

Assessment of Mechanical Properties of Polypropylene-Based Blends Incorporating Disposable Nonwoven Caps

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This study proposes a sustainable approach to repurposing plastic waste, focusing on nonwoven fabric (NWF) from disposable caps used in historic mine tours. These caps are essential for maintaining hygiene when sharing helmets but generate significant waste. Blends of virgin polypropylene (PP) and recycled NWF (rNWF) were developed with 25%, 50%, and 75%wt using thermokinetic homogenization, extrusion, and hot compression. The blends and control samples' mechanical, physical, structural, and thermal properties were evaluated. Tests revealed that stiffness increases with rNWF addition, while tensile strength decreases. The 50rNWF blend (50% NWF) stood out with a higher modulus of elasticity than virgin PP in both tensile (1.42 GPa vs. 1.22 GPa) and flexural (1.51 GPa vs. 1.28 GPa) tests. These results highlight 50rNWF as a promising substitute for PP, reducing environmental impacts and promoting the circular economy.

Keywords: Blend, Nonwoven fabric (NWF), Polypropylene (PP), Disposable caps, Waste repurposing.

1. Introduction

The increase in the generation and disposal of municipal solid waste, particularly plastics, is a growing environmental concern. Approximately 370 million tons of plastic are produced annually, of which only 9% are recycled¹. The accumulation of such waste leads to impacts such as landfill overuse, soil and water contamination, greenhouse gas emissions², and ocean pollution, with 4 to 12 million tons being dumped annually, underscoring the urgency for solutions to address these environmental liabilities³.

Polymer blends have emerged as a promising solution for reusing plastic waste. Formed by combining two or more polymers, these blends offer enhanced physical and mechanical properties, catering to various industries while reducing the costs of plastic synthesis⁴. Their applications span adhesive films, electronics, biomedicine, and the automotive sector⁵⁻⁷, as well as construction materials such as masonry components⁸, flame retardants⁹, and structural elements¹⁰. Incorporating recycled plastics into blends and composites reduces plastic waste, decreases the demand for virgin raw materials, and promotes a circular economy^{11,12}. Consequently, recycled plastics are converted into higher-value materials, mitigating waste accumulation¹³.

Blends of virgin and recycled polypropylene (PP) are particularly notable for their mechanical, chemical, and thermal properties, as well as their low cost and ease of processing¹⁴. Studies by Gabriel and Tiana¹⁵ and Hyie *et al.*¹⁶ demonstrate that, while recycled PP has inferior mechanical properties compared to virgin PP, recycled blends deliver satisfactory performance for various applications, reducing both costs and environmental impacts. PP is valued for its ability to be recycled multiple times without significant loss of quality¹⁷. A relevant example is Nonwoven Fabric (NWF), produced from PP fibers bonded through chemical, thermal, or mechanical processes. This material is widely used in Personal Protective Equipment (PPE) due to its rapid manufacturing, low cost, and high sterility¹⁸, including items such as shoe covers, caps, gowns, and disposable masks¹⁹. PPE items like disposable NWF caps are extensively used in healthcare, domestic settings, the food industry, and tourism to protect against pathogens and contaminants²⁰. In historical mines open for tourism, where helmet use is mandatory, disposable caps ensure hygiene for visitors due to high turnover and the difficulty of sanitizing helmets. However, this generates significant waste, highlighting the need for sustainable management solutions.

This study proposes repurposing disposable NWF caps used in historical mines by incorporating them into virgin PP to produce PP blends, analyzing their mechanical and thermal properties in comparison to control samples.

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This approach seeks to mitigate environmental impacts, promote efficient waste use, and generate revenue for mines, aligning with the UN’s SDGs 12, 13, and 14²¹. Beyond the tourism sector, disposable NWF caps also have potential as recyclable materials in the food and healthcare industries.

