



Recycling of wind turbine blades into polypropylene composites: influence of reprocessing on mechanical and thermal performance

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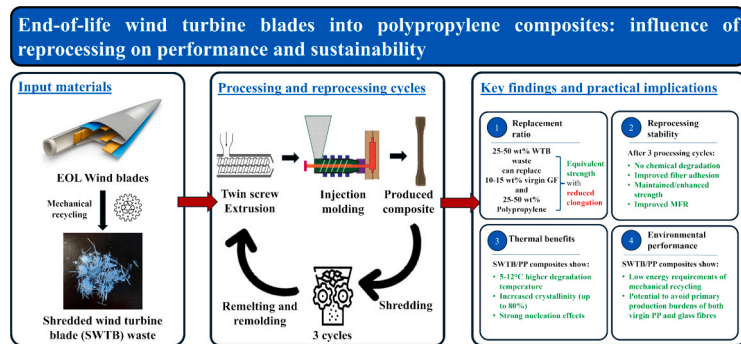
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HIGHLIGHTS

- Shredded wind turbine blade (SWTB) waste used up to 50 wt% in PP composites.
- Compatibilized SWTB/PP composites recovered mechanical properties after 3 cycles.
- Reprocessing enhanced strength via improved fiber dispersion and adhesion.
- Higher thermal stability and crystallinity due to stronger nucleation effect.
- SWTB demonstrated potential to replace 10–15 wt% virgin glass fibers.

GRAPHICAL ABSTRACT



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ABSTRACT

Recent studies have investigated shredded wind turbine blade (SWTB) waste as reinforcement in polypropylene (PP) composites; however, the recyclability and performance retention of these secondary composites remains largely unexplored. This study evaluates the effect of multiple reprocessing on the mechanical and thermal performance of SWTB-reinforced PP composites. Virgin PP/glass fiber composites (10 and 15 wt%) were compared with recycled SWTB composites (with and without compatibilization). Composites were produced via twin-screw extrusion and injection molding, followed by two additional reprocessing cycles. FTIR analysis showed no significant chemical degradation, while SEM revealed improved fibre–matrix adhesion in compatibilized composites. After three cycles, the 50 wt% compatibilized SWTB composite recovered its tensile strength and exhibited 5 % higher flexural strength than 15 wt% virgin PP/glass fiber composites. Thermal analysis indicated 5–12 °C higher degradation temperatures and increased crystallinity due to enhanced nucleation effects. Melt flow rate (MFR) increased after reprocessing, indicating improved processability. Additionally, these findings demonstrate that mechanically recycled SWTB has the potential to effectively substitute 10–15 wt% virgin glass fibers and 25–50 wt% PP while retaining equivalent mechanical performance after repeated reprocessing, highlighting its potential as a sustainable reinforcement for circular thermoplastic composite applications.

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1. Introduction

The wind energy industry is a primary source of global electricity generation, with an installed capacity exceeding 1346 GW in 2025 [1]. On the other hand, installations in the EU would have to reach 425 GW by 2030 from their current state of 285 GW in order to satisfy the 42.5 % renewable energy objective [2]. The massive demand for wind energy is mainly due to its sustainable production method, which emits only 12 g CO₂ eq/kWh, the second lowest behind hydroelectric energy [3]. The generation of electricity through wind energy costs between \$0.03/kWh (onshore) and \$0.08/kWh (offshore), which is still lower compared to electricity through bioenergy, geothermal, hydropower, and solar PV, which costs \$0.08, \$0.06, \$0.05, and \$0.04/kWh, respectively [4]. Due to these benefits, the Global Wind Energy Council (GWEC) has raised its growth projection by 10 % for 2024–2030 (1210 GW) [5,6].

