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Physical and mechanical evaluation of polymeric blends with residues of polypropylene masks*

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Abstract

The SARS-CoV-2 Coronavirus pandemic and the rise in climate disasters have fueled a surge in disposable mask production, exacerbating waste challenges. The study proposes a sustainable pathway for recycling Non-Woven Fabric (NWF) originating from masks made of Polypropylene (PP) used as Personal Protective Equipment (PPE). Eco-friendly blends of virgin polypropylene (vPP) and recycled non-woven fabric (NWF) were produced through extrusion, and the physicochemical and mechanical properties of the blends were evaluated. The addition of NWF resulted in lower tensile and flexural strengths than vPP. However, from 50%wt of recycled NWF, the blends proved to be as stiff as, or even stiffer than, the virgin polymer. While slightly lower, the 50%wt NWF blend achieved properties close to those of vPP, making it the ideal composition for replacing PP in conventional applications. This approach offers a sustainable solution for mask recycling, reducing disposal impacts and supporting a circular economy.

Keywords: *Non-Woven Fabric, pandemic waste, polymeric blend, polypropylene.*

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1. Introduction

Human activities have substantially affected natural cycles, consequently impacting the production chain and global economy. During the SARS-CoV-2 Coronavirus pandemic, the spread of the virus increased the demand for Personal Protective Equipment (PPE), such as procedure gowns and surgical masks[1,2]. According to the WHO, the global consumption of surgical masks reached 89 million per month for the health sector alone[3]. These PPEs are extensively used in surgical centers, wards, and clinics and are primarily made of Non-Woven Fabric (NWF), a polymeric material based on Polypropylene (PP). Due to the disposable nature of these products, their consumption by society has skyrocketed, particularly for masks, which are recommended for single use for up to 8 hours[4]. This has led to significant waste generation, worsening environmental issues associated with their disposal, as their decomposition can take centuries[5].

However, the demand for masks is not only due to the SARS-CoV-2 Coronavirus pandemic. Climate disasters worldwide, such as intense heat waves, wildfires, and increasingly frequent and devastating storms, have increased the need for respiratory protection[6]. This increase in the demand for masks, along with the disposable nature of these products, has further aggravated the problem of waste generation and its environmental impact.

In this context, polymeric blends emerge as a strategic alternative for the reuse of NWF. These eco-friendly blends allow for combining individual properties of polymers, creating materials with new characteristics[7], and offer an economical option for developing new materials compared to synthesizing new polymers[8]. Incorporating recycled materials, especially residual plastics, into polymeric blends can reduce the demand for incinerations, landfills, and virgin raw materials, while conserving natural resources and promoting a circular economy[9,10]. This practice helps mitigate waste accumulation by transforming it into value-added materials[11]. Polymer blends have wide applications in sectors such as adhesive films, electronics, biomedicine, and the automotive industry[12,13], in addition to being used in civil construction for masonry components[14] and flame retardants[15].

Numerous studies confirm the feasibility of using recycled polymers in blend production, with their properties evaluated and associated with their main applications[16-19]. Generally, recycled polymer costs about 40% less than virgin polymer; thus, replacing the virgin part with recycled material reduces cost and increases competitiveness while reducing dependence on non-renewable resources and environmental preservation[20]. However, as Ohta et al.[21] demonstrated, recycled polymers exhibit inferior mechanical properties compared to other materials and virgin polymers[22]. Adding fillers or producing blends is a viable path to minimize the impact of recycling on polymer properties[23,24]. PP is one of the most commercially sold thermoplastics. It is advantageous due to its low cost, recyclability, and high thermal stability, facilitating the production of various blends[25]. However, like other polymeric materials, the recycling of PP degrades its mechanical and thermal properties due to the high temperatures and shear involved in the process[26].