2. Materials and Methods

The virgin polypropylene (vPP) with a melt flow index of 3.5 g/10 minutes and a density of 0.905 g/cm³, supplied by Braskem, was used²². The recycled polypropylene was obtained from disposable NWF caps discarded at a historical mine located in Ouro Preto, Minas Gerais, Brazil, a controlled visitation environment with a low risk of biological contamination, reducing the need for additional cleaning procedures. A manual sorting process was performed to remove non-NWF materials before processing. The use of chemical cleaning agents was avoided to prevent the introduction of substances that could alter the composition of the blends and to minimize water and chemical consumption, aligning to develop a practical, scalable, and sustainable process for producing PP-based blends with recycled NWF.

The residual NWF (rNWF) was shredded using a knife mill (Marconi, MA 580) equipped with a 1.75 mm sieve. In order to evaluate the influence of rNWF addition on the mechanical performance of the blends, five formulations

were prepared. These included the pure materials (100% vPP and 100% rNWF) and three intermediate blends containing 25%, 50%, and 75% rNWF by weight according to Table 1. This composition range permitted a systematic assessment of how the progressive incorporation of rNWF affects the mechanical properties of the material while enabling the identification of transitional behaviors between the two materials across the blend ratios. These materials underwent thermokinetic homogenization in a high-speed homogenizer (MH Equipamentos, MH-100). After solidification, the mixture was re-shredded using the knife mill, this time without a sieve. Extrusion was performed using a laboratory single-screw extruder (Thermo Scientific, HAAKE Polylab) operating at 45 rpm with a temperature of 175 °C across three heating zones. The extruded material was pelletized using a granulator (AXPlástico, AX Gran), producing pellets approximately 3.40 mm in diameter and 3.70 mm in length. Control samples, 100vPP and 100rNWF, composed entirely of vPP and rNWF, respectively, were also prepared for comparative analysis.

The test specimens (TS) were fabricated from the pelletized granules using compression molding in a hydraulic press (Solab, SL11) at 180 °C and a pressure of approximately 25 MPa (of 5 tons) for 5 minutes. Figure 1 illustrates a flowchart of the raw materials and processes involved in the production of the blend and control sample TS.

Table 1. Control sample and blend formulations, expressed in mass and mass percentage.

Sample	Mass (g)		% by mass	
	vPP	rNWF	vPP	rNWF
100vPP	152	0	100	0
25rNWF	114	38	75	25
50rNWF	76	76	50	50
75rNWF	38	114	25	75
100rNWF	0	152	0	100

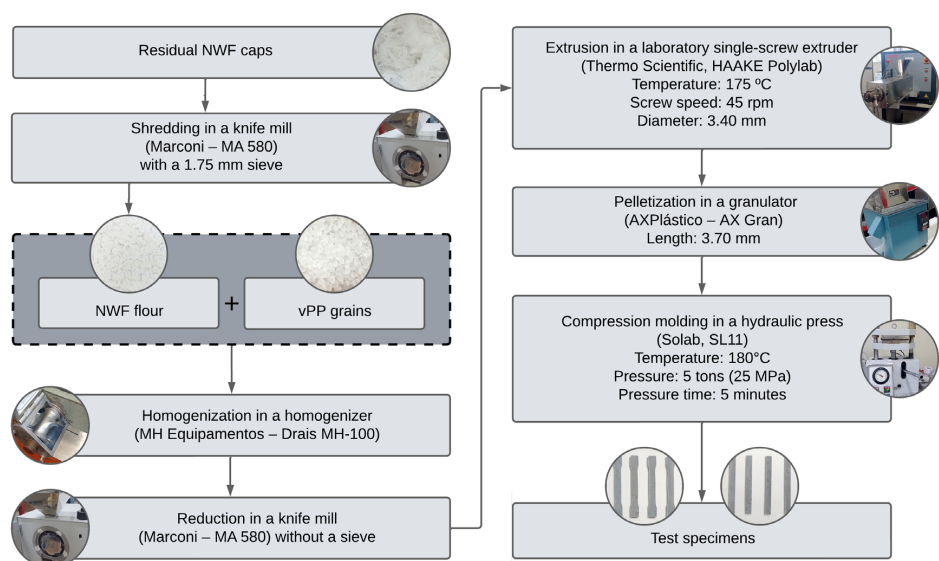


Figure 1. Processes involved in the production of the test specimens.

