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Mechanical Performance of Polypropylene-Wood Fiber Composites: Strength and Microstructure Analysis

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Abstract
This research investigates the optimization of injection molding parameters for PP Copolymer and PP Homopolymer, with a focus on the distribution of wood fibers and their influence on the materials' hardness and strength before and after UV irradiation exposure. By systematically adjusting injection molding parameters, the study aims to achieve optimal wood fiber dispersion within the polymer matrices. The effects of these parameters on the mechanical properties of the composites are evaluated through hardness and strength testing, both pre- and post-UV exposure. The findings of this study provide a comprehensive understanding of the interplay between injection molding conditions, wood fiber distribution, and the mechanical performance of PP Copolymer and PP Homopolymer composites on the durability and stability of these materials under various environmental conditions.

1. Introduction

Polypropylene (PP) homopolymer and copolymer blends with wood fiber are commonly used in the production of wood-plastic composites (WPCs) for various applications such as decking, fencing, and automotive parts. The addition of wood fiber to PP improves its stiffness, strength, and dimensional stability while reducing cost [1]. PP homopolymer is characterized by a high degree of crystallinity, which provides good mechanical properties and chemical resistance. PP copolymers, on the other hand, contain small amounts of ethylene or other α-olefins, which reduce crystallinity and improve impact strength, especially at low temperatures [2-4].

The primary weakness of homopolymer and copolymer blends is their susceptibility to environmental factors, such as moisture and temperature, which can significantly impact their mechanical properties and durability. Additionally, these blends often exhibit poor dimensional stability and are prone to warping and cracking over time, limiting their practical applications. Wood fibers provide a natural, affordable, and sustainable reinforcement to polymer mixes, thereby mitigating these disadvantages. In addition to improving dimensional stability and lowering the composite's total environmental effect, wood fibers provide better mechanical qualities, such as greater tensile strength and stiffness. Given that it impacts the composite's overall performance, the distribution of wood fibers inside the polymer matrix is critical. A consistent dispersion of wood fibers can improve the mechanical characteristics of the composite and lower the delamination, whereas an irregular distribution can result in specific stress concentrations and worse performance.

Blending PP homopolymer and copolymer with wood fiber can be done through melt mixing in an extruder or injection molding machine. The wood fiber is typically pre-treated with coupling agents like maleic anhydride-grafted PP (MAPP) to improve adhesion with the PP matrix [4],[5]. The properties of PP/wood fiber composites depend on the ratio of homopolymer to copolymer, wood fiber content, and the use of compatibilizers. Increasing the copolymer content generally improves impact strength but reduces stiffness and tensile strength. Higher wood fiber loadings increase stiffness and strength but reduce impact resistance [4],[5]. Injection molding is a widely used manufacturing process for producing polymer composite parts. Optimizing the injection molding parameters is critical to achieve the desired mechanical properties and minimize defects in the final product [6], [7],[8]. This study focuses on optimizing the injection molding parameters for a blend of PP copolymer and PP homopolymer reinforced with wood fibers.

The key injection molding parameters that affect the quality of the molded parts include mold temperature, injection temperature, injection pressure, and flow rate [6],[9]. These parameters influence the flow behavior of the polymer melt in the mold cavity, which in turn affects the distribution of the wood fibers and the resulting mechanical properties of the composite [7],[10]. In this research, the effects of wood fiber distribution on the hardness and strength of the PP copolymer/PP homopolymer blend were evaluated before and after UV irradiation exposure. UV irradiation can cause degradation of the polymer matrix and the wood fibers, leading to changes in the mechanical properties of the composite [10].

2. Experimental

2.1 Materials

Different ratios of wood fiber at 10,20,30, 40, and 50 % (wt/wt) ratio with virgin polypropylene copolymer and polypropylene homopolymer (Table 1) were heated and blended through screw type injection molding and turned into dumbbell specimens. The compositions were as follows:

Table 1 *PP and Wood fiber composition*

Material	Ratio (wt/wt)					
	100%	wood fiber				
		10%	20%	30%	40%	50%
PP Copolymer	√	√	√	√	√	√
PP Homopolymer	√	√	√	√	√	√

Fig. 1 *Raw materials of Polypropylene and Wood fiber*

2.2 Injection Molding

Material Specimens for tensile testing were prepared by means of injection molding according to ISO 527-2 standard. The injection molding was done using vertical injection molding (Plunger type), which doesn't have a screw. The parameters for the vertical injection molding process are shown in Table 2.

