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Effect of Chopped Glass Fibers on the Mechanical Properties of Virgin Polypropylene and Recycled Polypropylene Blends

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ABSTRACT

In this study, the effect of chopped glass fiber (CGF) reinforcement on the mechanical properties of polypropylene blends containing equal proportions of virgin and recycled polypropylene (RPP) (50/50 wt.%) was investigated. The composites were fabricated by incorporating E-glass fibers (3–12 mm length and 13 µm diameter) at different weight percentages (15, 25, and 35 wt.%) using a twin-screw extrusion process. Tensile and impact tests were conducted to evaluate mechanical performance, while scanning electron microscopy (SEM) was used to examine the fracture surface morphology. The results revealed a significant improvement in the mechanical properties when the blend was reinforced with glass fibers. The composite containing 25 wt.% CGF exhibited the mechanical performance, with a tensile strength of 92.2 MPa and a Young's modulus of 1.19 GPa, corresponding to improvements of approximately 193% and 183%, respectively, compared with the unreinforced blend. The highest impact resistance (20.20 kJ/m²) was also obtained at this fiber content. Conversely, increasing the fiber content to 35 wt.% resulted in a decline in mechanical performance. These results demonstrate that reinforcing virgin and RPP blends with CGFs is an effective way to improve their mechanical properties. The sample containing 25 wt.% CGF exhibited the best balance between strength, stiffness, and impact resistance, highlighting its potential for sustainable semi-structural and automotive applications while supporting the efficient utilization of recycled polymer materials.

1. INTRODUCTION

Global thermoplastic production has increased annually. Following a pandemic-related decline in international markets, the world has seen a serious rebound, and the application of polymer materials in novel uses and their adaptation has increased sharply. The use of plastics is also widespread across various markets, including automobiles, electronics and electrical, home appliances, packaging, consumer electronics, buildings, agriculture and horticulture, medicine, and sports. These are primarily polymeric substances and are members of thermoplastics. A key advantage of thermoplastics is their reprocessability; however, this potential is often underutilized, leading to significant landfilling [1-4]. Recycling is the process of converting used materials or waste into new and usable products to conserve natural resources and reduce reliance on conventional waste disposal methods. This process helps lower energy consumption, decrease air and water pollution, and reduce greenhouse gas emissions compared to the production of plastics from virgin materials. Recycling is a key component of the waste management hierarchy, along with waste reduction and reuse. Improper waste disposal leads to environmental pollution that negatively affects climate, human health, and environmental sustainability, making recycling an effective approach for achieving a cleaner and more sustainable environment [5, 6].

The European market has a thermoplastic production capacity of 58.7 Mt/year and 18.5% is in the form of mechanically recycled thermoplastic. The reported value includes 12.9% of post-consumer mechanically reprocessed materials and 5.6% of pre-consumer mechanically reprocessed materials. The European market has also the 0.2 level of recycling of chemicals. The use of bio-based plastics is 1% in volume, producing 1.7 Mt of bio-based and biodegradable polymers annually [7]. Polypropylene (PP) is one of the most extensively manufactured and utilized thermoplastic polymers in various industrial applications. PP has a wide variety of properties despite its straightforward chemical structure. The length of the PP polymer chains directly affects its molecular weight. PP plastics contain a variety of additives in addition to polymer chains. As a result, the type and quantity of additives, fillers, and reinforcements employed, along with the polymerization process, have a significant impact on the final qualities of PP [8]. PP is one of the most frequently used plastics in the production of automotive and industrial lead-acid batteries [9].

The large supply of thermoplastic-based composites in the market also contributes to the low rate of plastic waste reuse. These consist mostly of compounds filled with all kinds of fibers, especially glass fibers (in short, long, and continuous fibers) in increasing numbers of applications. Numerous examples can be found in the literature that analyze the effects of recycling or the application of recycled materials for the creation of new polymer materials [10-12].

This study is innovative in that it investigates the incorporation of pre-consumer waste streams to achieve a mixture consisting of the original polymer with regranulates and glass fibers that have not been subjected to recycling. The mixtures were produced using a compounding extruder. The majority of other authors provide research findings that are based on the recycling of polymer composites that contain glass fibers, or they analyze the properties of thermoplastic composites produced from secondary raw materials [13-16].

Significant efforts have been dedicated to designing and implementing lightweight structures to optimize energy efficiency across various industries. This is especially important in the automotive and aerospace industries, where weight reduction is directly proportional to energy savings. Continuous fiber-reinforced composites are commonly used in these industries; they are usually expensive, elaborate, and time-consuming to manufacture. Conversely, chopped fiber-reinforced composites are a cheaper and more manageable substitute that offer the same mechanical endurance and functionality for different testing procedures. Research studies have mostly been conducted on polymer matrix composites and not on metal or ceramic matrix composites because of their wide applicability. Several researchers have investigated ways of augmenting the properties of chopped fiber composites, and the literature shows that these composites have a lot of potential to be utilized in practice [17].

The twin-screw extruder has been designed to combine many processes, such as melting, mixing, and chemical reactions, into one process, which improves the efficiency of manufacturing processes [18]. This type of extruder provides the ability to control the temperature in the various areas of the barrel accurately, whereas the pressure is controlled by the screw design and rotational speed [19]. A twin-screw extruder is usually composed of three primary areas: the feeding, conveying, and intensive mixing zones. This is attributed to its high flexibility because of the ability to adjust the screw configurations based on the processing requirements [20]. There are two operational modes for extruders: co-rotating and counter-rotating. The counter-rotating mode is particularly effective in generating high pressure, which finds considerable application in the plastics industry [21].

