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RECYCLED SISAL FIBER-REINFORCED POLYPROPYLENE DERIVED FROM INDUSTRIAL WASTE STREAM

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ABSTRACT
This paper presents the development and comprehensive characterization of recycled polypropylene (rPP) composites reinforced with recovered sisal fibers sourced from secondary agricultural waste streams. The rPP matrix was obtained from post-industrial waste generated during the manufacturing of household appliances at Hisense GORENJE company (Slovenia). To enhance the interfacial compatibility between the hydrophobic polymer matrix and the lignocellulosic reinforcement, maleic anhydride-grafted polypropylene (MAPP) was incorporated at a constant concentration of 3 wt.% as a compatibilizing agent. Composite formulations containing 10, 20, and 30 wt.% of sisal fibers were systematically investigated through mechanical testing (tensile strength, tensile modulus, and impact resistance), morphological analysis (SEM), spectroscopic characterization (FTIR), and thermal analyses (TGA–DTA and DSC). FTIR analysis suggested the interactions between the functional groups of MAPP and the lignocellulosic fibers; however, no distinct absorption band attributable to ester carbonyl formation was detected. SEM observations revealed improved fiber–matrix adhesion in the compatibilized systems, supporting the effectiveness of MAPP in promoting the interfacial bonding. The addition of sisal fibers significantly enhanced the mechanical performance of the rPP, with increases of up to 45% in tensile modulus and 92% in tensile strength at 30 wt.% fiber loading. Nevertheless, the composite containing 20 wt.% sisal fibers exhibited the most favorable balance between stiffness, strength and impact resistance. Overall, the results demonstrate the strong potential of rPP/sisal composites as lightweight, sustainable materials, enabling the dual valorization of industrial and agricultural waste streams and supporting circular-economy-oriented applications in the white-goods sector.

1. INTRODUCTION

The steady increase in global plastic production and consumption has resulted in a waste crisis of considerable magnitude, with annual volumes exceeding 400 million tons. Polyolefins, particularly polypropylene (PP), constitute approximately half of this waste stream. Due to their chemical inertness and extremely slow degradation, the management of post-consumer and post-industrial polyolefin waste presents a major environmental challenge, thereby underscoring the need for advanced valorization strategies and circular economy models (Singh et al, 2023).

The household appliance industry, characterized by high production volumes and a reliance on durable plastic components, is a significant contributor to this stream. At GORENJE, a leading European manufacturer, substantial quantities of post-industrial PP waste, primarily in the form of purges and production lumps, are generated. The INCIRCULAR project, co-funded by the European Union's I3 Programme, was initiated to transform this internally generated waste into high-performance composite materials, with the overarching objective of closing the material loop within the industrial supply chain. In contrast to many previous studies employing model-grade recycled polymers, the rPP used in this work originates from a controlled post-industrial waste stream with documented thermo-mechanical degradation, making the results directly transferable to industrial manufacturing conditions in the white-goods sector. In the pursuit of sustainable material solutions, natural fibers such as flax, hemp, jute, and sisal have emerged as promising alternatives for synthetic reinforcements, in-

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cluding glass fibers. These lignocellulosic reinforcements offer several environmental and functional advantages, including renewability, biodegradability, low density, and the ability to enhance the mechanical performance of polymer matrices (Ajayi et al., 2025). In this study, the sisal fibers (SIS250) were sourced from secondary agricultural waste streams, specifically disused coffee bean bags. This approach provides a dual environmental benefit: the revalorization of industrial waste (rPP) and the upcycling of agricultural waste (sisal fibers). Consequently, the resulting composites represent a high-value, circular-economy material solution (Mahmud et al., 2021). Although numerous studies have investigated natural fiber-reinforced polypropylene composites, the majority focus on virgin PP matrices or prioritize stiffness enhancement at high fiber loadings, often at the expense of impact resistance and processability. Studies specifically addressing recycled polypropylene reinforced with natural fibers frequently remain limited to laboratory-scale formulations or lack direct relevance to industrial waste streams with known processing histories. In this context, the present work advances the state of the art by moving beyond material substitution and focusing on formulation-driven performance optimization. Rather than maximizing fiber content alone, this study identifies an optimal reinforcement window that balances stiffness, strength, and impact resistance in a fully recycled composite system derived from real industrial and agricultural waste streams.

Polypropylene, although recyclable, undergoes considerable thermo-mechanical degradation during repeated reprocessing (Caicedo et. al., 2017). This degradation reduces its molecular weight and negatively affects its mechanical properties, including tensile strength and modulus. The accompanying decline in toughness, typically manifested as a reduction in impact strength of approximately 20%, renders pure recycled polypropylene (rPP) unsuitable for applications that require reliable resistance to dynamic or impact loading. To address this inherent brittleness, reinforcement with high-performance materials is essential (Sanadi et al., 2023; Zhao et al., 2022; Ai-Huei Chiou & Chia-Hua Lin, 2023). The incorporation of natural fibers into polyolefin matrices such as PP presents a fundamental materials challenge arising from the polarity incompatibility. Whereas PP is hydrophobic, sisal cellulose fibers are inherently hydrophilic, resulting in weak interfacial bonding and inefficient stress transfer across the fiber–matrix interface (Ajayi et al., 2025). To address this limitation, polypropylene grafted with maleic anhydride (MAPP) is commonly employed as an effective coupling agent. MAPP acts as a molecular bridge: the PP backbone ensures compatibility with the rPP matrix, while the maleic anhydride moieties chemically react with the hydroxyl (-OH) groups of the sisal fibers. This reaction forms covalent ester linkages that enhance interfacial adhesion and facilitate efficient load transfer within the composite (Ibrahim et al., 2017).

