) and with CA. (a) crystallinity of PP-phase 1st heating; (b) crystallinity of PP-phase 2nd heating. The horizontal line represents the median value.

Appendix A.3. Mean Values and Standard Deviations of Mechanical Properties

Table A1. Mean values and standard deviations of the mechanical properties of neat PP and the investigated PP-based WPC compounds. The values are provided as supplementary descriptive statistics to support comparison and engineering interpretation of the mechanical data.

Property	Poly-Propylene	Spruce			Beech
	PP	Fresh F1	Recovered F2	Beetle-Infested F3	Fresh B1
Tensile modulus [GPa]	1.42 ± 0.04	3.92 ± 0.04	4.69 ± 0.09	4.47 ± 0.07	3.48 ± 0.09
Tensile strength [MPa]	33.0 ± 0.7	48.7 ± 0.7	54.5 ± 0.7	53.2 ± 0.4	45.8 ± 0.7
T-Elongation at break [%]	7.58 ± 0.11	3.17 ± 0.16	3.37 ± 0.04	3.43 ± 0.09	3.40 ± 0.12
Flexural modulus [GPa]	1.32 ± 0.02	3.79 ± 0.05	3.94 ± 0.12	3.82 ± 0.06	3.23 ± 0.06
Flexural strength [MPa]	36.5 ± 0.2	77.1 ± 0.5	80.9 ± 1.5	80.2 ± 1.6	71.8 ± 0.8
F-Elongation at break [%]	n.b.	3.47 ± 0.16	3.69 ± 0.16	3.81 ± 0.16	4.15 ± 0.26
Notched impact strength [kJ/m ²]	3.54 ± 0.11	2.72 ± 0.12	3.00 ± 0.44	2.92 ± 0.54	3.24 ± 0.61
Max. Force during impact [N]	186.6 ± 5.9	254.9 ± 19.0	249.7 ± 25.4	240.3 ± 31.7	239.5 ± 21.7
Density [kg/m ³]	0.911 ± 0.001	1.009 ± 0.001	1.007 ± 0.001	1.008 ± 0.001	1.011 ± 0.001

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