Tensile strength tests were performed using a universal testing machine (Instron, EMIC 23-20) following ASTM D638²³, with a 20 kN load cell and a crosshead separation speed of 50 mm/min. The fracture surface morphology of the tested specimens was analyzed via Scanning Electron Microscopy (SEM) using a TESCAN VEGA 3 microscope, operating with secondary electrons after gold coating in a sputter coater (QUORUM Q150R). Flexural tests adhered to ASTM D790²⁴, utilizing the same universal testing machine, a 20 kN load cell, and a test speed of 30 mm/min.

The determination of water absorption and thickness swelling of the samples was carried out based on immersion in distilled water at (22 ± 2) °C, monitoring mass and thickness gains over time. Four specimens of each mixture were used. Their masses were measured using a Mettler Toledo precision balance, model PG203-S, and their thicknesses were measured using an electronic digital caliper. Mass and thickness measurements were performed after 24 hours and 7 days of immersion. After removal from the water, the samples were surface dried using absorbent paper and then weighed again to determine the saturated mass, following the procedure indicated in ASTM D570²⁵.

Thermogravimetric analysis (TGA) was conducted using a Shimadzu DTG-60H device, with a heating rate of 10 °C/min under a nitrogen atmosphere (50 mL/min). Samples with an average mass of 8.0 mg were analyzed. Both the control samples and the produced blends were evaluated, with the equipment heating from room temperature to 750 °C.

3. Results and Discussion

The results of the tensile test, including maximum stress, strain at maximum force, and modulus of elasticity, are presented in Figure 2. As observed, the tensile strength of the blends progressively decreased with the increase in rNWF content. Using the tensile strength of the control sample, 100vPP, as a reference, the 25rNWF blend showed a reduction of 6.8%, followed by 50rNWF and 75rNWF blends, which exhibited reductions of 19.8% and 35.8%, respectively. It is noted that blending up to 40% recycled PP in a virgin PP matrix does not significantly affect its mechanical properties²⁶, which may explain the more moderate strength loss in the 25rNWF sample. The control sample composed entirely of recycled PP (100rNWF) exhibited the highest loss in tensile strength, with a reduction of 39.1% compared to the virgin PP control sample (100vPP).

There is a notable scarcity of studies employing recycled nonwoven fabric (rNWF) as a raw material in polypropylene-based blends. Most existing research focuses on producing nonwoven materials themselves rather than incorporating them as reinforcing agents in polymer matrices. Despite the resulting limitations for direct comparison, it remains valuable to contextualize our findings through related studies involving recycled polypropylene (PP) from alternative sources.

Stoian *et al.*²⁷ used raffia, sourced from fertilizer and bulk product sacks, as a recycled PP source and observed a 13% reduction in the tensile strength of the blend containing 50% recycled PP compared to virgin PP (from 35.7 MPa

to 31 MPa). In comparison, our 50rNWF blend showed a higher reduction of 19.8% (from 31.22 MPa to 25.03 MPa), which may be related to the distinct reinforcement nature provided by rNWF within the polymer matrix.

Furthermore, all blends developed in this study presented higher tensile strengths than those reported by Barbosa *et al.*²⁸ for PP blends processed by injection molding using recycled PP from industrial waste, while being slightly lower but comparable to those produced by Raj *et al.*²⁹ via extrusion-injection methods. These observations also highlight the importance of processing methods, as processes combining extrusion with compression or injection molding generally lead to enhanced mechanical performance due to improved sample compaction and molecular orientation³⁰.