Table 2 *Parameter for injection molding*

Parameter	*Heater*
Temperature (∘C)	195 ˚C
Pressure (Bar)	4.5 Bar
Time (s)	15s – 25s

Every parameter related to the injection molding process, such as cycle time, cooling time, and injection time, was recorded at 10.0 seconds. These intervals play a critical role in determining the effectiveness and calibre of the molding process. The time that molten material is injected into the mold cavity to ensure that the mold is filled and that the component takes on its original shape is referred to as the injection time. Cooling time is the amount of time that a molded item is given to settle and solidify inside the mold, avoiding distortion or flaws when the object is ejected. The whole time from the beginning of one injection cycle to the beginning of the subsequent one is known as the cycle time, and it comprises the injection, cooling, and any extra procedures like opening the mold and ejecting the component.

The dumbbell specimen was measured using its conventional dimensions, which are shown in Fig. 2. To guarantee consistency and dependability in test findings, the dumbbell specimen—which is frequently used for mechanical testing such as tensile strength and elongation at break—must conform to exact dimensional specifications. These measurements usually comprise the total length and breadth of the grip parts in addition to the width, length, and thickness of the narrow section.

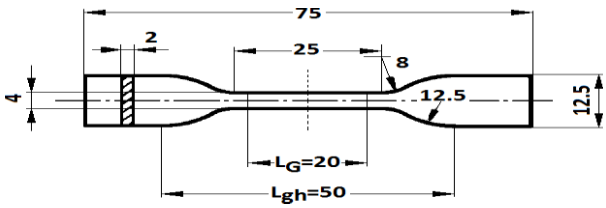


Fig. 2 *Dimension of dumbbell specimen [ISO 527 (5A)]*

2.3 Accelerated Weathering Tester of Wood – Polypropylene Composite

The UV Accelerated Weatherometer Haida International Equipment, as shown in Fig. 3, and its specimen rack holder were used to irradiate the tensile specimens with UV light. The UV accelerated weathering test was conducted in accordance with ASTM D 4587, which is the industry standard for paint exposure to light and water. The UV fluorescent bulbs that make up the UV Weatherometer emit light with a wavelength of 280–320 nm with a tail that reaches 400 nm. The WPC samples were exposed to UV radiation at 50˚C while being held in a rack holder. After 1000, 2000, 3000, 4000, and 5000 hours of UV irradiation exposure, each component of the dumbbell samples was examined to see how weathering affected the WPCs' mechanical characteristics. An example of the UV Accelerated Weatherometer is presented in Fig. 2.

Fig. 3 *a) UV Accelerated Weatherometer and b) dumbbell specimen in rack holder*

2.4 Tensile Test

The Wood-Fiber composite specimens were exposed to UV irradiation for periods of time ranging from 0 to 5000 hours. Following this, they were put through rigorous tensile testing in compliance with ISO 527-2 requirements. This testing was used to evaluate the composite materials' mechanical characteristics and long-term UV irradiation exposure stability. A sophisticated loading frame with a 5 kN load cell was used for the tensile tests, guaranteeing a precise and constant application of force throughout the testing procedure. Thorough calibration of the load cell ensured precise measurements of elongation and tensile strength. Consistent strain rates and reduce the possibility of human error, the specimens were tested at a controlled crosshead speed of 5 mm/min, which was controlled using an extensometer.

2.5 Scanning Electron Microscope (SEM) Testing

Using a Hitachi Scanning Electron Microscope (SEM), the morphological characterization of the fracture surfaces of Wood Plastic Composites (WPC) was carried out to examine microstructural alterations brought on by UV irradiation. We looked at the fracture surfaces before and after UV exposure to see how weathering affected the tensile characteristics. To assure conductivity, samples were first coated with a thin coating of gold using an Auto Fine Coater Machine that was running at a 25-mA current plasma and a 2 Pa chamber pressure. At 10 kV and high vacuum, the SEM produced pictures at magnifications of 50μm, 100μm, and 500μm. The intricate cellular microstructures shown in these high-resolution photos shed light on how UV radiation affects the mechanical properties and integrity of the material.