As the wind energy sector expands, 330,000 t/year of composite materials coming from wind turbine blades (WTB) will be burnt or landfilled worldwide until 2028, and 418,000 t/year between 2028 and 2040 [7]. Due to the use of steel, copper wire, hardware, and outfitting, which can be recycled commercially, current wind turbines have a recyclability of about 85 %. The remaining 15 % – primarily made up of glass or carbon fiber composites from wind turbine blades – poses a major environmental challenge, as these composites are specifically engineered to endure significant mechanical and environmental stresses over extended periods. The size and manufacturing methods are among the other factors that might affect the overall weight and composition of WTB [8]. For example, Liu and Barlow have reported that small blades for 1.5 MW wind turbines may comprise 60.4 % reinforcing fiber, 32.3 % resins and adhesives, 2.3 % balsa, and 5 % ancillary materials [9]. Among these materials, the matrix phase is mainly composed of thermoset resin, with epoxy and polyester resins being the most widely used materials by original equipment manufacturers (OEMs). For instance, the resin material used by Siemens Gamesa and Vestas is primarily epoxy, whereas LM Wind Power has extensively adopted polyester resins in blade manufacturing [10]. These thermoset resins form cross-linked structures during curing, which impart excellent mechanical performance and durability. However, this also makes conventional recycling (e.g., mechanical, chemical, etc.) challenging [11,12].

Recent EU waste treatment policies (EU 1999/31/EC (landfill of waste) and EU 2000/53/EC (End-of-life vehicles directive)) tend to significantly reduce the detrimental effects of waste on the environment by turning it into new resources. Landfilling is the least desirable choice in this regard. Another approach is to recover energy through incinerating these composite wastes; however, the effectiveness of incineration with energy recovery is strongly dependent on the composition of the composites [13]. For instance, the amount of energy recovered through incineration of glass fiber reinforced polymers (GFRPs) is rather limited compared to the high calorific value observed in carbon fiber reinforced polymers (CFRPs) [14]. Nevertheless, policies and regulations restrict the incineration of composite materials due to their high CO₂ emissions.

In this regard, industries and academia have focused increasingly on the circularity of materials in the wind energy sector, which produces massive volumes of obsolete turbine parts like blades [15]. Wind-farm-management companies are currently facing the principal issue of managing the decommissioned wind turbine blades, as numerous recycling options exist, although many remain in the research phase [12] due to the intricate composition of a wind-turbine blade, which includes glass or carbon fibers, thermoset polymers, and even wood [6]. Among the existing techniques, chemical and thermal treatments are used to recover carbon fibers, glass fibers, and, to some extent, resin [16]. However, thermal techniques such as pyrolysis and fluidized bed processes involve the decomposition of organic materials from the polymer composites under high temperatures ranging between 300 and 700 °C. On the other hand, chemical treatments such as solvolysis, hydrolysis, or glycolysis happen at lower temperatures (below 350 °C) and consume various chemicals that include catalytic solutions, alcohol, and sub/

supercritical fluids. Chemical recycling techniques remain under development or are only appropriate for laboratory scale due to the necessity for elevated temperature and pressure, as well as the need for costly equipment [17]. Additionally, the energy required to carry out recycling also plays a vital role for industries when considering the best recycling method. The required energy for thermal recycling ranges between 3 and 30 MJ/kg. Similarly, chemical recycling requires 63–91 MJ/kg to process end-of-life (EOL) waste of fiber-reinforced composites. Mechanical recycling, on the other hand, includes just pulverization or shredding, which consumes only 0.27–3.03 MJ/kg, which is lower energy than the other two recycling techniques [18]. Generally, shredded material contains powdered products (with a high content of resin) and fibers (rich in fibers along with residue), which can then be used as filler or reinforcement in a new polymer matrix [19,20]. The recovered fibers from mechanical recycling retain 70 % and 90 % of their tensile strength and modulus, respectively, relative to virgin fibers [21,22]. Therefore, mechanical recycling is the most sought-after method among industries these days [23].

Recently, researchers have developed secondary polymer composites by utilizing mechanically recycled wind blade waste. Pu et al. used WTB waste as a filler up to 50 wt.% together with additional compatibilizers to develop polypropylene composites using injection molding. The tensile strength, tensile modulus, and flexural strength of these composites increased significantly by 37.3 %, 147.3 %, and 165.5 %, respectively [24]. Mamanpush et al. utilized wind turbine blade waste as a feedstock in conjunction with high-density polyethylene (HDPE) to extrude profiled composites. Such composites demonstrated increased mechanical and physical characteristics, further confirming the prospective possibility of employing discarded wind turbine blades in secondary polymer composites [25]. Fonte and Xydis indicated that the processing cost of mechanically recycled glass fibers from WTB (assuming a plant processing 6000 tons per year) ranges between 0.09 and 0.32 €/kg. However, this may increase considerably due to the preprocessing and transportation costs, which were not included in their study [6]. On the other hand, industries look at the economic benefit that virgin fibers (€2.5/kg) [26] possess in comparison to the uncertainty in the costs associated with the recycled fibers. Nevertheless, to tackle competitiveness in the raw materials, the embodied energy of manufacturing for virgin glass (13–32 MJ/kg) must be considered, which is almost 10–20 times more than the energy consumed by mechanical recycling [27]. In this regard, the reprocessing of secondary composites helps to make such recycled composites more circular and cost-effective.