The main objective of this work is to rigorously evaluate and characterize rPP composites reinforced with recycled SIS250 sisal fiber. The effects of three fiber loadings (10, 20, and 30 wt.%) on the mechanical, thermal, and morphological properties of the material are investigated. The analysis aims to identify the optimal formulation that offers the best balance of strength, toughness, and processability, ensuring its suitability as a lightweight structural material for demanding applications in the white goods sector while supporting the waste-recovery model proposed under the INCIRCULAR project. The goal of this study is therefore not only to characterize the composites, but to identify a formulation window that reconciles mechanical performance, toughness, and processability, thereby enabling the practical substitution of virgin, glass-fiber-reinforced plastics in selected white-goods components.

2. MATERIALS AND METHODS

2.1 Matrix and Reinforcement Materials

2.1.1 Recycled Polymer Matrix (rPP)

The polymer matrix consisted of ground recycled polypropylene (rPP) obtained from a single post-industrial waste stream generated by GORENJE IPC Company during the manufacture of household appliances. The material originated from a controlled and homogeneous production process, and all experiments were conducted using material from the same production batch in order to eliminate batch-to-batch variability. It should be noted that the recycled polypropylene was not a neat polymer but contained approximately 30 wt.% of mineral fillers, primarily talc and calcium carbonate, as confirmed by compositional analysis. Thermal characterization by TGA under air further confirmed this filler content, showing a final residual mass of 21.46% at 800°C, corresponding to the thermally stable fraction of the mineral phase remaining after polymer decomposition and carbonate calcination. This inherent filler content contributes to the baseline stiffness and dimensional stability of the rPP, while also affecting its density and thermal behaviour. The presence of mineral fillers was taken into account when interpreting the mechanical and thermal performance of the developed composites.

2.1.2 Recycled Sisal Fiber Reinforcement

The reinforcement component selected were the recycled sisal fibers (SIS250), supplied by J. Rettenmaier & Söhne GmbH. Originating as secondary waste from coffee bean bags, these fibers highlight the circular nature of the material. Fiber loadings of 10, 20, and 30 wt.% were selected to establish a comprehensive performance profile and identify the most effective reinforcement concentration. The fibers were characterized to define their physicochemical properties. Particle size analysis indicated a median fiber length of approximately 300 μm, with the main fraction ranging between 100 and 300 μm. Elemental analysis revealed a carbon content of 38-45%, typical of lignocellulosic biomass. The moisture conFtent, determined according to ISO 18134-2, ranged between 5-8%, requiring drying at 70°C for 8h prior to compounding to prevent hydrolytic degradation during processing. Fiber purity was assessed by loss on ignition (LOI) at 950°C, yielding an ash content of 1.07% ± 0.19, confirming the effective removal of major inorganic impurities during the recycling process.

TABLE 1: Composition of rPP/Sisal (SIS250) Composite Formulations.

Formulation	Fiber load (wt.%)	rPP (wt.%)	SIS250 (wt.%)	MAPP (wt.%)
rPP	0	100	0	0
SIS250 10%	10	87	10	3
SIS250 20%	20	77	20	3
SIS250 30%	30	67	30	3

2.1.3 Coupling Agent (MAPP)

The commercial product Licocene® PP MA 7452 GR (Clariant), a maleic anhydride-grafted polypropylene (MAPP), was used as a compatibilizing agent. Its concentration was fixed at 3 wt.% in all formulations to improve the interfacial adhesion between the polar cellulosic fibers and the non-polar polymer matrix. This loading was selected based on our previous systematic study (Žepič Bogataj et al., 2019), in which 3 wt. % MAPP was identified as optimal for enhancing interfacial morphology and tensile performance in recycled polypropylene composites reinforced with cellulosic fibers, without compromising processability.

2.2 Formulation Design and Composite Preparation

Batches of composite materials were formulated and prepared with the rPP matrix and SIS250 sisal fibers in increasing concentrations as shown in Table 1.

2.3 Processing: Twin-Screw Extrusion Compounding and Injection Moulding

The preparation of the composite formulations involved a carefully controlled pre-mixing and compounding process, given the delicate nature of sisal fibers and the challenges associated with processing of rPP at high fiber loadings.

2.3.1 Pre-mixing and Matrix Preparation

The rPP matrix was first subjected to a classification process to ensure a uniform particle-size fraction, removing both coarse and excessively fine powder material—an essential step for maintaining a consistency during extrusion. The classified rPP, along with the SIS250 sisal fibers and MAPP pellets was then manually mixed to achieve initial homogenization prior to feeding.

2.3.2 Extrusion Compounding and Injection Moulding

Extrusion compounding process (Figure 1) was carried out using a USEON LAB-30 co-rotating twin-screw extruder with a length-to-diameter (L/D) ratio of 44. Processing parameters were carefully optimized to ensure uniform fiber dispersion and promote the MAPP reaction while avoiding thermal degradation of the sisal fibers. The barrel temperature was maintained between 30 and 60 °C in the Feed Zone and gradually increased to 190-195 °C at the Discharge Zone. Screw rotation speed was adjusted inversely with fiber content to minimize fiber damage, with 150 rpm employed for the 10 wt.% fiber formulation and 100 rpm for the 20 wt.% and 30 wt.% sisal composites.