The basic theoretical concepts related to the interfacial bonding between fibers and matrices, stress transfer behavior, and micromechanical modeling determine the mechanical performance of fiber-reinforced thermoplastic composites. The bonding between the PP matrix and glass fibers is essential for enhancing the successful transfer of stress by the ductile matrix to the stiff reinforcing fibers, thereby enhancing the stiffness and strength of the composite. The primary method of stress transfer in chopped fiber reinforced systems is interfacial shear stress, and its efficiency depends on the length, orientation, volume fraction, and quality of the fiber-matrix interface. The rule of mixtures and other analysis methods are typically used to approximate the composite properties, in which there is an ideal sharing of loads between the phases. The advanced micromechanical models, nevertheless, such as the Halpin-Tsai equations, are commonly used in short and discontinuous fiber systems since they are capable of accounting for the geometries of fibers, aspect ratio, and reinforcement efficiency. These theoretical frameworks are excellent starting points for explaining the differences in the experimentally measured mechanical properties of chopped glass fiber (CGF)-reinforced PP composites [22-25].

The mechanical behaviors of RPP and glass fiber-reinforced PP have been studied in several studies. Handayani et al. [26] determined the mechanical properties of commercial RPP prepared according to the standards of ASTM D638 Type II and found a yield strength of 16.357 + 2.65 MPa, a Young's modulus of 295.926 + 41.97 MPa, and an ultimate tensile strength of 19.701 + 1.261 MPa. The authors indicated that the yield stress of RPP was inferior to the already described values (approximately 21 MPa), but they explained the disparity by the variations in the quality of raw materials and previous processing. Similarly, Khademi et al. [27] studied the effect of the content of recycled materials, annealing conditions, and the addition of glass fiber on PP at room temperature. Their findings showed that the increase in recycled content influences the mechanical properties in a non-linear manner, and annealing contributes significantly to the yield strength (more than 10%) and Young’s modulus (approximately 50%). The inclusion of the glass fiber also increased the stiffness and yield stress by approximately 50%, which illustrates the efficiency of the fibers in reinforcing the systems, even when they are recycled. Colucci et al. [28] examined the impact of mechanical recycling, which involves auto parts reinforced with glass fibers, in the context of glass fiber-reinforced PP composites. Even though the tensile, flexural, and elastic modulus decreased slightly after recycling, a morphological study by scanning electron microscopy (SEM) revealed that both the microstructure and fiber-matrix interface were not significantly affected; therefore, recycled composites could be used in structural automotive applications. Moreover, an overall assessment conducted by Sathishkumar et al. [29] demonstrated the wide applicability of glass fiber-reinforced polymer composites in any industry because they are very strong, rigid, flexible, and chemically resistant. The review emphasized that the mechanical, thermal, tribological, and durability characteristics of such composites strongly depend on fiber type, form, and interfacial bonding within the polymer matrix.

This study aims to shift the focus to a circular economy, which has become a strategic focus at the global level, especially in areas where regulatory frameworks are increasingly focused on a higher percentage of recycling in manufactured goods [30, 31]. In this context, PP is one of the most important thermoplastics because it is widely used in the automotive industry, battery casings, packaging, and consumer goods [32]. Nonetheless, even though recycled polypropylene (RPP) can be recycled, there is a severe drop in mechanical characteristics due to thermo-oxidative degradation, chain scission, and contamination during the service life and reprocessing process that reduces the industrial reuse of RPP [33, 34]. Recycled PP also has low tensile strength, rigidity, and impact resistance, which is a major hindrance to the use of the material in load-bearing and semi-structural components [35]. As a result, recycled PP can be commonly down-cycled into low-value products, preventing the ability of circular material flows from being effective. Thus, it is important to eliminate this performance difference, support high-value reuse of recycled polymers and decrease the reliance on virgin raw materials [31, 36]. Fiber reinforcement is generally known to be an efficient method for addressing the loss of strength in degraded polymer matrices. Glass fiber-reinforced PP has already been employed in the automotive industry because it is characterized by a good strength-to-weight ratio, cost-effectiveness, and compatibility with processing [37, 38]. This is mainly attributed to the mechanical strengthening due to the effective stress transfer processes at the intersection of the fiber and matrix and the limitation of the polymer chain mobility [38]. Nevertheless, most past research has been conducted on virgin PP based on glass fiber reinforcement or recycling of existing fiber-filled composites [39, 40]. No systematic study has been conducted on the restoration of performance of industrially realistic reinforced virgin/recycled PP blends with CGFs with controlled compositions that reflect the manufacturing practice. Virgin polymers can never replace industrial cases, which have to regulate their quality and consistency. Alternatively, the use of both strategies, including 50/50 proportions of virgin and recycled plastics, is trendy in order to reach a compromise between cost reduction and performance stability [41]. Consequently, future studies on the reinforcement mechanisms in such realistic blend compositions are required to render laboratory results in the industry. The current study fills this gap by assessing the influence of CGF reinforcement (15, 25, and 35 wt.%) on the mechanical performance of a 50/50 virgin polypropylene (VPP)/RPP blend. This work can be utilized to create a viable material design pathway to enhance RPP for semi-structural and automotive applications by determining an optimal level of reinforcement that can restore tensile strength, stiffness, and impact resistance without compromising acceptable levels of ductility to support circular manufacturing strategies.