Many studies have been done in the past related to the reprocessing capability of virgin glass fiber-reinforced polypropylene composites. Colucci et al. used injection molding to study the impact of recycling on the performance behavior of virgin glass fiber (GF)/polypropylene (PP) composites. The samples were mechanically recycled only once, and it was discovered that their mechanical properties were inferior to those of polypropylene that had not been recycled [28]. Chen et al. examined the effects of three (3) injection molding machine processing cycles on the properties of PP and long glass fiber. Their findings showed that mechanical recycling had no effect on the composite's thermo-mechanical, rheological, and thermal properties [29]. Touati et al. conducted a similar study on reprocessing isotactic PP/Cloisite 15A (5 wt.%) nanocomposites with maleic anhydride-grafted polypropylene acting as a compatibilizer for 4 cycles and found that there was no change in the chemical structure even after 4 reprocessing cycles [30]. Achukwu et al. confirmed that glass fiber-reinforced PP composites can be reprocessed for a maximum of 3 cycles without significant deterioration of mechanical properties or chemical structure [31]. Despite various studies investigating the effect of reprocessing on the performance of PP-GF composites, the majority of the studies considered virgin glass fibers.

Despite various studies investigating the effects of reprocessing on the performance of PP-GF composites, the majority of them considered virgin glass fibers. Similar studies on secondary composites reinforced

with recycled WTB waste are currently lacking. The existing literature on shredded wind turbine blade (SWTB) reinforced thermoplastic composites has primarily focused on the fabrication and characterization of first-generation recycled materials, while their ability to undergo subsequent recycling cycles has remained largely unexplored. Consequently, it is still unclear whether these secondary composites can maintain their structural integrity and functional performance after repeated processing, which is a prerequisite for realizing a truly circular composite material system. Furthermore, the combined evolution of mechanical performance, thermal behaviour, crystallization characteristics, morphology, and environmental impacts during successive reprocessing cycles has not been comprehensively evaluated. Therefore, the novelty of this work lies in evaluating the recyclability of SWTB/PP composites through the integration of multiple reprocessing cycles, structure-property characterization, and an assessment of environmental impacts. By addressing this critical knowledge gap, this work advances recycled wind turbine blade composites from a one-time recycling solution towards reprocessable engineering materials capable of supporting closed-loop composite manufacturing.

2. Materials and methodology

2.1. Materials

To fabricate the new secondary polymer composites, SWTB waste (Fig. 1) was obtained from PreZero Gestion De Residuos SA in Tudela de Duero (Spain). The recycling plant receives the pre-cut end-of-life WTBs (from various producers). These pre-cut WTBs would be free from metallic and wooden components (as far as possible). However, another pre-treatment process was performed by PreZero to eliminate wooden elements completely from the internal structure. Subsequently, the blades were segmented into smaller pieces using a cross-flow shredder. This process produced SWTB particles of varying sizes and irregular shapes. Following shredding, the material was transported along a conveyor belt equipped with magnetic separation to extract any metallic residues from the internal blade components. Ultimately, the final SWTB were collected, with particle sizes ranging from 0.063 mm to 80 mm. There were four different size fractions provided by PreZero, as shown in Fig. S1. The 20 mm size fraction was selected for this research because the 40 and 60 mm size fractions had bigger particles unsuitable for the extrusion process, while the 10 mm size fractions contained an excessive amount of powdery material.

The thermoplastic polymer used in this work is polypropylene (PP) (SABIC PP 520P), which was purchased from Resinex (The Netherlands). The melt flow rate of PP is 10.5 g/10 min at 230°C and 2.16 kg load. Maleic anhydride-graft-polypropylene (MAPP), a coupling agent, was purchased from Sigma-Aldrich (The Netherlands). Chopped strands of virgin glass fibers (VF) DS 2200-13P with a diameter of 13 µm and a length of 4 mm were provided by 3B Fiberglass (Belgium). These glass fibers comprise 0.52 % of the sizing agent specifically formulated for PP composites.