This reduction in tensile strength can be attributed to heterogeneities in the polymer matrix due to recycled PP. Contaminants, dirt, and residual materials, such as elastic bands from the caps, act as defects that weaken the material's structure. Additionally, the recycling process often leads to the degradation of PP, resulting in chain scission and a consequent reduction in molecular weight and mechanical properties. During high-temperature extrusion processes, chain scission is the predominant degradation reaction³¹.

This effect could be mitigated by using a compatibilizer, which enhances the interaction between the blend phases. In its absence, poor interfacial adhesion leads to the formation of microvoids, which propagate cracks and reduce strength³². However, in this study, no compatibilizing agents were used, not only to reduce production costs but also to simplify the blending process, enabling practical and scalable manufacturing without the need for additional chemical additives. This approach minimizes environmental impacts associated with the production and disposal of compatibilizers. It allows the assessment of compositional ranges in which high-performance composites can be produced without compatibilizers, as observed for the 25rNWF sample, which exhibited mechanical properties close to those of virgin PP.

The results also showed a reduction in blend deformation with increasing rNWF content, evidenced by the increased modulus of elasticity. This behavior suggests that rNWF enhances blend stiffness while reducing flexibility, a consistent trend across all levels of rNWF incorporation.

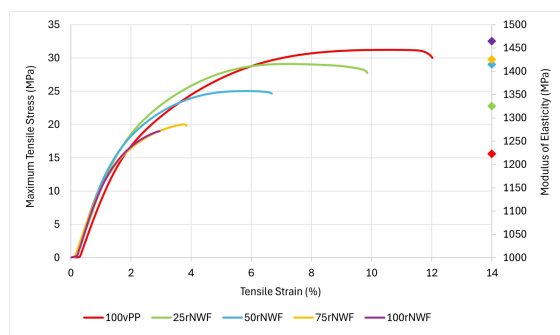


Figure 2. Tensile strength and modulus of elasticity.

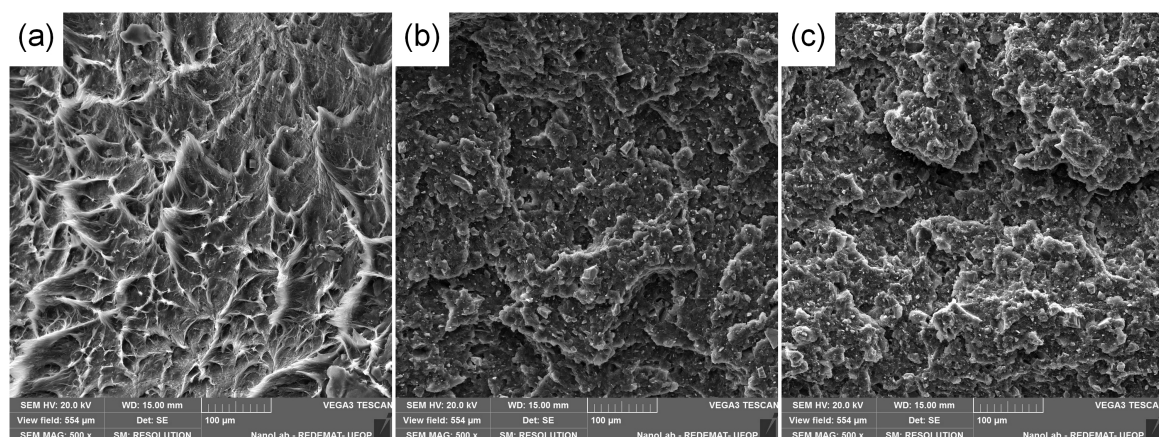


Figure 3. Fracture surface after tensile test: (a) vPP, (b) 50rNWF and (c) 100rNWF.