After compounding, all composite formulations, including the reference rPP sample, were subjected to a drying process at 70 °C for 8 h before the injection moulding. Testing specimens were produced using a Fanuc Roboshot ALPHA S50IA/330/IT injection molding machine under controlled processing conditions. The melt temperature was set to 180°C and the mould temperature to 22°C. The injection pressure was 800 bar, with a holding pressure of 500 bar and a back pressure of 20 bar. The injection speed was maintained at 80 mm s⁻¹, and the screw rotation speed

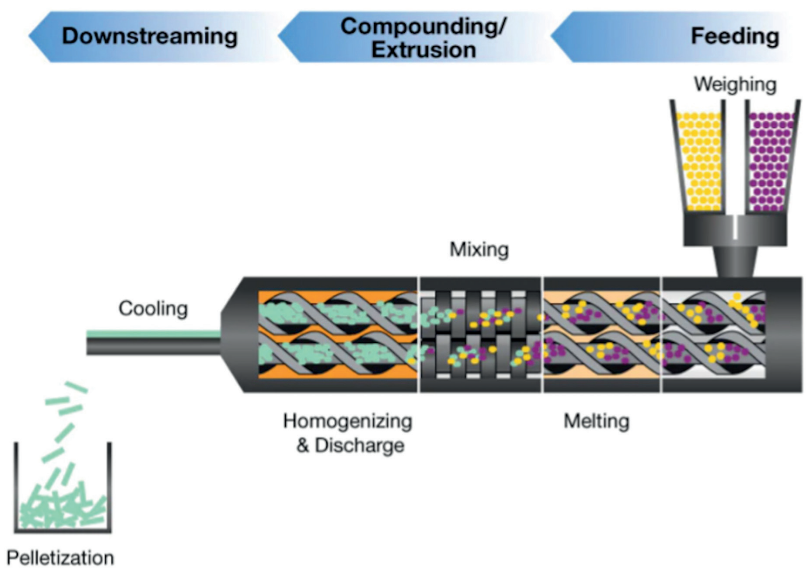

FIGURE 1: Twin extrusion compounding diagram.

was 50 rpm. The total injection cycle time was 40 s, including a cooling time of 20 s. A clamping force of 500 kN was applied during processing. All processing parameters were kept constant for all formulations to ensure comparability of the specimens.

2.4 Characterization Analyses

2.4.1 Mechanical Properties

Tensile strength, tensile modulus, and impact strength were determined in accordance with ISO 527-1/-2 and DIN EN ISO 179 standards. Uniaxial tensile tests were performed to evaluate tensile strength and modulus, providing insight into the load-bearing capacity and stiffness of the materials. Impact resistance was assessed using the unnotched Charpy method to quantify the energy absorption under dynamic loading conditions. For each material formulation, tensile parameters are reported as average values with standard deviation, calculated from measurements on ten specimens (n = 10). Impact strength results are presented as average values with the corresponding standard deviation, based on six specimens per formulation (n = 6). All specimens were conditioned and tested in accordance with the relevant standards to ensure reproducibility and comparability of the results. To evaluate the statistical significance of differences in tensile properties among the rPP and rPP/sisal formulations, one-way analysis of variance (ANOVA, single-factor analysis) was performed. The F-statistic and associated p-value were calculated using a significance level of 0.05.

2.4.2 Thermal Properties

Thermogravimetric analysis (TGA) was performed to assess the thermal stability and degradation behavior of the composites, while differential scanning calorimetry (DSC) was employed to investigate thermal transitions, including melting points and crystallinity, providing insights into the materials' structural characteristics and processability. Simultaneous TGA-DSC measurements were conducted using a TA Instruments SDT Q600 system, which records both heat flow and weight changes as a function of temperature under controlled atmospheres. The system operates from room temperature to 1450°C in either an oxidizing (air) or inert (N_2) atmosphere. Weight loss profiles were monitored as a function of temperature to characterize the thermal stability and decomposition behavior of the materials.

The relative change in onset degradation temperature (T_{onset}) was calculated with respect to neat rPP according to:

$$\Delta T_{onset}(\%) = \frac{T_{onset,ref} - T_{onset,sample}}{T_{onset,ref}} \times 100 \quad (1)$$

where:

$T_{onset,ref}$ is the onset degradation temperature of the reference material (e.g., neat rPP),

$T_{onset,sample}$ is the onset degradation temperature of the composite.

2.4.3 Chemical and Morphological Analysis

Fourier Transform Infrared Spectroscopy (FT-IR) was performed to identify the functional groups and molecular structure of the composite samples and the reference rPP. Spectra were recorded using a Spectrum 100 FT-IR spectrometer (PerkinElmer) equipped with a universal attenuated total reflectance (ATR) accessory. The fractured surfaces of mechanically tested specimens were examined using Scanning Electron Microscopy (SEM) to assess fiber dispersion and interfacial bonding. SEM observations were conducted on a Quanta 250 instrument (FEI Company, USA) under high vacuum at an acceleration voltage of 5 kV, a spot size of 2.0, and a working distance of approximately 9-10 mm.

3. RESULTS AND DISCUSSION

3.1 Mechanical Properties

3.1.1 Tensile strength and Tensile Modulus

Tensile testing confirmed the pronounced reinforcing effect of sisal fibers on recycled polypropylene matrix, demonstrating a progressive increase in both stiffness and strength with increasing fiber content (Table 2). The tensile modulus increased from 2414 MPa for neat rPP to 3492 MPa for the composite containing 30 wt.% SIS250 fibres, corresponding to an enhancement of approximately 45%. Similarly, the tensile strength increased from 21.8 MPa to 41.8 MPa, representing an improvement of about 92%. These results indicate highly efficient stress transfer from the polymer matrix to the fibrous reinforcement phase.