Recent studies on the properties of polymer blends based on virgin (vPP) and recycled PP (rPP) demonstrate variations in mechanical properties depending on the proportions used. Gabriel and Tiana[27] identified that the 30/70% rPP/vPP composition resulted in optimal improvement across four mechanical properties analyzed. Hyie et al.[28] found that the blend consisting of 75% vPP and 25% rPP was ideal, with a positive influence on tensile strength, elongation at break, and Young's modulus. Stoian et al.[29] observed a 20% increase in tensile strength and elastic modulus in a blend with 50% vPP, along with improved thermal stability in all combinations compared to virgin PP. These studies highlight the potential to optimize mechanical and thermal properties in blends of vPP and rPP. Despite the widespread use of PP in polymeric blends, few studies have been conducted on incorporating rPP from NWF waste. Therefore, this work has investigated how adding rPP from NWF masks affects the physical and mechanical properties of polymeric blends.

2. Materials and Methods

2.1 Materials, engineered recycled polymer, and design for blends

The commercial vPP used to prepare the polymeric blends has a flow index of 3.5 g/10 minutes and a density of 0.905 g/cm^3[30]. The NWF waste (wNWF) was obtained from the controlled disposal of surgical masks. The masks, with a base weight of 0.0025 g/cm^2, were purchased new and used for 24 hours. After disposal, they were washed in a Colormaq LCB semi-automatic washing machine using the Delicate wash program. They were soaked in 0.1% chlorine water for one minute for decontamination, then rinsed and air-dried[31]. After sanitization, non-PP components (elastics, metallic wires, etc.) were removed from the masks. The obtained rPP was fragmented in a Marconi brand knife mill, model MA 580, equipped with a 1.75 mm sieve.

Mixtures of wNWF and vPP, with a total mass of 100 g, were processed according to the content indicated in Table 1. For this purpose, a Thermo Scientific laboratory single-screw extruder, model HAAKE Polylab, was used with a temperature of 175 ºC in all three heating zones and a screw speed of 45 rpm. The extruded material, with an average diameter of 3.40 mm, was pelletized in an AXPlástico Granulator, Model AX Gran, into pellets approximately 3.70 mm in length.

Table 1. Composition and Codes of Polypropylene Blends.

Samples	vPP (wt %)	wNWF (wt %)
100vPP	100	0
75vPP25wNWF	75	25
50vPP50wNWF	50	50
25vPP75wNWF	25	75
100wNWF	0	100

Samples were molded from the pelletized grains by hot compression in a Solab brand hydraulic press, model SL11, at 180 ºC and 5 tons of closure (approximately 25 MPa) for 5 minutes. Two compression plates and a metal mold for dumbbell-shaped samples were used with the following dimensions: narrow section length of 57.0 mm, narrow section width of 13.0 mm, and thickness of 3.2 mm. After pressing, the samples were left to rest for 30 minutes under the same pressure as molding before being demolded. Figure 1 presents a flowchart of the raw materials and processes producing the blends and control samples.

2.2 Characterization of polymeric blends

Tensile tests were conducted on an Instron Universal Testing Machine, model EMIC 23-20, following the standard D638[32], using a 20 kN load cell with a 50 mm/min crosshead separation speed at room temperature. The results were obtained from the arithmetic mean of 6 tested specimens, with an accuracy of 0.1%. Tensile deformation parameters, modulus of elasticity, and maximum tensile stress were evaluated. After the tests, the fracture surface morphology of the specimens was analyzed by Scanning Electron Microscopy (SEM) through the TESCAN microscope, Model VEGA 3, using secondary electrons. Before tests, the fractured specimens were gold sputtered in a QUORUM Metalizer, Model Q150R. The flexural tests followed the standard D790[33], using the same Instron Universal Testing Machine, model EMIC 23-20, with a 20 kN load cell and a test speed of 30 mm/min. The distance between supports for the flexural test was 60 mm. Flexural strength and deformation properties were determined. The results were obtained from the arithmetic mean of 6 tested specimens, with an accuracy of 0.1%.

Six specimens were also used to evaluate the water absorption percentage of the blends. Their masses were determined using a Mettler Toledo precision scale, model PG203-S. The specimens were placed in distilled water at (25 ± 2) °C for 24 hours, then removed and surface dried. After drying, a new weighing was performed to determine the mass of the saturated samples, as indicated by the ASTM D570 standard[34].