2. MATERIALS AND METHODS

2.1 Materials

I. PP: The polymeric structures used in this experiment were VPP and RPP. SABIC provided VPP, an automotive-grade homopolymer polypropylene. According to ASTM D1238, the VPP had a melt flow index (MFI) of 9 g/10 min (230 °C/2.16 kg), which is sufficiently processable during melt compounding and injection molding processes. ASTM D1505 measured the density of VPP as 0.89–0.90 g/cm³.

Post-consumer automotive batteries were used to obtain the RPP. Before processing, the material was mechanically shredded and subjected to a standardized cleaning process, which included washing with a dilute aqueous solution of sodium hydroxide (NaOH) to eliminate remnants of electrolytes, surface contaminants, and attached organic impurities. The sample was then washed in warm distilled water and dried at 50 °C to room temperature to remove the remaining moisture.

To ascertain the reliability of the experiment, the RPP was described in terms of its rheological and physicochemical properties. ASTM D1238 showed that RPP had an MFI of 25 g/10 min (230 °C/2.16 kg), which is lower than the original molecular weight because of prior service exposure and reprocessing. RPP had a density of approximately 0.87 g/cm^3 (ASTM D1505). To ensure the reliability of the experimental results, the RPP was characterized in terms of its key physicochemical properties. The molecular weight distribution of RPP in the extrusion process typically ranges from 200,000 to 350,000 g/mol. During extrusion, exposure to high temperature and shear may cause a slight reduction in the molecular weight due to thermal degradation, while retaining the essential properties of the polymer.

The oxidation degree of the RPP depends on the number of recycling cycles, which was not determined in this study, as it was not required.

Potential impurities in the RPP, such as residual fillers, leftover acids, oils, greases, and inorganic contaminants originating from the battery casing, were minimized through the cleaning process. No significant contamination that could adversely affect processing or interfacial bonding with the glass fibers was detected.

Based on these characterizations, RPP was deemed suitable for the partial replacement of VPP in glass fiber–reinforced composites, allowing a meaningful assessment of mechanical performance while maintaining material sustainability. The use of both VPP and RPP strikes a balance between the consideration of sustainability and the relatively acceptable mechanical performance of glass fiber-reinforced composites.

II. CGF: JUSHI Group Co., Ltd. provided CGF 562A of a commercial grade. The fibers are E-glass in nature, and they are sized with a silane-based sizing, which is intended to enhance the interfacial bonding between the fibers and the polymer matrices. The mean diameter of the fibers was 13 µm, and the fibers were provided in chop lengths of 3-12 mm, with uniform dimensions, as it offers a compromise between fiber dispersion and stress transfer efficiency. The glass fibers had a low moisture level (without exceeding 0.10) and a loss on ignition (LOI) of 0.80 ± 0.15, indicating that they were well treated and processed on the surface. The selected cut glass fibers are well dispersed, exhibit a low fuzzing nature, and have good flowing properties, making them compatible with thermoplastic processing methods. These properties render the fibers especially suitable for the strengthening VPP/RPP mixes that are to be used in structural and semi-structural parts, including automotive brackets. Table 1 illustrates materials used in the preparation of VPP/RPP reinforced with CGFs.

Table 1. Materials used in the preparation of VPP/RPP reinforced with CGF

Material	Grade / Type	Supplier	Key Technical Properties	Purpose
VPP	Homopolymer PP	SABIC	MFI (typical automotive grade): 9 g/10 min (230 °C/2.16 kg); Mw ≈ 250,000–500,000 g/mol	Primary polymer matrix
RPP	Post-consumer PP	Automotive battery casings (local source)	Higher MFI than VPP (indicating moderate molecular weight reduction); Mw estimated within typical PP range (≈ 200,000–350,000 g/mol); cleaned and dried prior to extrusion	Partial replacement of VPP
CGF	562A, E-glass	JUSHI Group Co., Ltd.	Filament diameter: 13 µm; chop length: 3–12 mm; silane-based sizing compatible with PP	Reinforcement agent

Note: Virgin Polypropylene (VPP), Recycled Polypropylene (RPP), Melt flow index (MFI), Chopped Glass Fiber (CGF).

Table 2. Experimental design and composite formulations of VPP/RPP blends

Reinforced with CGF Sample Code	 VPP (wt.%)	 RPP (wt.%)	**CGF (wt.%)**	**Fiber Lengths (mm)**	**Fibers Diameter (µm)**
VPP/RPP	50	50	0	_	_
CGF-15%	50	50	15	3-12	13
CGF-25%	50	50	25	3-12	13
CGF-35%	50	50	35	3-12	13

Note: Virgin Polypropylene (VPP), Recycled Polypropylene (RPP), Melt flow index (MFI), Chopped Glass Fiber (CGF).

2.2 Methods

2.2.1 Composite formulations and experimental design

The purpose of the experimental design was to determine the impact of the content of CGF on the mechanical characteristics of VPP/RPP blends using the extrusion process. A weight ratio of 50/50 was used to indicate a realistic recycled polymer blend that can be used by industries. This ratio is very beneficial for industries seeking to decrease their cost by utilizing recycled materials [27]. The extrusion process was carried out at a temperature range of 155–165 °C in zones 1 and 2, with the pressure depending on the screw's motion, and no specific pressure value is defined. The reinforcing effect was assessed by altering the degree of weight fraction of CGFs. The composite formulations were prepared with different glass fiber contents, as listed in Table 2.