To statistically validate the observed trends, one-way ANOVA was performed on the tensile data. The statistical results are summarized in Table 2. The extremely low p-values ($p < 0.05$) confirm that the differences among formulations are statistically significant. Moreover, the high F-values indicate that the between-group variability (effect of fiber content) greatly exceeds the within-group experimental variability, confirming excellent reproducibility of the measurements. The magnitude of the mechanical improvements—particularly the 92% increase in tensile strength—further demonstrates that the observed enhancements are not only statistically significant but also

TABLE 2: Comparison of tensile parameters — tensile modulus (E_t), tensile strength (σ_M), and elongation at break (ε_t) (mean ± SD) — with corresponding one-way ANOVA statistical results (F-statistic and p–value).

Formulation	E_t [MPa]	σ_M [MPa]	ε_t [%]	F - value	p - value
rPP	2414 ± 58	21.8 ± 0.8	3.7 ± 1.0	11759.6	6.9×10^{-54}
SIS250 10%	2691 ± 34	30.8 ± 0.6	2.9 ± 0.4	36623.7	9.2×10^{-63}
SIS250 20%	3140 ± 42	38.2 ± 0.6	3.1 ± 0.1	37290.6	6.7×10^{-63}
SIS250 30%	3492 ± 58	41.8 ± 0.8	2.7 ± 0.3	25351.8	6.9×10^{-60}

physically meaningful, clearly exceeding typical experimental scatter associated with injection-molded composites.

These findings are consistent with literature reports. Joseph et al. (2003) observed comparable improvements in polypropylene-sisal composites, primarily attributed to the high intrinsic stiffness of fibers and improved interfacial adhesion when compatibilizers such as MAPP are employed. Similarly, Garkhail et al. 2000 reported simultaneous increases in modulus and strength with increasing sisal content, explaining this behavior by the fibers' ability to restrict matrix deformation and carry a signifciant portion of the applied load.

As commonly observed in natural fiber-reinforced composites, the increase in stiffness and strength was accompanied by a reduction in ductility (Table 2). The elongation at break decreased from 3.7% for neat rPP to 2.7% for the SIS250 30 wt.% composite, reflecting reduced polymer chain mobility and the more brittle mechanical response introduced by the fibrous phase. Overall, the results confirm that the incorporation of sisal fiber significantly enhances the stiffness and strength of recycled polypropylene composite, in agreement with well-established trends for lignocellulosic fiber-reinforced PP systems.

3.1.2 Impact strength

Charpy impact resistance (unnotched) indicates that the addition of sisal fiber enhances the toughness of rPP, but only up to an optimum reinforcement level. All fiber-reinforced formulations exhibit higher impact energy than neat rPP (10.6 kJ/m²), as shown in Figure 2. The SIS250 10% composite reaches 11.3 kJ/m² (approximately 7% increase), while SIS250 20% exhibits the highest value, 14.1 kJ/m² - an improvement of about 33% relative to the matrix. In contrast, the impact resistance of SIS250 30% decreases slightly to 12.9 kJ/m², although it remains above that of rPP. This trend indicates that, although tensile strength and modulus increase nearly monotonically up to 30 wt. % fiber loading, impact toughness exhibits an intermediate maximum at 20 wt.%, evidencing a stiffness-toughness trade-off typical of short-fiber composites. This behavior is consistent with the well-established inverse relationship between excessive stiffness and the ability of a composite to absorb impact energy.

At moderate fiber loadings, mechanisms such as fiber pull-out and crack deflection contribute to energy dissipation. However, at higher fiber contents, the formation of agglomerates and microstructural defects – also observed in the SEM analysis – becomes more pronounced. These defects act as stress concentration sites, limiting effective stress transfer across the interface and reducing the composite's ability to absorb dynamic energy. Similar trends have been reported for sisal-reinforced polypropylene composites, where impact resistance increases with fiber content only up to an optimal level and subsequently declines when the reinforcement becomes excessive, primarily due to a reduced effective matrix fraction and heightened stress concentration (Ferede & Atalie, 2022; Muralidhar, 2020). Overall, these findings are consistent with the tensile results: although maximum stiffness and strength are achieved at 30 wt.% of sisal fibres, the most favorable balance between toughness and rigidity occurs at 20 wt.%. This makes the SIS250 20% formulation the most suitable option for applications requiring enhanced impact absorption without compromising structural performance (Žepič Bogataj et al., 2019). In contrast, higher fiber loading (30 wt.%) may limit applicability in impact-sensitive components due to reduced energy dissipation despite increased stiffness.

3.2 Thermal properties

3.2.1 Thermogravimetric analysis (TGA)

TGA analysis performed up to 1000°C confirms the dual effect of sisal fibers on the thermal stability of the composite. All samples remain thermally stable up to approximately 280-300°C (Figure 3), however, the SIS250 formulations exhibit a slightly earlier onset of degradation compared with neat rPP. This behaviour is attributed to the lower intrinsic thermostability of the lignocellulosic constituents of sisal fibres - hemicellulose, cellulose, and lignin – which serve as activation sites for thermal degradation. These findings are consistent with previous studies, reporting that the incorporation of natural fibers decreases the onset temperature of polypropylene due to their higher reactivity and the presence of oxygen-containing functional groups (Patel et al., 2023; Arrakhiz et al., 2013). At high