3. Results and Discussion

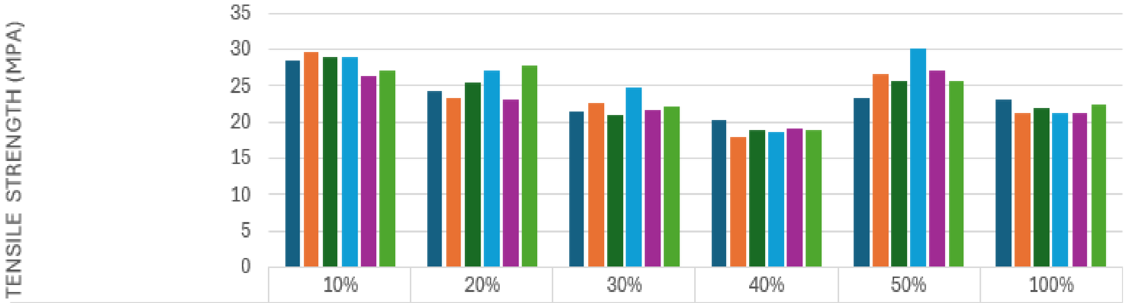
3.1 Tensile Properties for Polypropylene Copolymer blend with Wood fiber

Table 3 shows the ratio of wood fiber to polymer significantly affects the tensile strength of the material, both before and after UV irradiation exposure. The highest UV irradiated tensile strength is seen at a 10% fiber ratio (28.5309 MPa), and it decreases as the ratio increases. This suggests that a lower fiber ratio ensures better mechanical properties. Post-UV tensile strength data also supports this, with 10% and 20% ratios maintaining higher strengths across various UV exposure levels (1000 K to 5000 K). These findings indicate that keeping the fiber ratio low helps to preserve the material's integrity under UV exposure. Additionally, the changes in tensile strength at different temperatures need to carefully control during UV irradiation exposure, as higher temperatures tend to reduce tensile strength more significantly. Looking at the wood fiber distribution, it seems that lower ratios (10% and 20%) allow for a more even and effective distribution of fibers within the polymer matrix, which enhances tensile strength. In contrast, higher fiber ratios might cause the fibers to clump together or distribute unevenly, leading to weaker mechanical properties, especially after UV exposure. With an increase in the amount of wood fibre, the composites' tensile and flexural strengths rose. But when the amount of wood fibre in the composites increased, the impact strength of the materials reduced [11].

Table 3 *Tensile strength for pre- and post-UV for each ratio*

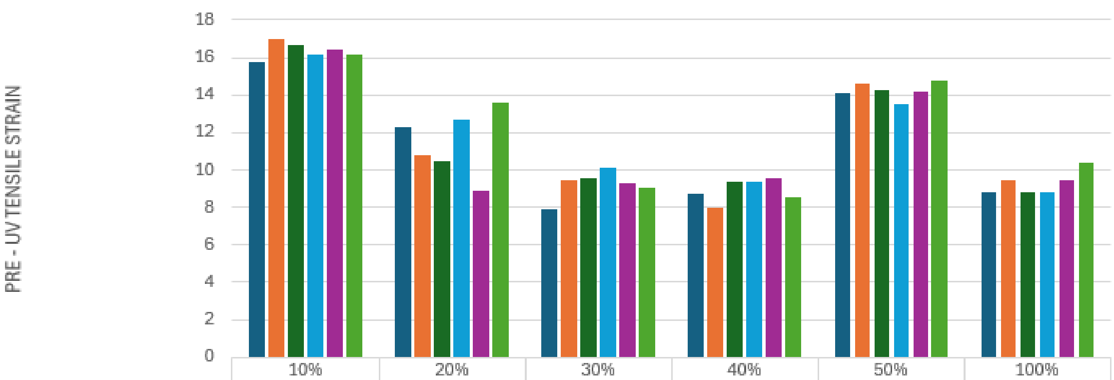
RATIO	PRE - UV TENSILE STRENGTH	1K	2K	3K	4K	5K
10%	28.5309	29.7302	29.0021	28.8681	26.3549	26.9737
20%	24.198	23.2746	25.3961	26.9835	23.0941	27.6634
30%	21.4701	22.5871	20.8764	24.7973	21.6229	22.0198
40%	20.3553	17.8073	18.896	18.6605	19.0816	18.837
50%	23.2407	26.6239	25.6211	30.041	27.0269	25.641
100%	23.0503	21.3009	22.0112	21.254	21.103	22.4148