2.2.2 Preparation of composite samples

The weight ratio of VPP and RPP was determined, and blend fabrication was performed with a blend of the two polypropylenes: VPP/RPP. Before compounding, the two polymers were dried to eliminate moisture traces, and stable processing conditions were assured. The blending procedure was aimed at deriving a homogeneous polymer structure and maintaining the mechanical integrity of the used PP.

Following the VPP/RPP, blends were prepared, with CGFs added at several weight fractions, as shown in Table 2. The presence of silane on the glass fibers promoted adhesion between the fibers and the matrix, enabling successful stress transfer when the subject was subjected to mechanical loading. Compounding was performed using a twin-screw extruder model (SLJ30A) to uniformly disperse the fibers in the polymer matrix. The screw fed the hopper of the mixed materials. The materials were then pumped through the barrel while it was heated by conduction via the barrel heaters and subjected to shear due to its movement along the screw flight. At the conclusion of the extrusion, the melt flows through a die in the form of a sheet. The extruder was operated at a screw speed of 25 rpm. The blends were prepared at temperatures of 155–165 ℃ in zones 1 and 2.

After the material melts and emerges from the extruder, it is pressurized through two co-rotating rollers to achieve a high molecular orientation and remove voids. The samples were cut into the required shapes using a Computer Numerical Control (CNC) laser machine according to the ASTM standards for tensile and impact tests, which is important for industrial production in automotive and semi-structural parts.

2.2.3 Analysis of mechanical characteristics: Tensile and impact test

The tensile and impact characteristics of the produced VPP/RPP composites reinforced with CGFs were evaluated to investigate the influence of the glass fiber addition on the mechanical performance of the blend.

Tensile Test. During tensile testing, key mechanical parameters were determined, including tensile strength, elongation at break, and Young's modulus. The machine used for testing the tensile properties was a microcomputer-controlled electronic universal testing machine (WDW-5E) model, China, according to ASTM-D 638, and the dimensions of the specimen are shown in Figure 1. The two ends of the sample were connected to the jaws of the device. The test was conducted at an applied load (5 KN) and speed (10 mm/min) for all samples at room temperature. Tensile stress was applied until the sample failed. The tensile test results were used to evaluate the influence of CGF reinforcement on the elastic modulus, tensile strength, and deformability of VPP/RPP composites.

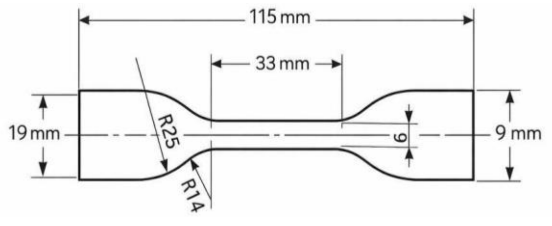


Figure 1. Dimensions of specimen tensile test [42]

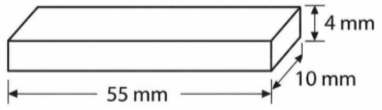


Figure 2. Dimensions of specimen impact test [42]

Charpy Impact Test. In the Charpy Impact Test, Charpy impact strength was determined using a tester Model WP 400 German, Gunt (HAMBURG) Company, according to ISO-179, and the dimensions of the specimen are shown in Figure 2. The machine used for testing the tensile properties is a WDW-5E model. The specimen was fixed to its respective position, and then the energy gauge was started (at the zero position), followed by the freeing of the pendulum, where the potential energy was converted to kinetic energy. Three samples of the pendulum were taken, and the average of these values was calculated. To compute the impact strength, the relationship is applied as shown in Eq. (1):

$$I.S = \frac{UC}{A} \tag{1}$$

where,

- S: impact strength of the material (KJ/m^2).
- UC: impact energy (KJ).
- A: cross-sectional area of the sample (m^2).

The impact test was conducted to examine the influence of CGFs on the VPP/RPP blend and calculate the impact strength. The obtained results provide essential insights into the potential of VPP/RPP composites reinforced with CGFs for industrial applications, particularly in automotive and semi-structural components, while supporting material recycling and sustainable manufacturing practices.

2.2.4 Analysis of the morphology test

In both organic and inorganic materials, SEMs provide effective approaches for monitoring and characterizing surfaces, providing significant data regarding the sample morphology. In this study, the homogeneity of the blend was examined, and the bonding between the glass fiber and PP was studied. The samples were examined with a VEGA III Series, TESCAN, SEM, Belgium. The surface of each sample was coated with gold (Au) before the test to improve its electrical conductivity.

3. RESULTS AND DISCUSSION

3.1 Mechanical properties

3.1.1 The results of the analysis of the impact strength of the tested samples

Table 3 and Figure 3 present the impact strengths of the VPP/RPP composites, based on the CGF content. The results show that the impact strength is increased when the glass fibers are introduced over the unreinforced VPP/RPP mixture. It also indicates an increase in the impact strength associated with that of the neat blend, from 11.98 kJ/m^2 to 18.60 kJ/m^2 and 20.20 kJ/m^2 at 15% and 25 wt.% CGF contents, respectively. This can be explained by the reinforcing effect of the fibers, which absorb and dissipate the impact energy through fiber breaking, fiber pulling out, and better redistribution of the stress in the polymer matrix.

The impact strength decreased significantly at a higher fiber loading of 35 wt.% to 11.21 kJ/m^2. This decrease is greatly attributed to the fact that the composite becomes brittle at high levels of fiber content. High fiber contents inhibit the mobility of polymer chains, impair the plastic deformation capability of the matrix, and may cause fiber agglomeration and low stress transfer, causing the onset of cracks and their rapid growth.