For the thermogravimetric analysis (TGA), Shimadzu equipment, model DTG-60H, was used with a heating rate of 10 °C/min and a nitrogen atmosphere (50 ml/min). Samples with an average mass of 9 mg were used. The pure polymers and the produced blends were evaluated, heating the equipment from room temperature to 600 °C. Differential scanning calorimetry (DSC) analyses were conducted on

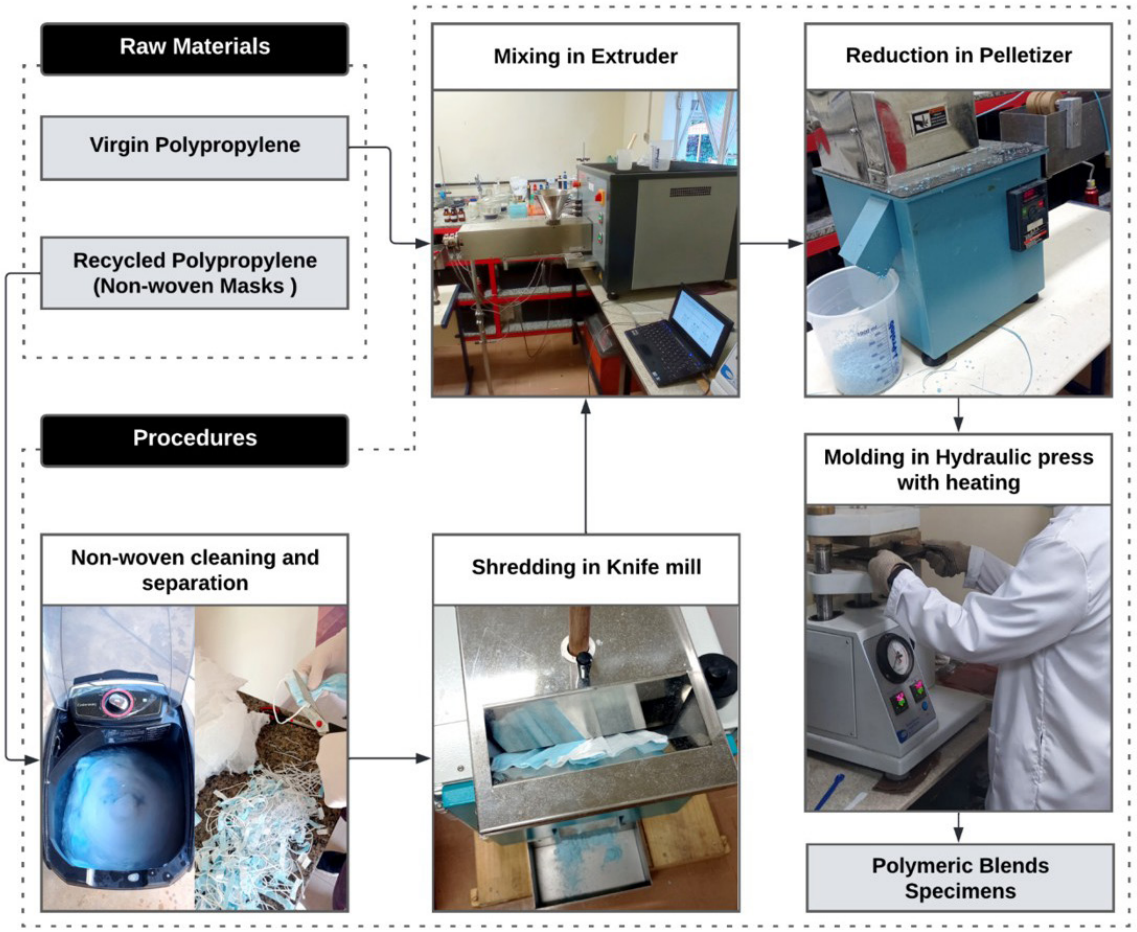

Figure 1. Schematic representation of the blends and control samples preparation.

a DSC-60 device from Shimadzu. The samples, with an average mass of 7 mg, were analyzed in aluminum cells under a nitrogen atmosphere at a 20 mL/min flow rate. Two heating runs were performed: (i) from room temperature up to 190 °C, holding the final temperature for 3 minutes, followed by cooling to -30 °C; (ii) from -30 °C up to 250 °C. In all stages, the heating rate was 10 °C/min. The degree of crystallinity (X_c) was calculated using Equation 1, where it is defined as the ratio of the melting enthalpy variation of the sample (ΔH_m) to the melting enthalpy of a sample with 100% crystallinity (ΔH_m^{100}).

$$X_c = \frac{\Delta H_m}{\Delta H_m^{100}} \times 100 \quad (1)$$

In this case, ΔH_m^{100} has a constant value of 169 Jg^{-1}[35].