2.2. Methodology

2.2.1. Characterization of SWTB

For initial characterization tests, SWTB was sieved using the Retsch AS 200 control sieve shaker into three different size fractions: (a) 400 µm, (b) 150 µm, and (c) PAN sample, as some of the characterization techniques do not support higher size fractions. The properties of the final product are mostly influenced by the chemical composition and mineralogy of the raw material. For this purpose, Attenuated Total Reflectance - Fourier Transform Infrared (ATR-FTIR) spectroscopy was performed in the 400 cm⁻¹ to 4000 cm⁻¹ range using the Frontier Spectrometer from PerkinElmer. The SWTB sample was subjected to a 4-hour loss-on-ignition (LOI) test at 600°C in a furnace. This sample was then combined in a 1:10 ratio with a 67 % Li₂B₄O₇-33 % LiBO₂ anhydrous fusion mixture, and 170 µl of 2 M LiBr was added to produce the fused beads that were later utilized for X-ray Fluorescence (XRF). The glass fiber content of SWTB was determined by thermogravimetric analysis (TGA) (TG 209 Tarsus, Netzsch). All three size fractions were heated from room temperature to 800 °C in a nitrogen atmosphere at a heating rate of 10 °C/min. In order to comprehend the raw material's morphology and microstructure, SWTB was then characterized under a scanning electron microscope (SEM) (Phenom ProX, ThermoFischer) at an acceleration voltage of 10 kV. All SWTB samples were sputter-coated with gold for 30 seconds at 30 milliamperes prior to the analysis. The Particle size distribution (PSD) based on the sieving analysis was also conducted. The as-received SWTB (≤ 20 mm) was processed through sieving into 8 mm, 4 mm, 2 mm, 1 mm, 500 µm, 250 µm fractions, and a bottom pan, employing an amplitude of 1 mm and a 10-second interval over a 15-minute period. The sieves were weighed prior to and following the sieving process to determine the mass of material retained on each sieve. To evaluate the distribution of length, diameter, and aspect ratio of fiber aggregates and single fibers in the as-received SWTB (≤ 20 mm), Polarized Optical Microscopy (POM) was used. The Zeiss Axiocam 305 color microscope was employed for this objective. A representative sample of fiber aggregate was chosen from sieving fractions of as-received 20 mm SWTB, i.e., 4 mm (n = 25), 2 mm (n = 25), 1 mm (n = 220), 500 µm (n = 220), 250 µm (n = 220), and the residual fraction (n = 40). Individual single fibers (n = 265) were predominantly chosen from the lower fraction (PAN).

2.2.2. Extrusion and injection molding

Before extrusion, the 20 mm fraction was subjected to a one-off sieving process utilizing the Endecotts Octagon 200 test sieve shaker at an amplitude of 8 mm/g for 5 minutes to eliminate finer particles, and fibers ranging from 500 µm to 20 mm were employed for extrusion. Twin-screw extrusion and injection molding were the two main processing techniques employed to create novel secondary composites from various PP and SWTB formulations (Table 1). As shown in Fig. 2, in the first cycle, secondary composites without a coupling agent were produced by feeding different weight fractions of virgin PP into feeder 1 and SWTB into feeder 2 of the twin-screw extruder (HAAKE Rheomex OS



Fig. 1. Physical appearance of as-received SWTB (≤20 mm) (a) and as-received VF (b).

Table 1
Formulation of secondary polymer composites.

Samples	PP (wt. %)	SWTB (wt. %)	Virgin glass fibers (wt. %)	MAPP (wt. %)
90PP10VF	90	0	10	0
85PP15VF	85	0	15	0
75PP25RM	75	25	0	0
50PP50RM	50	50	0	0
70PP25RM5CA	70	25	0	5
45PP50RM5CA	45	50	0	5