The highest impact performance at 25 wt.% CGF content suggests that there is an equilibrium between the reinforcement efficiency and ductile composites. In this structure, the fibers are adequately distributed to maximize the energy uptake without reducing the toughness of the PP matrix. According to previous research, intermediate fiber loadings have better impact properties than low or very high fiber fractions.

Regarding the error percentages, the error bars were relatively small compared to the measured values, with minimal overlap between the compositions. This indicates a low experimental scatter and good repeatability of the measurements. Moreover, the differences between the mean values were substantially larger than the associated experimental errors, suggesting that the observed trends were statistically meaningful and not attributable to random measurement fluctuations.

Taken as a whole, these findings verify that the controlled addition of CGFs greatly increases the impact resistance of VPP/RPP composites, whereas overloading of fibers causes embrittlement and degradation of the impact performance.

Table 3. Effect of CGF content on impact strength of VPP/RPP composites

Sample Code	Glass Fiber Content (wt.%)	Impact Strength (kJ/m^2)	Standard Deviation
VPP/RPP Blend	0	11.98	0.47
CGF-15%	15	18.60	1.24
CGF-25%	25	20.20	0.24
CGF-35%	35	11.21	0.29

Note: Virgin Polypropylene (VPP), Recycled Polypropylene (RPP), Chopped Glass Fiber (CGF).

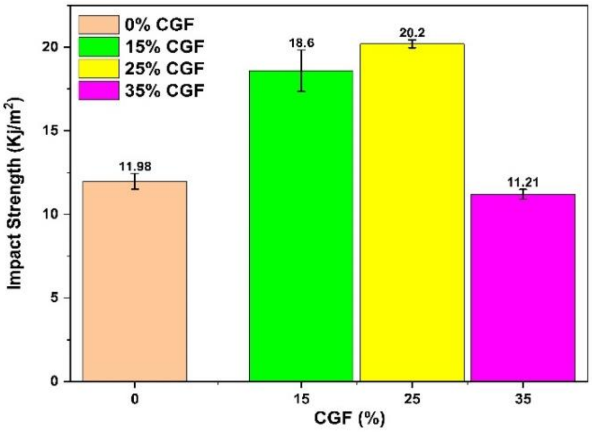


Figure 3. Impact strength vs. CGF% of VPP/RPP-CGF composites

Note: Virgin Polypropylene (VPP), Recycled Polypropylene (RPP), Chopped Glass Fiber (CGF).

3.1.2 The results of the analysis of the tensile properties of the tested samples

Tensile tests on the VPP/RPP composite reinforced with CGFs were conducted through tensile testing, whereby each time the tensile test was performed, three times to determine reliability and reproducibility. Tensile strength, Young's modulus, and elongation at break were considered primary parameters. Tables 4 and 5 and Figures 4-6 indicate that the incorporation of glass fibers had a pronounced effect on the mechanical behavior of the composites.

This study examined the effect of CGFs on the mechanical behavior of VPP/RPP blends through tensile testing. The results show that adding glass fibers significantly improves the stiffness and strength of the composites, affecting their deformation behavior.

Unreinforced VPP/RPP blend (0 wt.% CGF) had a tensile strength of 31.5 MPa, and it can be described by the fact that the polymer matrix has low load-bearing capacity and a corresponding decrease in the mechanical performance due to the presence of the RPP. When 15 wt.% and 25 wt.% CGFs were added, tensile strength was significantly improved to 45.8 MPa and 92.2 MPa, respectively. This is mainly because of the reinforcing influence of the glass fibers, which are effective in transferring applied load between the matrix and fibers through interfacial bonding. However, at a higher fiber content of 35 wt.%, the tensile strength was reduced to 75.2 MPa. The cause of this reduction is probably due to fiber agglomeration, inadequate wetting of the matrix, and more stress concentration locations, which reduce the productivity of the load transfer. This action is in line with other studies that have found that overloading fiber may have the negative effect of weakening tensile strength. The error bars for the tensile strength value were extremely small. The 25% CGF concentration and other concentrations do not significantly overlap. This implies that the increase may be statistically significant.

Table 4. Mechanical characteristics of VPP/RPP (50/50) blend reinforced with CGF

Glass Fiber Content (wt.%)	Tensile Strength, σ (MPa)	Young's Modulus, E (GPa)	Elongation at Break, ε (%)
(VPP/RPP 50/50) 0	31.5	0.42	15.0
15	45.8	0.61	14.5
25	92.2	1.19	12.5
35	75.2	0.94	8.5

Note: Virgin Polypropylene (VPP), Recycled Polypropylene (RPP).

Table 5. The standard deviation of mechanical characteristics of VPP/RPP (50/50) blend reinforced with CGF

Glass Fiber Content (wt.%)	Standard Deviation of Tensile Strength	Standard Deviation of Young's Modulus	Standard Deviation of Elongation at Break
(VPP/RPP 50/50) 0	1.32	0.02	1
15	0.72	0.01	0.5
25	0.2	0.01	0.5
35	0.2	0.01	0.5

Note: Virgin Polypropylene (VPP), Recycled Polypropylene (RPP), Chopped Glass Fiber (CGF).