3. Result and Discussion

The results from the uniaxial tensile test, illustrated in Figure 2a, indicate that all the blends exhibit tensile strength values that are intermediate between those of the pure polymers, as observed in other studies[29,36,37]. Specifically, the tensile strength of the blends is higher than that of recycled polypropylene (wNWF) (22.8 ± 0.9 MPa) but lower than that of virgin polypropylene (vPP) (30.5 ± 1.2 MPa). As the proportion of rPP increases in the blends, there is a decrease in tensile strength. For instance, the 25vPP75wNWF (23.2 ± 1.7 MPa) blend shows lower strength than 75vPP25wNWF (28.6 ± 1.3 MPa) and 50vPP50wNWF (26.9 ± 1.7 MPa), reducing 18.8 and 13.8%, respectively. These values suggest that the higher the recycled material content in the blend, the weaker the resulting material tends to be, likely due to polymer chain degradation from prior processing cycles. The reduced tensile strength in polymer blends with a higher recycled content can also be attributed to the presence of macroscopic particles remaining in the rPP and to contaminants and processing aids typically present in recycled polymers. Such materials are likely subjected to multiple thermal and mechanical stresses, which deteriorate the polymer chains, contributing to a lower performance compared to virgin plastic[38,39]. The vPP typically has higher mechanical properties due to its unaltered molecular structure, which provides greater strength. On the other hand, the recycled wNWF often exhibits slightly degraded properties due to prior processing and potential contamination, which can reduce molecular weight and some degree of polymer

chain scission as also reported in the literature[40-42]. This intermediate strength demonstrates the influence of blending different proportions of virgin and recycled polymers, which balances the mechanical properties through the synergistic effects of the mixed polymers.

The modulus of elasticity appears relatively consistent across all samples (Figure 2b), suggesting that the vPP and wNWF blend ratios do not drastically alter the material's stiffness. Finally, the elongation at break for vPP is higher than wNWF and blends vPP/wNWF (Figure 2a). The decrease in elongation is more pronounced when the blend has a higher content of wNWF, 25vPP75wNWF. This trend underscores the importance of considering the proportions of virgin and recycled materials in applications where elasticity and the ability to withstand deformation without fracturing are critical.

The SEM images shown in Figure 3 reveal that the inclusion of rPP affects the microstructure of the blend. The vPP exhibits significant plastic deformation, characterized by the presence of elongated fibrils, indicative of its ductile nature. The vPP generally exhibits a ductile failure and good distribution of the matrix filaments in the deformation[43,44]. In contrast, the SEM image of the 50vPP50wNWF blend exhibits a markedly different morphology and shows a noticeably rougher surface compared to the control sample of 100% vPP. The incorporation of recycled material results in a morphology with reduced plastic deformation, displaying a more brittle behavior, as evidenced by the absence of fibrils and the presence of flat regions[44]. This suggests that the recycled content compromises the material's ability to deform plastically. Compared to pure virgin PP, this morphological disparity typically results in reduced mechanical properties, such as lower tensile strength and reduced elasticity (Figure 2b).

Comparing these results with similar studies in the literature, all blends produced by extrusion followed by hot