Tensile strength of materials is influenced by temperature, wood fibre ratio, and UV irradiation exposure. The graph below in Fig. 4 illustrates how these factors work together to cause a general decline in tensile strength. Tensile strengths are greater at all ratios and temperatures before UV exposure. Temperature has a major effect on tensile strength after UV irradiation exposure hours; greater strengths are maintained at lower temperatures, such as 1000 and 2000 hours. The ratio of wood fibre is also important; at a 50% ratio, the maximum post-UV tensile strength is recorded at 2000 hours, indicating that this combination is ideal. The endurance and mechanical qualities of wood fibre-reinforced composites after UV irradiation exposure can be enhanced by improving injection moulding parameters, namely temperature and fibre ratio. Temperature and fibre content are two production variables that have a major impact on the mechanical characteristics of wood fibre composites, these factors may be tuned to increase strength and durability [12]. Manufacturers may create materials with higher tensile strength and greater resilience by adjusting these factors; these materials are perfect for applications that need Ultra–Violet resistance. To obtain the ideal balance of hardness and strength in composite materials, the graph highlights the necessity of having exact control over processing conditions.



	10%	20%	30%	40%	50%	100%
PRE - UV TENSILE STRENGTH	28.5309	24.198	21.4701	20.3553	23.2407	23.0503
1K	29.7302	23.2746	22.5871	17.8073	26.6239	21.3009
2K	29.0021	25.3961	20.8764	18.896	25.6211	22.0112
3K	28.8681	26.9835	24.7973	18.6605	30.041	21.254
4K	26.3549	23.0941	21.6229	19.0816	27.0269	21.103
5K	26.9737	27.6634	21.0198	18.837	25.641	22.4148

Fig. 4 *Tensile strength for WPC (PP Copolymer) before and after UV irradiation exposure*



	10%	20%	30%	40%	50%	100%
PRE - UV TENSILE STRAIN	15.7958	12.29	7.8535	8.7329	14.0761	8.8258
1K	16.9681	10.7777	9.4329	7.9656	14.591	9.4488
2K	16.685	10.4326	9.5385	9.3993	14.2371	8.7966
3K	16.1787	12.668	10.1105	9.3724	13.529	8.78444
4K	16.3888	8.8461	9.3147	9.5174	14.1831	9.4272
5K	16.1884	13.5715	9.0777	8.5848	14.7465	10.3946

Fig. 5 *Maximum strain for WPC (PP Copolymer) before and after UV irradiation exposure*

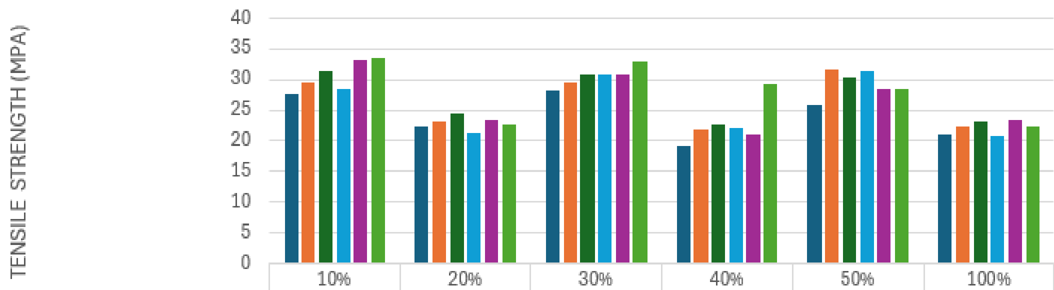
The improvement in material performance using injection moulding is optimized, and the wood fibre distribution was evaluated. The graph in Fig. 5 shows how the maximum strain of a blend of wood fibre and PP copolymer at different UV irradiation exposure settings and strain ratios. UV irradiation exposure drastically lowers the mechanical characteristics of the material. When the composites are first exposed to UV irradiation, their high tensile strain values indicate their strength and flexibility. On the other hand, post-UV exposure data show a considerable decrease in maximum strain, particularly at higher exposure hours (1000 to 5000), indicating that UV irradiation has a deteriorating impact. When comparing greater wood fibre ratios (50 and 100%) to lower ratios (10% and 20%), the strain decreases more noticeably, suggesting that the material's ductility is better maintained under lower stress circumstances. This tendency highlights how crucial it is to optimize injection moulding parameters like temperature, pressure, and cooling rate to guarantee that wood fibres are distributed uniformly throughout the polymer matrix.