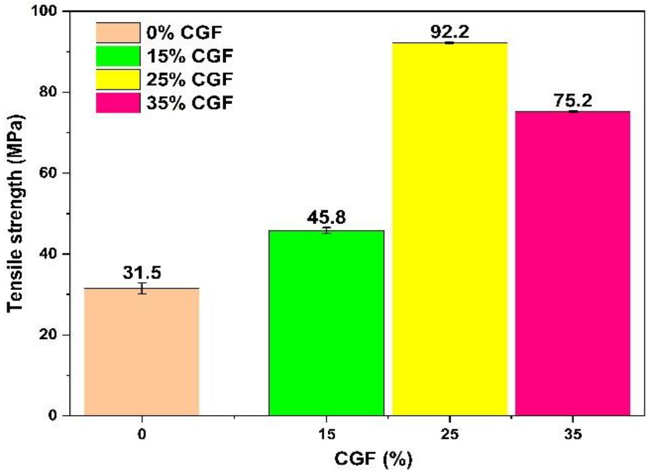


Figure 4. Tensile strength vs. CGF% of VPP/RPP-CGF composites
Note: Virgin Polypropylene (VPP), Recycled Polypropylene (RPP), Chopped Glass Fiber (CGF).

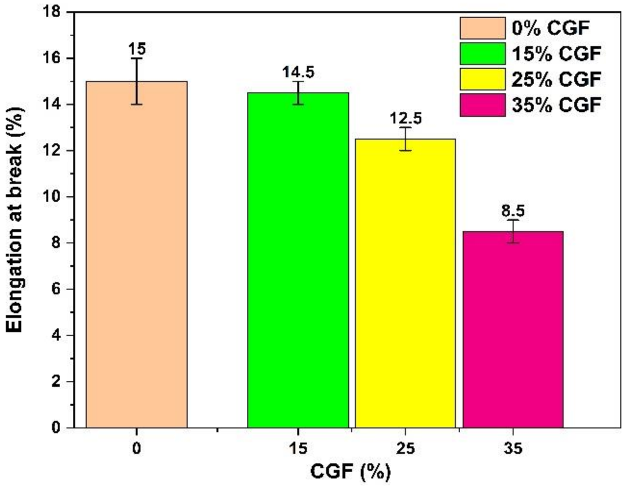


Figure 6. Elongation at break vs. CGF% of VPP/RPP-CGF composites
Note: Virgin Polypropylene (VPP), Recycled Polypropylene (RPP), Chopped Glass Fiber (CGF).

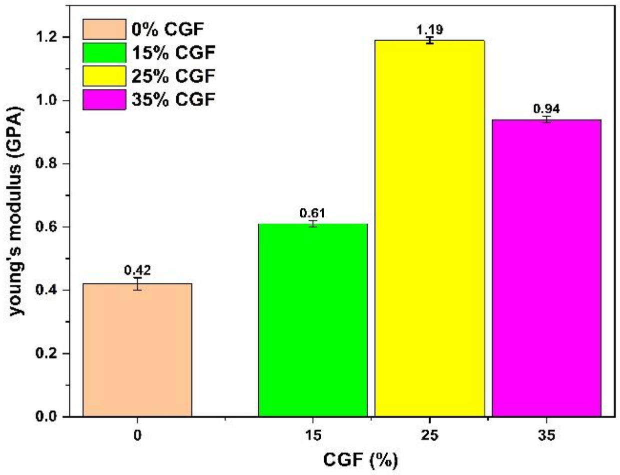


Figure 5. Young's modulus vs. CGF% of moduli of elasticity of the obtained composites
Note: Chopped Glass Fiber (CGF).

This was also the case for Young's modulus. The value of the modulus changed gradually with the addition of the neat blend to 0.42, 0.61, and 1.19 GPa with content of CGF 15 wt.%, 25 wt.%, and 35 wt.%, respectively, and the stiff and rigid nature of the glass fibers that inhibits the movement of the polymer chains. However, a minor decrease in the modulus was observed at 35 wt.% CGF, 0.94 GPa, which could be attributed to a lack of efficient transmission of stress between fibers and non-uniform dispersion at high fiber content. There was little dispersion. Regarding the mistake size, the differences between 0% and 25% were significant. This increases the dependability of the inference.

In terms of elongation at break, the neat VPP/RPP blend exhibited a high elongation of 15%, indicating ductility. Even in a 15 wt.% CGF, the elongation at break was slightly reduced to 14.5%, indicating that a moderate amount of additions did not essentially lower the ductile nature of the composite. Adding more fiber to a 25 wt.% fiber content, the break elongation reduced to 12.5%. This decrease indicates the growing limitation in the mobility of polymer chains brought about by stiff glass fibers, with reasonable deformation potentials owing to a sound stress distribution and fiber-matrix contact. Conversely, at 35 wt.% CGF. The elongation at break drastically reduced to 8.5%, which shows that it was highly embrittled. Such an action is ascribed to the poor continuity of the matrices and low mobility of the chains, as well as the appearance of brittle fiber-fiber contacts that favor early fracture. The error bars are relatively small and do not clearly overlap between 0% and 35%, indicating low data dispersion, good reliability of the measurements, and real differences that are not random.

Overall, these results indicate that a glass fiber content of approximately 25 wt.% is the most acceptable to offer the best combinations of tensile strength, stiffness, and ductility to VPP/RPP composites. Overloading of fiber causes a decreased mechanical performance as a result of fiber agglomeration and ineffective stress distribution, and it is very important to make the fiber content and dispersion in the processing very optimal.