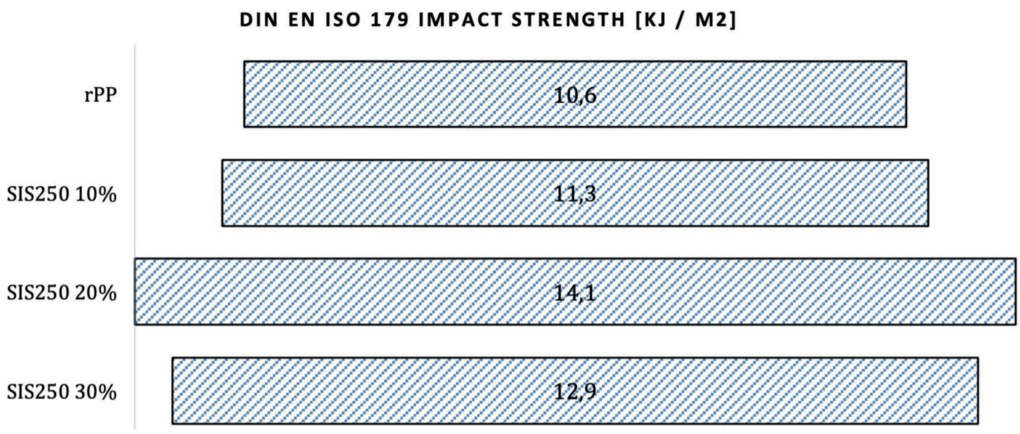

FIGURE 2: Impact Strength kJ/m².

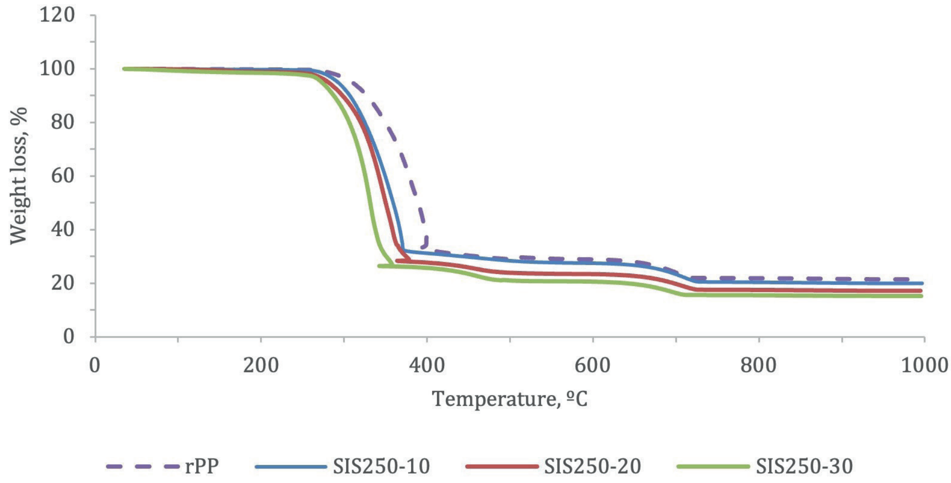

FIGURE 3: TGA of samples: rPP and SIS250 10, 20 and 30 wt.%.

temperatures (700-900°C), the composites show a greater carbonaceous residue than rPP, particularly at 30 wt.% fiber content, indicating enhanced char formation resulting from cellulose carbonization. This carbonaceous residue acts as a physical barrier that restricts heat and mass transfer between the flame and the polymer matrix, a mechanism well-documented to potentially delay flame spread in natural fiber composites (Fan & Naughton, 2016; Tajvidi et al., 2009). While this charring behavior is beneficial for fire-performance scenarios in white-goods components, the associated reduction in the degradation onset temperature (T_{onset}) imposes a limitation on the processing window. Consequently, strict temperature control (below 200°C) is required during extrusion and moulding to prevent the thermal deterioration while leveraging the flame-retardant potential of the high fiber loading. Overall, this thermal behaviour aligns with the morphological observations discussed below and the mechanical results presented earlier. Increasing the fiber content improves stiffness and load transfer but simultaneously introduces microstructural heterogeneities – evident in SEM images – that reduce toughness and increase the material susceptibility to early thermal degradation (Ordoñez Benavides, 2016).

Thus, the observed thermal behavior reinforces the overall interpretation of the materials performance: moderate fiber contents (20 wt.%) provide the best balance among mechanical properties, thermal stability, and microstructural homogeneity. In contrast, higher loadings (30 wt.%) promote increased formation of carbonaceous residue but at the cost of reduced initial thermal stability and diminished impact resistance. From the thermogravimetric analysis, the characteristic degradation temperatures and the final residual mass attributable to sisal can be determined. The corresponding values for each composite family are summarized in Table 3.

Where, T_{onset} (°C) is the initial degradation temperature, $T_{50\%}$ (°C) is the temperature at which 50% mass loss is reached, T_{max} (°C) indicates the temperature at which the maximum degradation rate occurs, and FR (%wt) means the final residue remaining ager degradation. The percentage decrease in onset degradation temperature (T_{onset}) was calculated relative to neat rPP using Equation 1. A reduction of 3.8%, 3.4% and 3.1% was observed for the composite containing 10, 20, and 30 wt. % of sisal fibers, respectively.