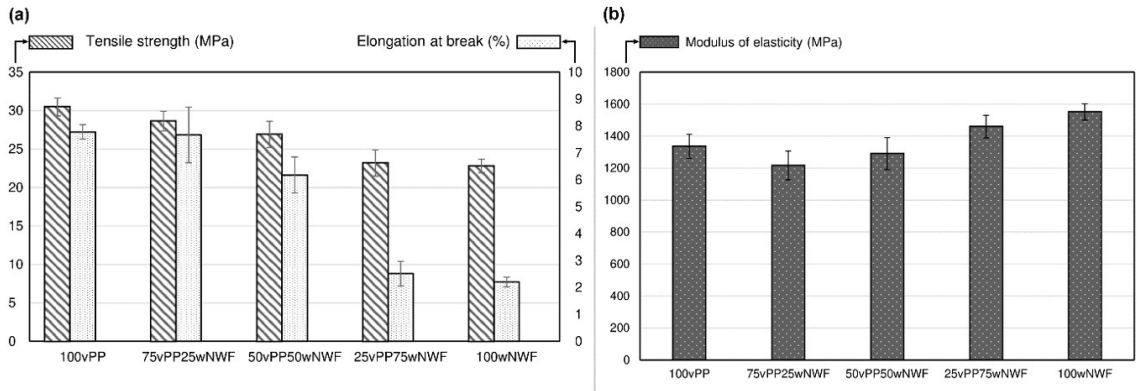

Figure 2. Bar graph showing (a) tensile strength, deformation, and (b) modulus of elasticity of pure polymers vPP and wNWF and blends vPP/wNWF.

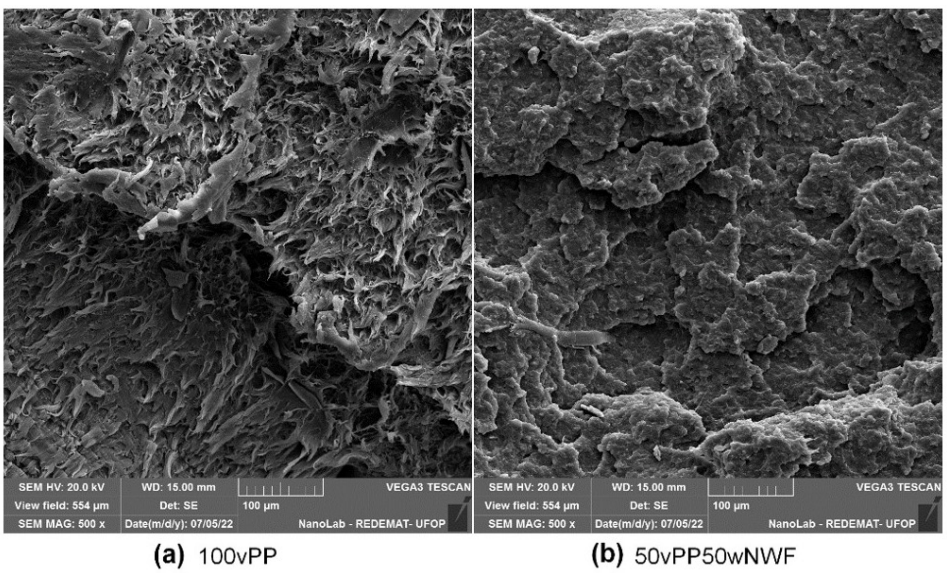

Figure 3. SEM images of the fracture surface after tensile test of the samples (a) 100vPP and (b) 50vPP50wNWF.

compression showed superior tensile strength compared to those made by Barbosa et al.[45], who used injection to mix vPP with wNWF provided by a plastic waste recycling company. On the other hand, these blends showed lower strength than the samples produced by Raj et al.[46] via extrusion followed by injection, using mixtures of vPP with wNWF from a municipal collection center. Therefore, the type of processing appears to be a decisive factor for the performance of the polymeric blends with vPP, being more promising when the extrusion process is combined with compression or injection. The injection products with superior mechanical properties are attributed to better compaction of the samples and the induction of molecular orientation[47,48].

The results of stress and elongation at break to blend are presented in Figure 4. It is noted that pure rPP showed a significant reduction of 37.3% in the blend strength, decreasing from 57.4 MPa to 36.0 MPa compared to vPP. Furthermore, as in the tensile test, the deformation of the blends is intermediate for wNWF compared to vPP. This decrease was expected, as wNWF has a more brittle characteristic and lower deformation capacity than virgin resin[49]. However, the properties are superior to those of wNWF.

The values of the blend strength and maximum flexural deformation with higher vPP contents, 75% and 50%wt, are similar to those obtained for pure vPP, considering the standard deviation. For the blend with 75% wNWF, the obtained values were intermediate between those of the pure materials.