3.2 Morphological properties

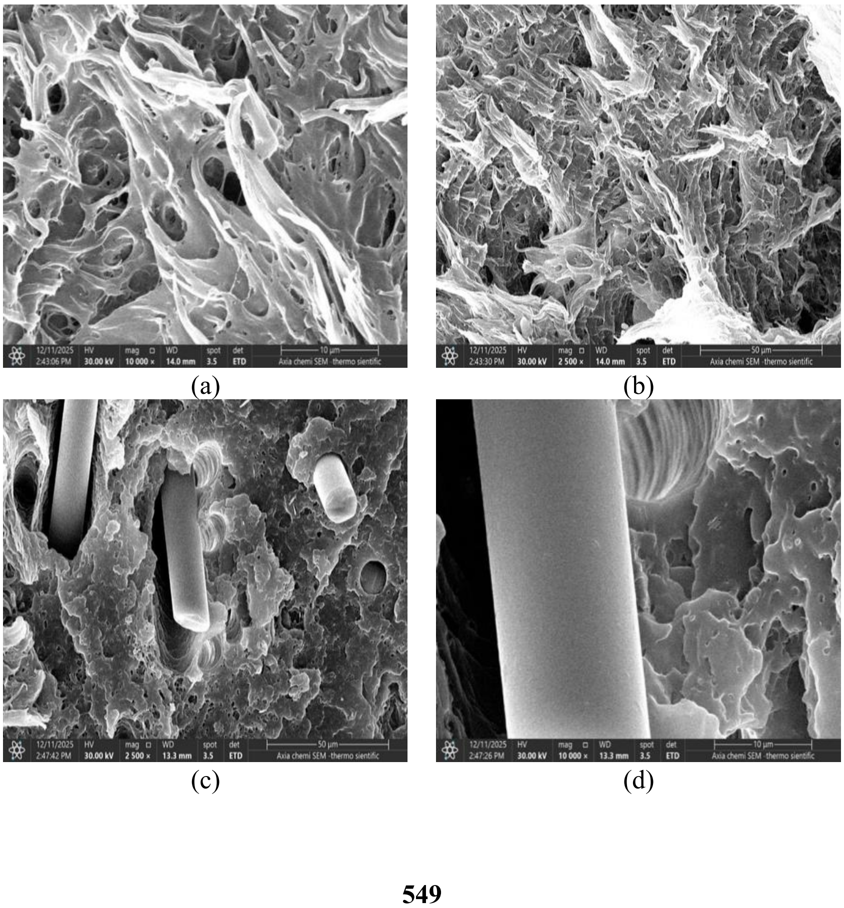
Figure 7 shows the SEM images of VPP/RPP/CGF composites at two magnifications (50 and 10 µm).

SEM analysis revealed a clear evolution in the fracture behavior with increasing glass fiber content, reflecting the transition from matrix-dominated ductile failure to fiber-controlled semi-brittle fracture. In the unreinforced 50 VPP/50 RPP blend, the fracture surface exhibited extensive plastic deformation, elongated polymer ligaments, and microvoid coalescence, confirming that crack propagation occurred entirely through matrix shear yielding. The rough, fibrillated morphology at higher magnification indicates significant energy absorption through plastic flow; the absence of a secondary load-bearing phase results in limited stiffness and strength. Therefore, the intrinsic ductile behavior of PP completely controlled its mechanical behavior.

The fracture mechanism changes to interfacial debonding and fiber pull-out as the dominant factor with the addition of 15 wt.% of the CGFs. SEM micrographs revealed observable interfacial discontinuities and fairly smooth and long-retained fibers, which signified inadequate fiber-to-matrix bonding and ineffective stress conduction. The shear-lag theory and Kelly-Tyson model postulate that inadequate interfacial shear strength causes the fibers to fail to attain tensile strength; hence, whereas pull-out is the major cause of failure, fiber fracture in this case is less common. Although this mechanism enhances energy absorption, there are limited gains in strength because not all loads are transferred.

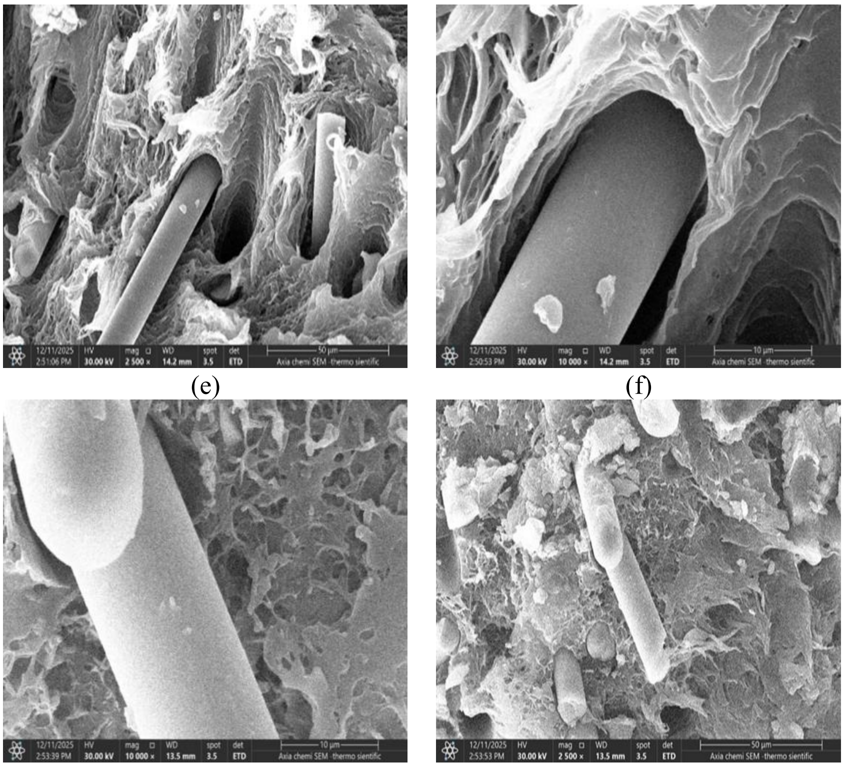
The fracture morphology is significantly different at 25 wt.% CGFs. The fibers seem to be more entrenched, and polymer residues stick to their surface, which proves better interfacial bonding. The remaining fiber length is reduced, and a composite-type failure mode develops, which is a combination of pull-out and partial fiber fracture. This indicates that a higher fiber level is closer to or even greater than the critical fiber length necessary to provide effective reinforcement. Fiber fracture guarantees increased stress transfer efficiency, which is consistent with the critical fiber length theory and the rule of mixtures. Therefore, this composition has a more balanced mechanical performance with the resultant enhanced strength and reasonable toughness due to effective load sharing between the matrix and fibers.