The results show that the fiber-reinforced samples exhibit a slightly lower degradation onset temperature (T_{onset}) than neat rPP, indicating that the incorporation of sisal fibers reduces the initial thermal stability of the material. This decrease is attributed to the lower intrinsic thermostability of the lignocellulosic constituents – primarily hemicellulose and cellulose – which degrade earlier than polypropylene and act as activation sites for thermal decomposition, particularly at higher fiber loadings. Consequently, the fibers do not inhibit degradation but rather promote its earlier initiation, a behavior widely reported for natural fiber-reinforced biocomposites (Krishnasamy et al. 2019; Munde et al. 2019; Joseph et al. 2003). Although the addition of sisal fibers reduced T_{onset} to approximately 263°C, this reduction does not compromise the manufacturing feasibility. The extrusion and injection moulding processes were optimized with a maximum temperature profile of 190-195°C

TABLE 3: Relevant temperatures vs. sisal fiber percentage.

Formulation	T_{onset} [°C]	$T_{50\%}$ [°C]	T_{max} [°C]	$FR_{\%}$ [%]	ΔT_{onset} [%]
rPP	274.31	377.55	722.72	21.46	
SIS250 10%	263.90	350.00	730.46	19.96	-3.79
SIS250 20%	265.03	343.14	729.50	17.22	-3.38
SIS250 30%	265.83	327.15	717.07	15.24	-3.09

for extrusion and 180°C for injection, respectively, ensuring a thermal safety margin greater than 60°C relative to the degradation onset. Under these conditions, the residence time in the processing equipment does not induce significant thermal deterioration of the fibers, thereby preserving their reinforcing efficiency. From a service-life perspective, natural fibers may act as thermal catalysts by locally weakening the crystalline structure of polypropylene and promoting earlier degradation. However, for the intended application in white-goods components (e.g., interior parts), where operating temperatures typically remain below 100°C, the composite functions well within its thermal stability range. Therefore, while the reduction in T_{onset} limits its potential use in high-temperature environments (>200°C), it does not adversely affect the durability under standard household appliance operating conditions. This behavior is consistent with the overall thermal and mechanical trends observed: increasing fiber content enhances composite stiffness but simultaneously introduces microstructural heterogeneities that facilitate earlier thermal activation.

3.3 Chemical and Morphological Characterization

3.3.1 Interfacial Interaction using FTIR Spectroscopy

The FTIR spectra of the composites (Figure 4) show that the characteristic absorption bands of polypropylene remain essentially unchanged after the incorporation of sisal fibers, indicating that the crystalline and chemical structure of the rPP matrix is preserved. Only slight variations in band intensity and baseline are observed, which are attributed to the presence of lignocellulosic components in the fibres - principally hydroxyl (–OH) groups and C–O–C vibrations. Regarding chemical interactions, the spectra did not reveal a distinct new peak corresponding to the ester linkage (expected near 1700-1740 cm^{-1}). This absence is attributed to the low concentration of MAPP coupling agent (3 wt. %) and the overlap of the carbonyl signal with the dominant spectral envelope of the polypropylene matrix. Such limitations are consistent with previous reports on MAPP-reinforced composites, where the esterification bands were either masked or below the detection limit of standard FTIR-ATR measurements (Bassyouni et al 2018; Bermello et al 2008).

While complementary techniques such as XPS could theoretically isolate surface chemical changes, the effectiveness of compatibilization in this study is strongly evidenced by the macroscopic performance. The significant increase in tensile strength (up to 92% relative to neat rPP) and the fiber wetting observed in SEM micrographs demonstrate efficient stress transfer across the interface. Overall, the FTIR analysis supports the interpretation that the composite behavior is governed by adequate interfacial compatibility and physical adhesion, which is corroborated by the mechanical results rather than by the isolated detection of new chemical bonds (Paredes García, 2024).

3.3.2 Fracture morphology by SEM

Scanning electron microscopy (SEM) analysis confirms the close relationship between microstructural features and the mechanical and thermal behavior of the rPP-sisal composites. Neat rPP exhibits a homogeneous and ductile fracture surface, whereas the formulations with moderate fiber contents, particularly SIS250 20%, display well-dispersed fibers with excellent wetting and strong interfacial adhesion (Figure 5). This is evidenced by matrix residues adhering to the fiber surfaces and the absence of significant voids. Such morphology promotes efficient