A uniform distribution of fibres improves the composite's resistance to UV irradiation exposure and helps it retain its mechanical qualities, such as strength and hardness. Stronger fibre- matrix interactions can result from effective optimization, which can lessen weak regions that are more susceptible to UV irradiation exposure deterioration. Consequently, wood fibre composites with enhanced resistance to UV-induced deterioration may be created by optimizing the injection moulding procedure, preserving their structural integrity over time. For applications that need for extended exposure to outdoor settings, this is essential [13].

3.2 Polypropylene Homopolymer blend with Wood fiber

Fig. 6 illustrates the influence of the different ratios of fibers and UV irradiation exposure that affect the mechanical characteristics of a wood fiber-based PP homopolymer composite. The tensile strength indicates the material's vulnerability to UV deterioration by showing a notable decline in tensile strength with increased UV exposure. The ratio with the highest pre-UV strength, seen at 40% (33.2662 MPa), is comparatively better at lower UV irradiation exposure hours (1000 and 2000 hours). Post-UV exposure results in a decrease in strength across all ratios. Based on current trends, it may be possible to preserve the mechanical strength of the material by reducing UV exposure during manufacturing and application.

The maximal strain graph in Figure 3.4 displays a similar trend, with strain increasing with more UV irradiation exposure, suggesting that the material becomes more brittle. Fig. 7 also illustrates how exposure to UV light and different temperatures impacts a combination of PP homopolymer and wood fiber at its maximum strain. The material exhibits a high tensile strain at first, but exposure to UV light drastically decreases its strength at all mixed ratios. The tensile strain drops more as the UV irradiation hours rise from 1000 to 5000 hours, peaking at 3000 hours, particularly at larger blend ratios (40% and 50%). While the strain is somewhat better at 5000 hours than it is at 3000 and 4000hours, the material's pre-UV tensile strength is not restored. Additionally, the mechanical qualities of WPCs are greatly diminished by weathering, highlighting the necessity of manufacturing settings that are optimized to improve UV resistance and sustain structural integrity over time [14].



	10%	20%	30%	40%	50%	100%
PRE - UV TENSILE STRENGTH	27.787	22.401	28.287	19.088	25.833	21.055
1K	29.418	23.281	29.576	21.948	31.673	22.449
2K	31.463	24.545	30.891	22.508	30.235	23.188
3K	28.462	21.335	30.891	22.11	31.478	20.676
4K	33.266	23.331	30.763	21.125	28.332	23.375
5K	33.567	22.613	33.013	29.139	28.529	22.352

RATIO

PRE - UV TENSILE STRENGTH 1K 2K 3K 4K 5K

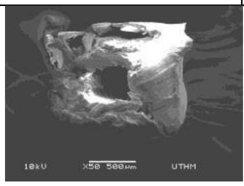
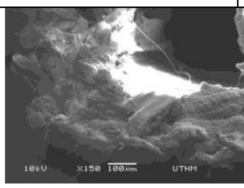
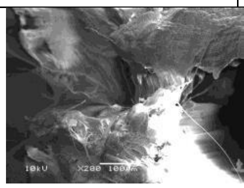
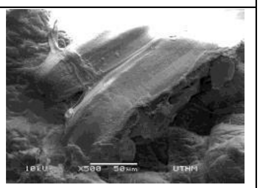
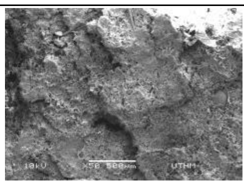
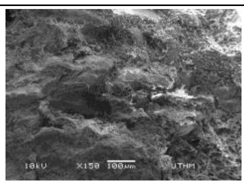
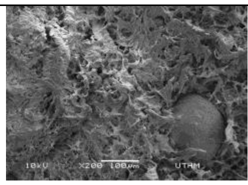
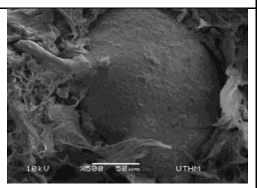
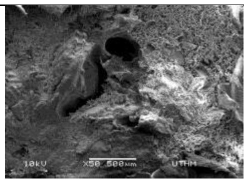
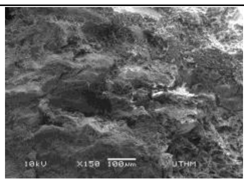
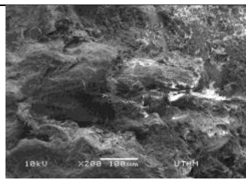
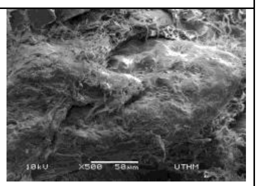
Fig. 6 *Tensile strength of WPC (PP Homopolymer) before and after UV irradiation exposure*