Table 2 presents the average values of absorption of the vPP, wNWF, and blends after 24 hours of immersion in distilled water. All blends, as well as the pure polymer, showed an absorption close to 0.01%. The control sample of wNWF showed absorption of 0.04% by mass, higher than the blends containing virgin resin. This may be due to the additives in the masks, even in small quantities. Overall, the absorption values of all samples indicate an effective interaction between the vPP and wNWF, as well as adequate coating of the blends, without the presence of pores on the surface of the specimens.

The thermogravimetric (TG) and derivative (DTG) curves of the polymeric blends and pure polymers are shown in Figure 5, and the respective temperature data are described in Table 3. The initial degradation temperatures of the samples ranged from 375.7 °C for the blend to 419.4 °C. Although thermal stability in industrial applications is influenced by operational temperature and exposure time, the high onset temperature of degradation further suggests that the materials have adequate thermal stability to withstand a wide range of operational temperatures[50].

The comparison between the thermal degradation curves of vPP and the blend with 25% wNWF shows similar behavior, suggesting good integration of wNWF into the vPP matrix. In contrast, the blend with 75% wNWF exhibits a thermal profile closer to that of wNWF pure, which may indicate a predominance of the wNWF matrix over vPP. Notably, the samples with a lower proportion of wNWF demonstrate thermal degradation at temperatures lower than those of the blends with higher wNWF content and of wNWF pure, reinforcing the idea that rPP can positively contribute to the thermal stability of the blends. At the same time, vPP has a less significant effect in this regard[51].

The blend 50%wt showed a reduction of about 25 °C in thermal stability compared to pure vPP. In contrast, Stoian et al.[29] reported increased thermal stability of blends 50%wt based on vPP and industrial rPP (recycled PP). This difference in results can be attributed to the nature of the recycled PP used in the two studies. In the present work, the recycled PP came from post-consumer waste, which may have resulted in a less efficient dispersion between the polymers, forming heterogeneous regions and compromising thermal stability. This observation is supported by the Differential Scanning Calorimetry (DSC) curves (Figure 6), where during cooling (Figure 6a), two overlapping peaks can be identified, indicating that the materials are not completely mixed and that there is a phase separation, where each PP (virgin and recycled) maintains its distinct crystals, resulting in two thermal events instead of one, as observed in other

Table 2. Average absorption values (%) and respective standard deviations pure polymers vPP and wNWF and blends vPP/ wNWF.

Sample	absorption (%)
100vPP	0.013±0.009
75vPP25wNWF	0.012±0.020
50vPP50wNWF	0.014±0.012
25vPP75wNWF	0.014±0.017
100wNWF	0.037±0.026

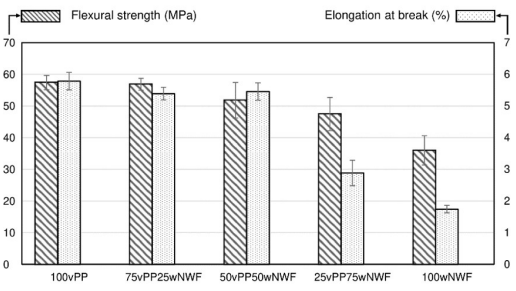

Figure 4. Bar graph of flexural Strength and deformation of blends and pure polymers.

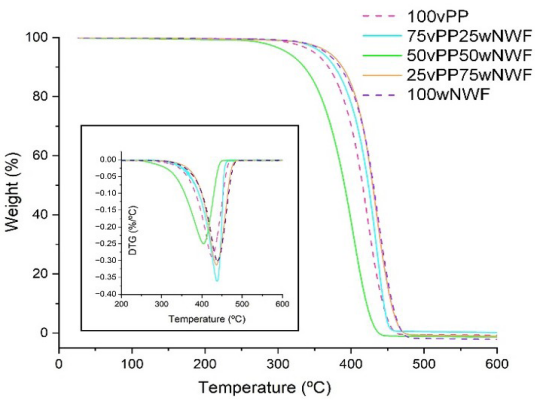

Figure 5. TG and DTG curves.

samples. Similarly, in the second heating curve, there is a broadening in the melting for the mentioned sample, where the initial temperature is 141.80 °C, lower than the initial melting temperature of the control vPP sample, which is 145.23 °C (Figure 6b).