The reduced flexibility of recycled PP, which tends to be stiffer and more brittle, likely explains this decrease in deformation³³. The nonwoven fabric has a fibrous structure that, when incorporated into the polymer matrix, hinders the mobility of polymer chains. This results in a stiffer and less flexible matrix, as evidenced by the increase in the modulus of elasticity. Additionally, the addition of rNWF creates reinforcement points within the matrix that resist deformation under load. While this enhances stiffness, it also reduces the material's ability to deform elastically. Additionally, contaminants in the blend may act as nucleating agents, increase the crystallinity of the PP phase and result in greater stiffness³⁴.

Scanning Electron Microscopy (SEM) images obtained after the tensile test, shown in Figure 3, highlight the distinct behaviors of virgin PP (100vPP), recycled PP (100rNWF), and the 50rNWF. The incorporation of recycled PP significantly modifies the microstructure of the mixture. Virgin PP (Figure 3a) displays pronounced plastic deformation, with elongated and evenly distributed fibrils during strain, a typical characteristic of ductile materials as previously reported^{35,36}. In contrast, recycled PP (Figure 3c) exhibits a markedly different morphology, with an irregular and rough surface texture. These characteristics can be attributed to the thermal and mechanical degradation experienced by the material throughout its lifecycle, compromising structural integrity. The 50rNWF blend (Figure 3b) shows a morphology similar to recycled PP but with a slight reduction in irregularities, likely due to the influence of virgin PP mitigating some structural defects.

In the latter two cases, recycled material has reduced plastic deformation, reflecting a more brittle behavior characterized by the absence of fibrils and the predominance of flat regions³⁶. These microstructural changes highlight the significant impact of incorporating recycled materials into the polymer matrix, which compromises mechanical properties such as tensile strength and elasticity, as observed in Figure 3.

The results of the flexural test, including maximum stress, deformation at maximum force, and modulus of elasticity, are presented in Figure 4.

Matias *et al.*³⁷ reported that incorporating 30 wt% recycled Polyethylene Terephthalate (PET) into virgin PET

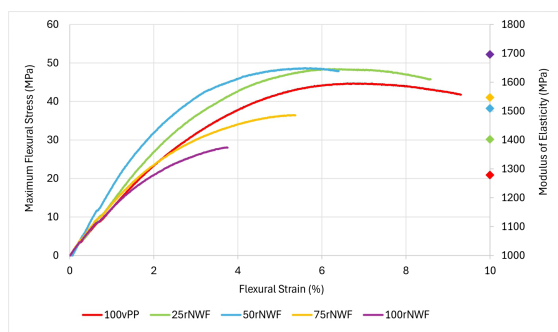


Figure 4. Flexural strength and modulus of elasticity.

led to a minor decrease (~9%) in flexural strength unless compatibilizers were added. A similar trend has been observed in virgin/recycled PP blends, where compatibilizers are often necessary to achieve mechanical properties comparable to or superior to virgin materials. In contrast, in this study, the 25rNWF and 50rNWF blends demonstrated an 8.3% and 8.9% increase in flexural strength (48.44 and 48.68 MPa, respectively) compared to virgin PP (44.71 MPa), without the need for compatibilizers, demonstrating the effectiveness of rNWF as a reinforcement. However, the blend containing 75% recycled PP (75rNWF) demonstrated a significant 18.4% reduction in flexural strength, while the control sample with recycled PP exhibited the lowest performance (28.09 MPa).

This behavior can be attributed to the phase distribution in the blends. At low to moderate recycled PP concentrations, the distribution tends to be more homogeneous, enhancing strength. However, at higher concentrations, phase incompatibility increases, creating failure points. This occurs because recycled PP is more brittle and has a lower deformation capacity compared to virgin PP³⁸. Thus, while the addition of recycled PP can initially increase flexural strength due to higher crystallinity³¹, at elevated concentrations, the presence of defects and heterogeneities reduces strength.

The thermogravimetric (TGA) and derivative thermogravimetric (DTG) curves for the blends and individual polymers are shown in Figure 5, with the corresponding temperature data detailed in Table 2.