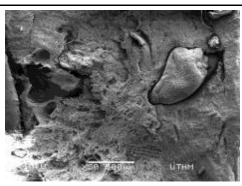
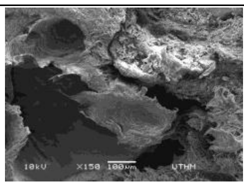
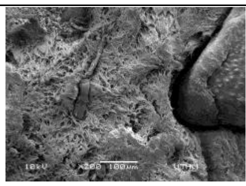
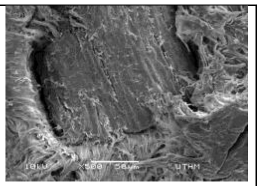
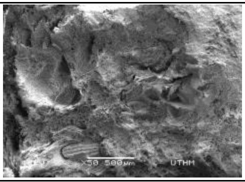
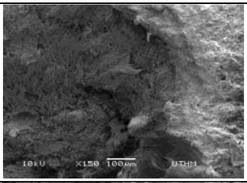
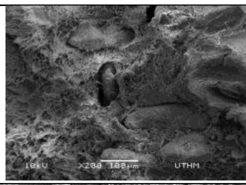
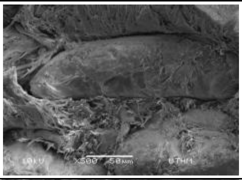
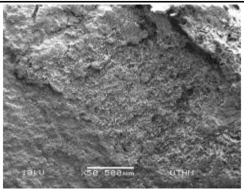
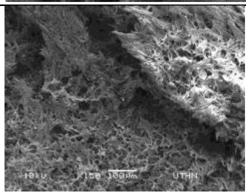
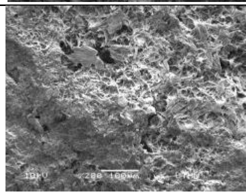
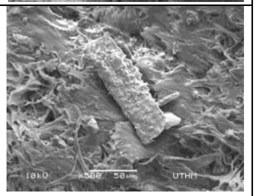
3.2.1 Characterization of fracture surface

The Scanning Electron Microscope (SEM) provided an important insight into the distribution of fibre, which affects the composite's properties. An overview of the fracture surfaces is shown in the x50 magnification photos, which indicate that fracture patterns with a greater wood fibre content are rougher. Under x150 magnification, PP Copolymer with smooth surfaces at the fracture, while from 10% to 50% WF, rougher surfaces and fibre pull-out are visible, suggesting increasing energy absorption and fibre-matrix interaction during splitting. Well-dispersed fibres with few voids are observed at lower fibre concentrations (10% and 20%) at x200 magnification, but agglomeration and void formation are more noticeable at higher values (30% to 50%). Lastly, when looking at the microstructure of wood fibres at x500 magnification, little surface damage is seen for 10% and 20% WF, but significant damage and pull-out happen at 30% to 50% WF. This highlights the difficulties in maintaining fibre-matrix adhesion and the requirement for optimal injection moulding parameters to improve the composites' mechanical qualities and longevity.

Fig. 7 *Maximum strain for WPC (PP Homopolymer) before and after UV irradiation exposure*

Table 4 *The microstructure of fracture surface of the specimens for each wt/wt ratio of PP Copolymer*