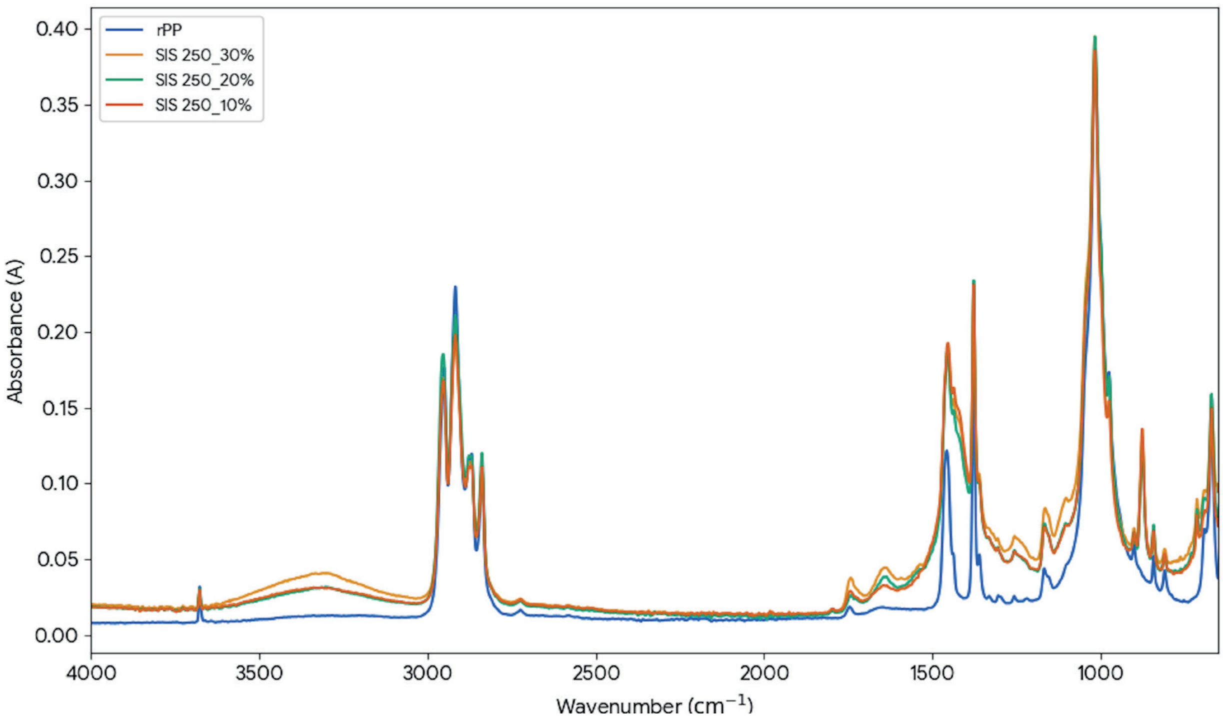

FIGURE 4: FTIR Spectra of a) rPP, and b) composite samples.

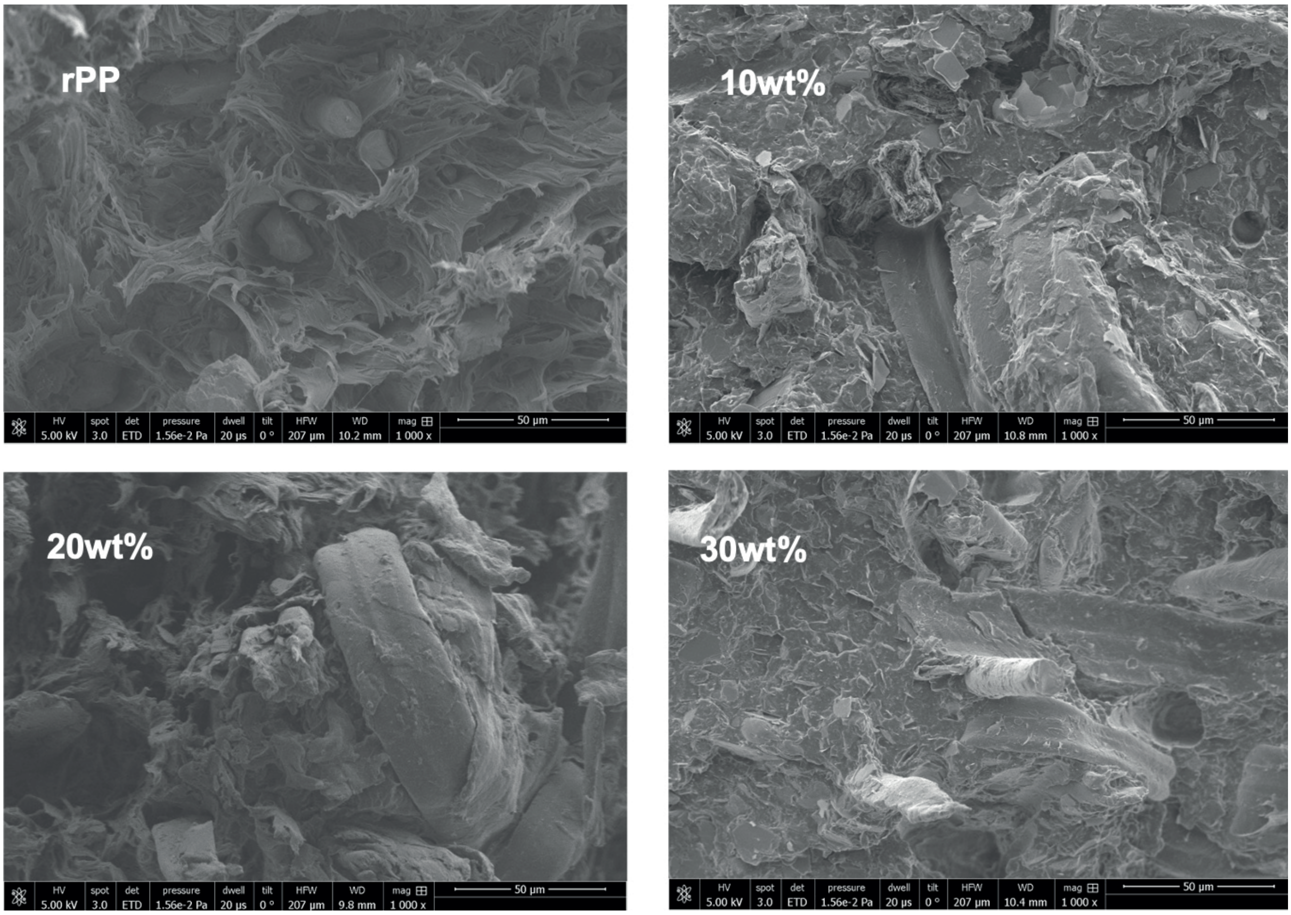

FIGURE 5: SEM images for rPP composites reinforced with 10 wt. %, 20 wt.% and 30 wt.% of sisal fibers.