twin screw, ThermoFischer) at a rotation speed of 110 rpm and at processing temperatures of 180 °C for zones 1 and 2, 190 °C for zones 3 up to zone 8, and 200 °C for zones 9 and 10. Two separate feeders were used in order to avoid the clogging of fibers. Similarly, MAPP was combined with virgin PP in feeder 1 and was fed to the extruder alongside SWTB (feeder 2) to produce compatibilized composites. Later, VF and PP in different proportions were combined in feeder 1 to produce virgin composites for comparative research. Thoroughly compounded composites were then pelletized into pellets of 2-3 mm. Thereafter, pellets were dried at 60 °C, and a BOY XS injection molding machine was used to produce tensile (75 mm × 5 mm × 2 mm) and bending specimens (80 mm × 10 mm × 4 mm). Melt temperature (200 °C), mold temperature (210 °C), injection speed (110 mm/s), injection time (15 s), cooling time (15 s), and cycle duration (120 s) were the parameters selected for injection molding. Similar procedures and parameters were used to prepare virgin composites, except that virgin glass fibers (VF) were fed into feeder 1 alongside virgin PP. A coupling agent was unnecessary for virgin composites, as they already included a sizing agent. Fig. S2 shows the injection-molded specimens for all different compositions.

2.2.3. Reprocessing of secondary composites

To enable recycling in subsequent cycles, the composites produced in the first cycle were mechanically shredded and reused. The shredded material was then mixed with pellets of the same composition from the same cycle, which can be considered production waste generated during extrusion. This mixture was processed again using the same extrusion and injection molding procedures described earlier to produce new composites. For example, second-cycle composites were produced by

shredding first-cycle samples and blending them with corresponding first-cycle pellets, followed by reprocessing. The same approach was repeated to produce third-cycle composites.

To understand the nomenclature of the composites in this research, each composition will be referred to as XA/YB/ZC, where X is the weight of the polypropylene concentration, Y is the weight of the recycled material (RM) or SWTB waste, and Z is the weight of the coupling agent (CA). In the same manner, A, B, and C correspond to the material's abbreviated designations. For example, the composition 70PP/25RM/5CA has 70 wt% polypropylene, 25 wt% recycled material or SWTB waste, and 5 wt% coupling agent. A similar nomenclature rule was applied to the virgin composites, where VF represented virgin glass fibers.

2.2.4. Characterization of secondary composites

The functional groups found in the secondary composites following many reprocessing cycles were characterized using FTIR. The thermal stability of the composites was characterized by TGA. The same parameters were used for FTIR as discussed in section 2.2.1 but TGA was carried out from room temperature to 600 °C in a nitrogen atmosphere at a heating rate of 10 °C/min. Differential scanning calorimetry (DSC) (Q2000, TA Instruments Co., Ltd., USA) was used to measure the degree of crystallinity (X_c), melting, and crystallization behaviors of all three cycles of extruded samples. The study was conducted in a nitrogen environment with a flow rate of 50 mL/min and a temperature range of -90 °C to 220 °C, using 5 °C/min for both heating and cooling cycles. Each sample underwent two cycles of heating and cooling. X_c was calculated using the following equation:

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

where ΔH_m denotes the melting enthalpy of the PP in the composition, ΔH_m^* is the enthalpy of melting of fully crystalline PP taken as 209 J/kg [32], and w_f is the fiber weight fraction.

The Zwick Roell ZW010 equipped with a 2.5 kN load cell was used to perform tensile and three-point bending tests in accordance with ISO 527-2 [33] and ISO 178 [34], respectively, to evaluate the tensile and flexural characteristics of the injection-molded composites. Tensile and