The continued addition of fiber to 35 wt.% leads to a high level of fiber density and a low level of matrix continuity. Although fiber fracture is now more common, showing high stress transfer, fiber clustering and localized interfacial debonding are also observed in the micrographs. The retained fiber lengths and brittle regions are short, which indicates that there is no uniform stress distribution and stress concentration effects. This limited plasticity of the matrix dilutes ductility, as is expected by classical composite fracture mechanics, which postulates that toughness decreases when reinforcement is too high because the matrix is not allowed to deform and the load distribution is non-uniform.



(a) (b)

(c) (d)



(e) (f)

(g) (h)

Figure 7. SEM images of VPP/RPP (50/50) blends with different CGF contents at two magnifications (50 and 10 µm): (a, b) 0% CGF, (c, d) 15% CGF, (e, f) 25% CGF, and (g, h) 35% CGF

Note: Scanning electron microscopy (SEM), Virgin Polypropylene (VPP), Recycled Polypropylene (RPP), Chopped Glass Fiber (CGF).

In general, the microstructural data show that the ductile fracture process, controlled by matrix-to-fiber-controlled failure, can be explained by the growth of fiber contents in the material. The composition of 25 wt.% is the most effective as far as reinforcement is concerned; the optimization of the interfacial bonding and stress transfer occurs without causing extreme stress concentration and brittleness.

4. CONCLUSIONS

This study methodically assessed the mechanical and microstructural capabilities of VPP/RPP blends reinforced with CGF using controlled twin-screw extrusion. The findings of this study demonstrate that glass fiber reinforcement is an appropriate method of compensating for the fundamental mechanical degradation of RPP and imparts substantial strength to the composite behavior.

The composite with 25 wt.% CGF recorded the best mechanical performance of all the formulations studied. The tensile strength in the unreinforced blend of 31.5 MPa was improved to 92.2 MPa, which is approximately a 193% improvement, whereas the Young's modulus was raised to 1.19 GPa, which is approximately a 183% improvement. In addition, the strength of the impact increased by 68.6% (11.98-20.20 kJ/m^2). Notably, this reinforcement level maintained an acceptable elongation at break (12.5%) without making the stiffness and strength too high. SEM Observations established that there was uniformity in dispersion of the fiber, good interfaces between the fiber and the matrix, and fracture characteristics characterized by fiber breakage and restricted pull-out, which together point to effective stress transfer between the matrix and reinforcement.

Moderate mechanical performance was achieved at 15 wt.% CGF, which proves the efficiency of the fiber reinforcement, but the results hint at the fact that the efficiency of reinforcement was not the highest at this point. Conversely, adding more fiber up to 35 wt.% led to a decrease in tensile strength (75.2 MPa), extension at break (8.5%), and impact strength (11.21 kJ/m^2). SEM analysis showed the presence of fiber agglomeration, interfacial debonding, and increased microstructural heterogeneity, which led to stress concentration and brittle fracture behavior. These results verify that excess fiber loading causes inefficiency of reinforcements through large wetting, diminished continuity of the matrix, and inefficient distribution of stress.

Moreover, the error percentages were quite low, the error bars were not wide, and there was not much overlap between various compositions, which showed that they had good repeatability and measurement reliability. The differences in the mechanical properties that were observed were considerably higher than the experimental uncertainties, which confirmed that the observed improvements were structurally, rather than experimentally, based.

Application-wise, the optimized composite with 25 wt.% CGF has great potential in semi-structural automotive use like battery cases, covers, brackets, and other non-load-related applications. To realize industrial scalability, a high level of fiber dispersion, controlled processing conditions, and good fiber-matrix interfacial adhesion are needed, which is necessary to guarantee uniform mechanical performance.

However, some constraints must be considered. The PP recycled in this study was obtained through one post-consumer recycling, and the reproducibility under manufacturing circumstances could be affected by the composition of the changed recycled feedstock, the degree of degradation, and contamination. Future studies should focus on the assessment of alternative recycled sources, surface treatment of fibers, and the determination of long-term durability and environmental performance.

In general, this study shows that glass fiber reinforcement (especially 25 wt.%) can successfully homogenize the RPP blends into a competitively strong composite in terms of mechanics and structural properties. The enhanced mechanical performance, validated microstructural integrity, and reduced experimental variability indicate the promise of such composites in sustainable engineering and encourage the wider use of recycled polymers in high-performance semi-structural parts.

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NOMENCLATURE

CGF	chopped glass fiber
RPP	recycled polypropylene
VPP	virgin polypropylene
PP	polypropylene
LOI	loss on ignition

Greek symbols

σ	tensile strength, MPa
ε	elongation at break, %