While 100vPP exhibited a single mass loss event, the blends and 100rNWF displayed two distinct events, with the first being the most pronounced. The initial degradation temperatures for the blends ranged from 393.24 °C to 412.20 °C. Although thermal stability in industrial applications depends on both the operational temperature and exposure time, the high onset degradation temperatures indicate that these materials possess sufficient thermal stability for a wide range of operational conditions³⁹.

A comparison of the thermal degradation curves reveals that the blends exhibit an intermediate behavior between virgin PP and recycled PP, though more closely aligned with 100rNWF. This suggests a predominant influence of the rNWF matrix over the virgin PP in the blends. Furthermore, both the blends and 100rNWF show

higher degradation temperatures than vPP, supporting the hypothesis that recycled PP from rNWF improves the thermal stability of the blends, while virgin PP has a less pronounced effect in this regard⁴⁰. The nonwoven fabric (rNWF) contributes to the thermal stability of the blends due to its inherent thermal properties. The enhanced thermal stability of the blends compared to vPP can be attributed to the inorganic fillers present in rNWF, which hinder decomposition by blocking or delaying the release of decomposition products and absorbing free radicals²⁷. This is corroborated by the residual mass at 750 °C, which is significantly higher in recycled PP than in virgin PP and increases with the amount of rNWF in the blends (Table 2, Figure 4). Notably, the recycled NWF caps were not cleaned, potentially containing inorganic residues such as dust, soil, and rock particles from the mines, as well as additives or fillers incorporated during their original manufacturing. These non-volatile materials remain as solid residues after thermal degradation, contributing to the lower total mass loss compared to virgin polymer.

Although the blends exhibit greater thermal stability than vPP, their reduced mechanical strength may limit their application in industries requiring high durability, such as construction and automotive sectors. However, the increased rigidity is advantageous for applications demanding dimensional stability and less deformable materials, such as modular panels and corrugated roofing. This underscores the importance of controlling the quality of recycled materials and achieving a balanced formulation for the blends.

Table 3 presents the average values of water absorption and swelling for 100vPP, 100rNWF, and the produced blends after 24 hours and 7 days of immersion in distilled water.

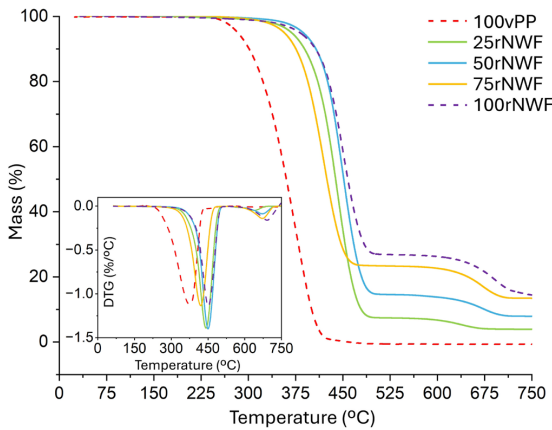


Figure 5. TGA and DTG Curves.

Table 2. Thermal degradation temperatures and weight loss of the samples.

Data	100vPP	25rNWF	Sample 50rNWF	75rNWF	100rNWF
1 st event					
T OnSet (°C)	304.1	412.2	426.8	393.2	427.0
T MidPoint (°C)	359.3	437.6	447.6	415.7	447.6
T EndSet (°C)	414.5	461.7	469.1	440.4	472.2
Weight loss (%)	99.7	92.4	85.2	76.2	72.7
2 nd event					
Weight loss (%)	-	3.7	6.9	10.1	12.3
Total weight loss (%)	99.7	96.1	92.1	86.3	85.0

Table 3. Average water absorption (%) and thickness swelling (%) with respective standard deviations after 24 hours and 7 days of immersion in distilled water.