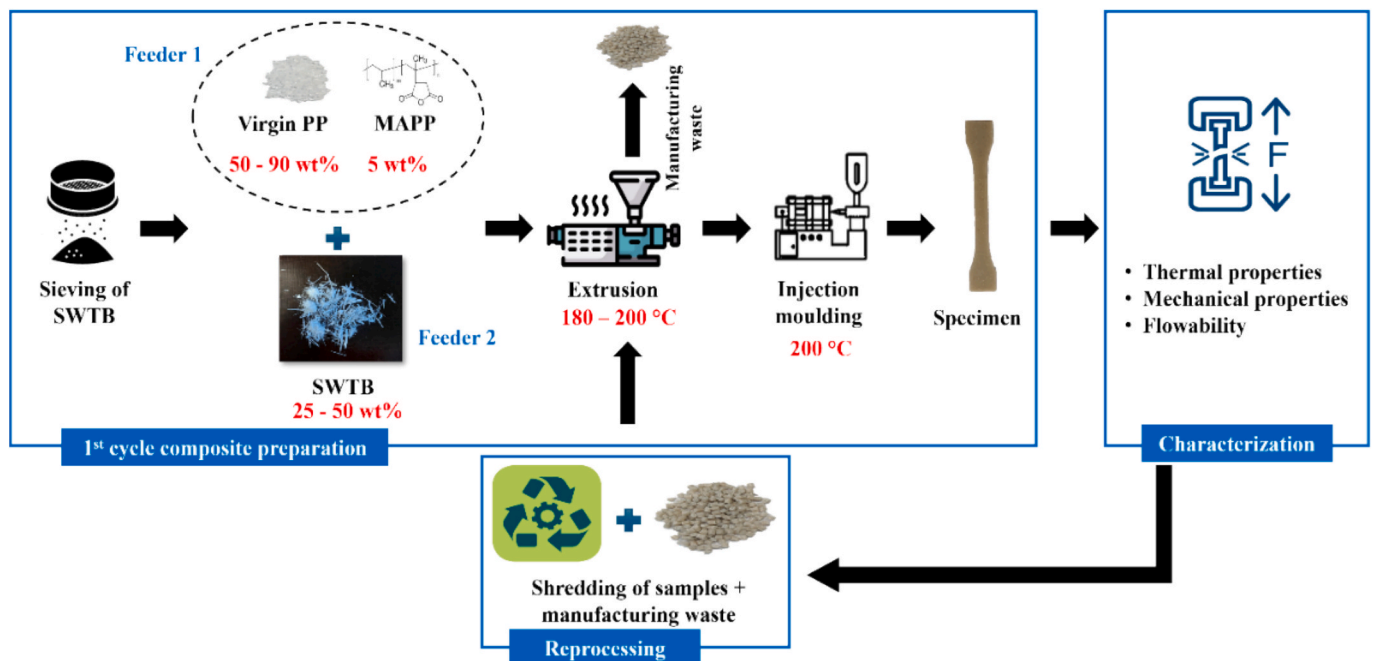


Fig. 2. Schematic representation of the steps involved in the reprocessing of secondary composites from SWTB.

bending tests were conducted using typical test settings of 5 mm/min and 10 mm/min crosshead speeds, respectively. Up to 10% deformation was tested in the flexural test. The average of five samples for each composition was used to determine the results. A DMA850 Dynamic Mechanical Analyzer (DMA) (TA Instruments) operated in a tensile fixture mode at a frequency of 1 Hz was used to evaluate dynamic mechanical parameters at a heating rate of 1°C/min from −50°C to 140°C. A rectangular part (30 mm × 5 mm × 4 mm) from the middle of a tensile specimen was cut and used for further testing.

Using a Cflow Extrusion Plastometer (Zwick Roell 4100) and ISO 1133-1 (Method A), the MFR was measured on all of the extruded samples from three cycles. A standard procedure was followed, with an applied weight of 2.16 kg at 230°C. The following equation was used to compute the melt flow rate (MFR):

$$MFR = \frac{600m}{t} \quad (2)$$

where m denotes the mass of the cut-offs, in grams, and t denotes the cut-off time interval, in seconds.

SEM imaging was performed at an acceleration voltage of 10 kV using an SEM (Phenom ProX, ThermoFischer). The developed secondary composites' adhesion and interaction between the matrix and reinforcement were then characterized. All of the samples were sputter-coated with platinum for 40 seconds at 30 milliamperes prior to the analysis. A backscattering detector was used. Furthermore, a Zeiss Axiocam 305 color polarized light optical microscope with a Linkam hot stage was used to examine the crystal morphologies of all the composites under crossed polarizers. Extrusion-derived pellets were heated to 210°C for five minutes before being hot-pressed into a film. The films were then reheated on the hot stage to 180°C (for PP and virgin composites) and 220°C (for recycled composites) at a rate of 50°C/min and held for three minutes. The molten samples were then immediately cooled to 140°C at a rate of 50°C/min, and between 140°C and 120°C, samples were cooled at a rate of 1°C/min. The crystal morphologies were captured on camera during this cooling period.