Meanwhile, the study by Stoian et al.[29] used recycled PP from an industrial source, which likely contained inorganic additives and fillers that act by delaying the transfer of decomposition products through mass transport. This mechanism was evidenced by the continuous increase in residual mass with the increment of the rPP proportion, which reached twice that of vPP[29]. This difference between the types of recycled PP used in the two studies highlights the importance of the specific characteristics and composition of recycled materials in determining the thermal properties and stability of the resulting polymer blends.

The Table 4 presents data on melting temperature (Tm), crystallization temperature (Tc), and crystallinity index for different blends vPP/wNWF. The analysis of the data reveals how the presence of wNWF affects the thermal and crystallization properties of the samples. The wNWF showed higher crystalline organization, likely due to its initial fiber morphology, which may have provided additional alignment of the polymer chains. Consequently, the presence of wNWF in the blends increased both the melting and crystallization temperatures. Additionally, wNWF increases the crystallinity of the blend, but in a nonlinear behavior. This variation in crystallinity indices suggests that crystallization efficiency depends not only on the presence of wNWF but also on how it interacts with the PP matrix. In the 50vPP50wNWF blend, the drop in melting temperature can be attributed to the reduced efficiency of interaction between wNWF and the virgin PP matrix, promoting greater difficulty in structural ordering. These disruptions can weaken the chemical bonds, especially at the interfaces between the wNWF and the vPP. The chemical structure of the polymer chains, such as the presence of crystalline regions as opposed to amorphous regions, also plays a fundamental role. Higher crystallinity indicates more ordered regions with stronger intermolecular forces, which increases stiffness.

Table 3. Thermal degradation temperatures and weight loss of blends and control samples.

Sample	T OnSet (°C)	T Mid Point (°C)	T EndSet (°C)	weight loss (%)
100vPP	400.99	417.70	442.49	99.645
75vPP25wNWF	401.38	423,84	447.52	99.818
50vPP50wNWF	375.71	392.75	424.02	99.860
25vPP75wNWF	419.40	431.56	452.97	99.139
100wNWF	415.38	433.31	455.26	99.767

Table 4. Thermal properties and crystallinity index for different blends vPP/ wNWF.

Sample	Tm (°C)	Tc (°C)	Crystallinity index (%)
100vPP	154.6	119.8	57.7
75vPP25wNWF	156.1	119.8	58.4
50vPP50wNWF	157.1	120.2	55.9
25vPP75wNWF	150.1	120.9	58.5
100wNWF	162.1	122.6	68.1

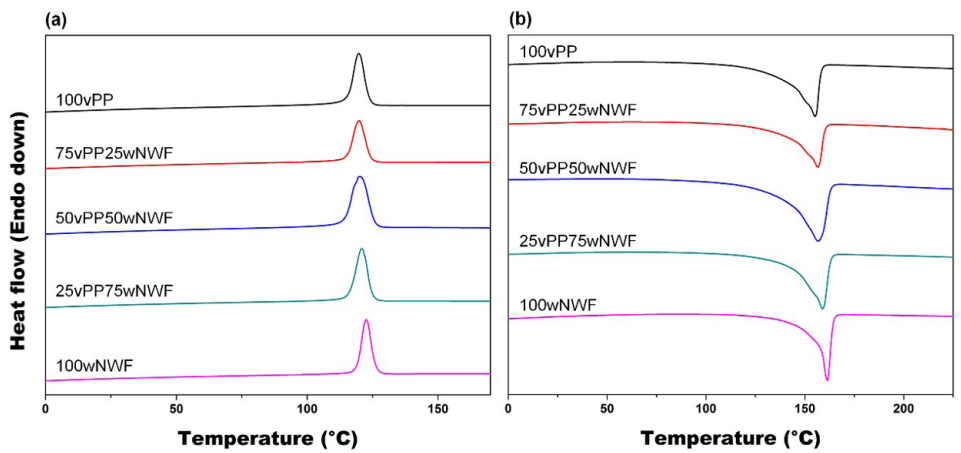

Figure 6. DSC curves of (a) Cooling and (b) second heating of the samples.