Sample	Water absorption		Thickness swelling	
	24 hours	7 days	24 hours	7 days
100vPP	0.010 ± 0.009	0.011 ± 0.014	0.00 ± 0.00	0.22 ± 0.20
25rNWF	0.012 ± 0.005	0.014 ± 0.021	0.00 ± 0.00	0.21 ± 0.18
50rNWF	0.024 ± 0.008	0.029 ± 0.004	0.00 ± 0.00	0.22 ± 0.38
75rNWF	0.021 ± 0.020	0.045 ± 0.049	0.22 ± 0.19	0.23 ± 0.20
100rNWF	0.155 ± 0.124	0.747 ± 0.736	0.32 ± 0.31	0.34 ± 0.34

The blends exhibited very low water absorption values (0.012 to 0.021% after 24 h, reaching 0.014 to 0.045% after 7 days) and low swelling (0.00 to 0.22% after 24 h, reaching 0.21 to 0.23% after 7 days). These values are consistent with hydrophobic behavior of polypropylene, attributable to its low polarity and poor affinity for water, as well as its high dimensional stability even under prolonged immersion⁴¹⁻⁴³. The 100rNWF control sample, composed solely of rNWF, showed higher water absorption of 0.155% and swelling of 0.32% after 24 h, and 0.747% absorption and 0.34% swelling after 7 days of immersion. Samples investigated by Xi *et al.*⁴⁴ exhibited stabilization of water absorption between days 7 and 9, with saturation occurring at approximately 0.28%. Notably, the polypropylene samples in that study reached saturation at higher absorption levels than those observed in the present work, suggesting that the blends developed here offer enhanced resistance to water uptake over an equivalent immersion period.

The higher water absorption and swelling values observed for the 100rNWF sample compared to the blends containing virgin resin may be associated with additives or inorganic fillers present in the discarded caps, even in small quantities. This hypothesis is supported by the thermogravimetric analysis (TGA) (Figure 5), which showed a significantly higher residual mass at 750 °C for the 100rNWF sample and the blends with higher recycled content. Even with the progressive increase in rNWF content in the blends, there was no significant increase in water absorption or dimensional swelling, suggesting that the processing method and the compatibility between virgin and recycled PP resulted in a compact microstructure with low porosity or closed, non-interconnected pores that hinder water penetration. The maintenance of low swelling values after 7 days reinforces the dimensional stability of the blends in humid environments, a crucial feature for outdoor applications.

4. Conclusion

The incorporation of rNWF into virgin PP blends significantly influences their mechanical properties, as demonstrated by the tensile test results. The increased modulus of elasticity across all blends indicates that rNWF enhances stiffness while reducing flexibility, a trend consistent with the inherent properties of recycled PP and the fibrous structure of the nonwoven fabric. Furthermore, the addition of higher rNWF content in the blends, the sample containing 50% rNWF demonstrated promising results. It exhibited the best flexural strength (48.68 MPa, 8.9% higher than 100vPP) and significant increases in modulus of elasticity, along with superior thermal stability compared to virgin resin. Additionally, the blends maintained very low water absorption and dimensional swelling even with increasing rNWF content, reinforcing their hydrophobic character and high dimensional stability under prolonged immersion, a crucial aspect for outdoor and humid environment applications. Based on these properties, we suggest potential applications in products where rigidity and dimensional stability are critical, such as modular panels and corrugated roofing. However, it is important to note that these application suggestions are exploratory in nature, and further testing, particularly under environmental aging conditions, is required to confirm

their suitability for real-world use. Reusing rNWF, which would otherwise be discarded as waste, reduces the need for virgin PP production, mitigates environmental impacts, and promotes the conservation of fossil resources. Furthermore, it provides economic benefits by lowering industrial costs and social advantages by creating income opportunities for tourism-based mines. The findings underscore the potential of these blends as a sustainable and innovative alternative, aligned with circular economy principles and efficient plastic waste management.

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Data Availability

The data will be made available upon request.