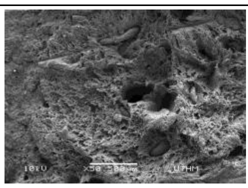
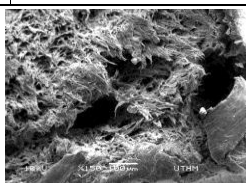
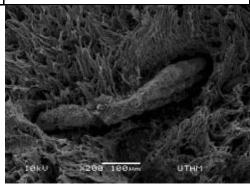
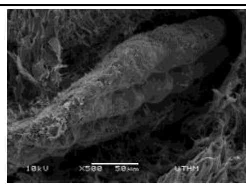
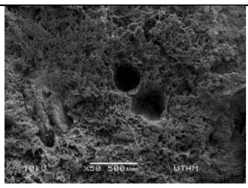
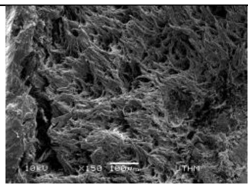
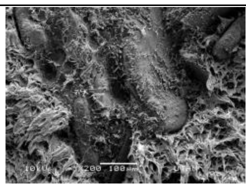
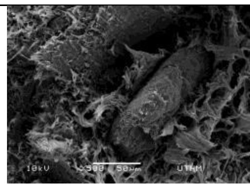
Ratio	X50	X150	X200	X500
90% PP COPO + 10% WF				
80% PP COPO + 20% WF				
70% PP COPO + 30% WF				

60% PP COPO + 40% WF				
50% PP COPO + 50% WF				
100% COPO				

Referring to Table 4, the SEM picture of polypropylene copolymer (PP C0P0) reinforced with varying wood fiber (WF) ratios (0%, 10%, 20%, 30%, 40%, and 50%) at different magnification (x50, x150, x200, and x500) offer through insight into the microstructural characteristic of the fracture surfaces and the distribution of fiber. The photo shows that as the WF content increases, the surface becomes rougher and more uneven, suggesting greater fiber–matrix interactions. This is shown at x50 magnification, which provides an overview of the fracture surface. As it shows improved stress between fiber the fibers and the polymer matrix, this enhanced interaction is important for mechanical qualities like hardness and strength. On the other hand, the picture exhibits considerable fibre aggregation and voids at greater WF levels (30%, 40%, and 50%), which suggests worse fibre–matrix adhesion and poorer dispersion. The photos, magnified at x150 and focused on the fracture's right line, demonstrate smoother surfaces for pure PP COPO (0% WF) and progressively rougher surfaces with more noticeable fiber pull-out as the WF percentage increases. This suggests that increased fiber contents cause fiber-matrix debonding, which results in more complicated fracture processes and may reduce the material's overall strength. Under x200 magnification, the images highlight areas that contain wood fibers. At lower contents (10% and 20% WF), the fibers are well-embedded and have few voids; at higher contents (30%, 40%, and 50% WF), there is significant agglomeration and void formation, which can have an adverse effect on mechanical properties and UV resistance.

Examining the wood fibers' microstructure at x500 magnification, the photos show little surface damage and strong fiber-matrix bonding at lower fiber concentrations. Nevertheless, considerable fiber pull-out and surface damage became visible at increasing fiber concentrations, indicating inadequate fiber-matrix adhesion and heightened UV degradation sensitivity. The mechanical performance and longevity of the composite during UV exposure can only be improved by adjusting injection molding parameters, such as temperature, pressure, and cooling rates, to produce uniform fiber distribution and strong fiber-matrix adhesion [15],[16].

Table 5 *The microstructure of fracture surface for each wt/wt ratio for PP Homoplymer*