load transfer through the MAPP-compatibilized interface and enables energy-dissipating mechanisms such as controlled fiber pull-out, in which fibers slide from the matrix during fracture. These mechanisms explain why this formulation achieves the most favorable balance among stiffness, strength, and toughness. In contrast, the composites containg 30 wt.% of sisal fibres, show the presence fo fiber agglomerates, interfacial voids, and regions of incomplete impregnation. These microstructural defects act as stress concentrators and reduce the materials ability to absorb energy, consistent with the observed decrease in impact resistance and elongation at break for this formulation. This behavior coincides with reports in the literature on PP composites reinforced with lignocellulosic fibers, where excessive fiber loading weakens interfacial efficiency and generates defects that diminish toughness despite increasing stiffness (Faruk et al., 2014; Essabir et al., 2013). Overall, the SEM observations corroborate the mechanical trends and are consistent with thermal analysis, which likewise indicates increased structural heterogeneity and higher initial reactivity in composites with elevated fiber content.

3.4 Industrial Feasibility, Resource Considerations and Potential Applications

The developed rPP/sisal composites demonstrate favorable potential for industrial implementation. Based on the present study, the 20 wt.% fiber formulation provides the optimal balance between stiffness, tensile strength, and impact resistance, while remaining compatible with realistic material availability. Post-industrial polypropylene waste is generated in substantially larger volumes than suitable lignocellulosic streams, suggesting that partial substitution, rather than high-fiber loadings, represents a more scalable strategy. Although natural fibers may be cost-sensitive in certain markets, sisal fibers are accessible not only through agricultural supply chains but also via urban post-consumer streams, such as discarded coffee sacks, ropes, carpets, and packaging textiles, providing additional opportunities for localized material recovery. From an economic perspective, the use of post-industrial polypropylene reduces reliance on virgin feedstock, while moderate fiber incorporation minimizes processing complications and avoids excessive material costs associated with high natural-fiber contents. As the composites were produced using conventional compounding and injection molding without specialized modifications, the approach is fully compatible with existing manufacturing infrastructure, supporting industrial scalability and transferability to regions with comparable waste streams and processing capabilities. Building on the mechanical and thermal characterization presented in this study, the 20 wt.% rPP/sisal formulation exhibits properties suitable for lightweight structural and semi-structural applications. Potential uses include white-goods components, such as clips, panels, and housings, as well as automotive interior parts requiring moderate stiffness and impact resistance. The materials are compatible with conventional injection molding, facilitating integration into existing manufacturing lines. Furthermore, the concept can be extended to hybrid composites or alternative lignocellulosic waste streams, enabling broader implementation within regional circular value chains and further supporting the objectives of the INCIRCULAR project.

4. CONCLUSIONS

This study demonstrates the technical feasibility and high potential of recycled polypropylene (rPP) composites reinforced with recycled sisal fiber (SIS250) for structural applications in the white goods sector. The proposed material system embodies the principles of the circular economy by simultaneously valorizing post-industrial polymer waste (rPP from Gorenje) and secondary agricultural waste (sisal fibers recovered from coffee bags). The most significant outcomes of this research are summarized as follows:

- Effective Mechanical Reinforcement: The addition of sisal fibers in combination with MAPP compatibilizer, produced highly efficient load transfer. The composites exhibited substantial improvements in stiffness (tensile modulus up to +45%) and tensile strength (up to +92%) at 30 wt.% sisal relative to neat rPP.
- Optimal Formulation: Although the 30 wt.% formulation provided the highest stiffness, the SIS250 20% composite offered the most balanced mechanical profile. It achieved the maximum Charpy impact strength (+33% compared with rPP) while maintaining significant gains in stiffness and strength, making it the most mechanically robust and energy-absorbing formulation.
- Morphological Validation: SEM observations confirmed excellent fiber-matrix adhesion and uniform dispersion at 20 wt.% of sisal fibres added, enabling efficient stress transfer. At 30 wt.%, however, fiber agglomerates and interfacial voids appeared, acting as stress concentrators and reducing toughness, fully consistent with the mechanical trends.
- Thermal Stability: The addition of sisal fibers slightly lowered the degradation onset temperature due to the lower intrinsic thermal stability of lignocellulosic components. However, composites with higher fiber contents exhibited increased carbonaceous residue at elevated temperatures. While this char formation suggests a positive tendency towards improved fire reaction behavior, specific flammability testing (e.g., UL-94) would be required to certify this performance.
- Industrial Viability: The SIS250 20% composite emerges as a promising candidate for semi-structural components in the white-goods sector. While long-term durability tests (fatigue, creep) are recommended for critical load-bearing parts, the current static mechanical profile meets the requirements for various rigid casing and internal support applications, demonstrating that the dual valorization of polymer and natural-fiber waste streams can yield high-performance materials. Neverthelles, future studies should evaluate the potential long-term effects, including moisture uptake, biodegradation, and UV exposure, to confirm the composite's durability under industrial service conditions.

Overall, this study supports the circular-economy strategy advanced within the INCIRCULAR project by demonstrating the technical feasibility of transforming post-industrial polypropylene waste into high-performance bio-composites through conventional processing technologies. The findings provide material-level validation for scalable circular value chains integrating recycled plastics and lignocellulosic reinforcements, supporting further pilot-scale implementation and end-of-life circularity assessments. While the environmental benefits of this approach are discussed qualitatively, a comprehensive life-cycle assessment (LCA) would be required to quantitatively substantiate reductions in environmental impact, representing an important direction for future work.

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