The stiffness results (Young's modulus) obtained in the tensile and flexural tests are aligned with the crystallinity indices observed in the different samples. The samples with higher rPP (100% wNWF and 75% wNWF) showed greater stiffness, which can be explained by the higher crystallinity of these blends. However, the tensile strength, which is associated with the material's ability to withstand stress before breaking, was negatively influenced by the lower efficiency of the blend between the wNWF and the PP matrix. The wNWF may act as a defect point in the matrix, weakening the structure and resulting in lower tensile strength. This decrease in strength occurs because wNWF compromises the integrity of the matrix by introducing discontinuities that reduce material cohesion. On the other hand, tensile strength involves plastic deformation of the matrix, unlike stiffness, which is evaluated in the elastic regime and is, therefore, less impacted by defects caused by the presence of wNWF. The same applies to elongation at break, which reflects the material's ability to deform before failure. Thus, while wNWF increases stiffness due to higher crystallinity, it negatively impacts tensile strength, especially at higher concentrations, due to its less efficient interaction with the PP matrix. Nonetheless, the use of wNWF remains a valuable strategy for reducing environmental impact, as it promotes sustainable solutions by incorporating waste materials into polymer blends, aligning with broader industry efforts to minimize natural resource exploitation and manage industrial waste responsibly[10,23].

4. Conclusion

This study investigated the effects of combining rPP from non-woven fabric (NWF) masks (wNWF) and vPP to produce polymeric blends. The mixing was easily accomplished since they are composed of the same polymer (PP), although one is post-consumer. While preparing rPP, fragmentation in a knife mill was chosen to facilitate extrusion, as the equipment used requires manual feeding in the case of low-density materials like NWF.

Although the 75vPP25wNWF sample showed behavior closer to the control vPP sample, its mechanical properties were superior to those of other studies with commercial and recycled PP blends. The addition of wNWF resulted in lower tensile and flexural strengths compared to vPP, but from 50 wt% wNWF, the blends proved to be as rigid as or more rigid than vPP, indicating less tendency to deform. Considering also that the onset temperatures of degradation of the blends are considerably higher than those used during their production, the findings of thermal stability reinforce the viability of the blends as a sustainable alternative for managing plastic waste.

It is concluded that the production of blends contributes to a more appropriate disposal of waste, such as wNWF, than landfilling or incineration processes, which can release harmful emissions into the atmosphere and worsen the effects of climate change. Furthermore, the evaluated methodology can be extended to other hospital waste made with NWF, such as aprons and caps, offering a sustainable solution that reduces environmental impact and promotes recycling valuable resources.

5. Author's Contribution

- **Conceptualization** – Anderson Ravik Santos; Patrícia Santiago de Oliveira Patricio; Wanna Carvalho Fontes.
- **Data curation** – Anderson Ravik Santos; Ítalo Rocha Coura.
- **Formal analysis** – Anderson Ravik Santos; Ítalo Rocha Coura.
- **Funding acquisition** – Patrícia Santiago de Oliveira Patricio; Wanna Carvalho Fontes.
- **Investigation** – Anderson Ravik Santos; Ítalo Rocha Coura; Tiago Vieira da Silva.
- **Methodology** – Anderson Ravik Santos; Ítalo Rocha Coura; Tiago Vieira da Silva.
- **Project administration** – Patrícia Santiago de Oliveira Patricio; Wanna Carvalho Fontes.
- **Resources** – Patrícia Santiago de Oliveira Patricio; Wanna Carvalho Fontes
- **Software** – NA.
- **Supervision** – Patrícia Santiago de Oliveira Patricio; Wanna Carvalho Fontes.
- **Validation** –Patrícia Santiago de Oliveira Patricio; Wanna Carvalho Fontes.
- **Visualization** – NA.
- **Writing – original draft** – Anderson Ravik Santos; Patrícia Santiago de Oliveira Patricio; Wanna Carvalho Fontes.
- **Writing – review & editing** – Patrícia Santiago de Oliveira Patricio; Wanna Carvalho Fontes.

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