Ratio	X50	X150	X200	X500
90% PP HOMO + 10% WF				
80% PP HOMO + 20% WF				

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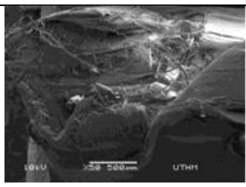
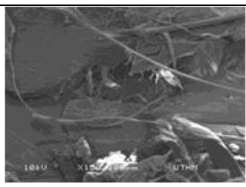
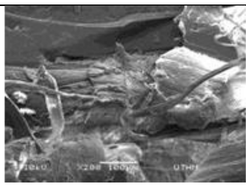
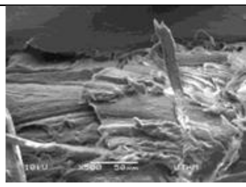
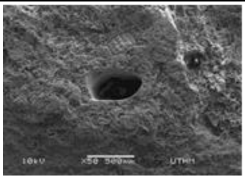
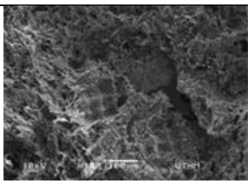
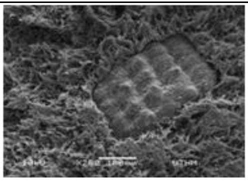
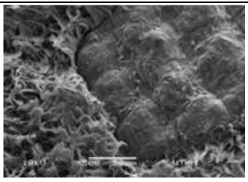
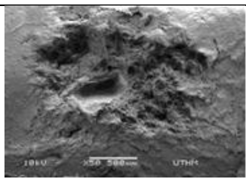
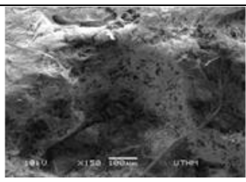
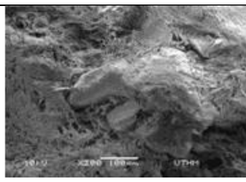
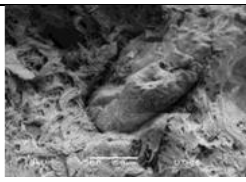
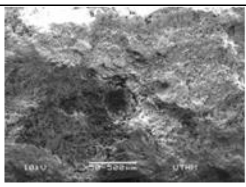
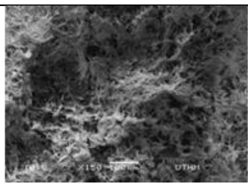
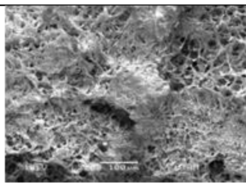
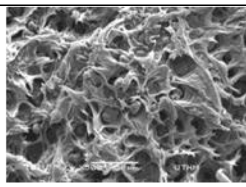
70% PP HOMO + 30% WF				
60% PP HOMO + 40% WF				
50% PP HOMO + 50% WF				
100% HOMO				

Referring to Table 5, fiber distribution, fracture surface microstructure analysis, and injection molding parameter optimization are all made possible by the SEM pictures of polypropylene (PP) homopolymer composites with varied wood fiber (WF) contents (10%–50%). The photos depict the general dispersion of fibers inside the PP matrix at lower magnifications (X50 and X150). For example, at 10% WF, the fibers seem evenly distributed, indicating that lower fiber concentrations promote greater dispersion and mixing. Conversely, fiber agglomeration and clustering are seen at higher WF levels (30%–50%), suggesting that injection molding parameters such as mixing time, temperature, and pressure need to be optimized to promote fiber dispersion and minimize void formation. The interfacial adhesion quality between the wood fibers and the PP matrix is seen at higher magnifications (X200 and X500). The presence of noticeable voids and poor adhesion at 50% WF raises the possibility that processing issues may result in worse mechanical performance for composites with greater fiber content. According to the fracture surface study at X500, fracture surfaces with lower WF concentrations (10%–20%) show more ductile, smoother surfaces, whereas those with greater WF contents (40%–50%) show more brittle behavior, rougher surfaces with more fiber pull-out.

These findings emphasize how crucial it is to strike a balance between WF content and mechanical qualities to maximize longevity. The creation of PP/WF composites with improved strength and resilience would be guided by an evaluation of these microstructural changes before and after UV exposure. This would further reveal the influence of environmental conditions on the composite's performance. The mechanical performance and longevity of the composite during UV exposure can only be improved by adjusting injection moulding parameters, such as temperature, pressure, and cooling rates, to produce uniform fibre distribution and strong fibre-matrix adhesion.

4 Conclusion

The mechanical tensile strength and hardness are typically improved by increasing the amount of wood fiber in the composite. Composite materials with 30% wood fiber content had the best strength and elongation, whereas those with greater fiber contents such as 40% and 50% exhibited a decrease in performance. The possible agglomeration and insufficient bonding between the fibers and the polymer matrix resulted the decreases in mechanical qualities with inconsistent distribution of the filler in the composites. In addition, the mechanical characteristics of these composites are considerably impacted by extended exposure to UV radiation, exhibiting a progressive decline in tensile strength and flexibility, suggesting that UV radiation degrades the polymer matrix as well as the wood fibers. These findings highlight that adding UV stabilizers as protective material is essential to improving the endurance of composites in outdoor settings. Also, retaining the mechanical qualities of the composite depends on attaining an equal distribution of wood fibers inside the polymer matrix, which can only be achieved by optimizing injection molding conditions. Therefore, wood fiber-polypropylene composites offer a practical and environmentally friendly substitute for pure polymer materials, maximizing their performance and longevity in real-world applications. However, careful consideration of the fiber content, injection molding parameters, and surrounding circumstances is required to achieve this.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

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