To evaluate the statistical significance of parameters affecting the mechanical performance of the low (90PP10VF, 75PP25RM, 70PP25RM5CA) and high (85PP15VF, 50PP50RM, 45PP50RM5CA) fiber-loaded composites, a two-way analysis of variance (ANOVA) was conducted on the measured properties, including tensile strength, tensile modulus, flexural strength, and flexural modulus. This analysis was performed to determine whether the type of composition and the number of reprocessing cycles had statistically significant effects on mechanical behavior. The two-way ANOVA calculations were executed using Minitab 22 statistical software, adopting a significance level of $\alpha = 0.05$ for all evaluations.

3. Results and discussion

3.1. Raw material characterization

FTIR analysis of two distinct samples revealed the presence of two thermoset resin types: polyester and epoxy. The spectra in Fig. 3 revealed a wide band at around 3350 cm^{-1} attributed to O–H or N–H stretching vibrations and peaks at 2850–2950 cm^{-1} caused by C–H stretches (V_{sym} , V_{asym}). Furthermore, the aromatic C=C bond was responsible for the peak at around 1500 cm^{-1} , whereas the C–O–C stretching vibration was represented by the peak at about 1250 cm^{-1} . The spectrum indicated that the resin of composite sample 1 was most likely epoxy [35,36].

Similarly, the spectrum showed that the resin matrix for this composite component waste was an unsaturated ester resin. The band at 1736 cm^{-1} confirmed the existence of the C=O ester group and showed that the substance is polyester resin, along with a significant peak at 1260 cm^{-1} , which is attributed to the C–O bond of the ester linkage [37,38]. This demonstrated that the recycled material, which came from

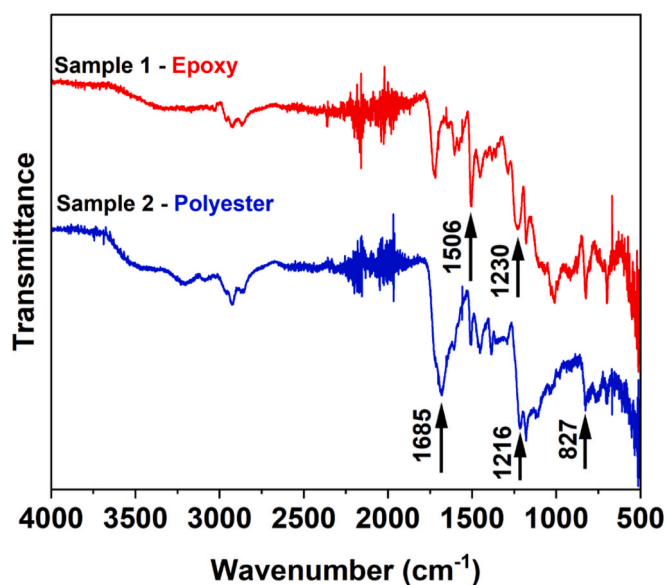


Fig. 3. FTIR bands of SWTB samples.

several producers, contained two distinct kinds of thermoset resins.

Table 2 shows the XRF results for each of the three SWTB size fractions. They demonstrate that SiO_2 , Al_2O_3 , and CaO make up the majority of the basic material. A few additional compounds, such as TiO_2 , MnO , Fe_2O_3 , etc., make up around 2% of the total. It was observed that when particle size decreases, the proportion of SiO_2 rises. Given that SiO_2 is the main component of E-glass fiber, this suggests a significant proportion of glass fibers in the PAN sample.

The thermal stability and glass fiber content of SWTB were determined by TGA. According to Fig. 4, the organic material exhibited significant decomposition between 310°C and 430°C in an inert environment, and the maximum degradation of organic resin occurred at around 371°C. The substantial proportion of glass fibers in the PAN samples (73.3% of residue) is further confirmed by their mass loss of around 26.7%, which is lower than that of the other two size fractions. Zhao et al. have made similar observations in their study [39]. Therefore, it may be inferred that around 35–40% of the SWTB consists of organic material, while the rest is glass fiber.

Fig. S3 shows the presence of large aggregated particles in fractions larger than 250 μm . Other materials, including fluffy aggregates, wood, and resin particles, can be seen in fractions larger than 1 mm. Further description of fiber morphology using SEM is provided in the following paragraph. The dimensions of fiber clusters and single fibers exhibit a broad and random distribution, with the sole exception being the width (diameter) of the individual fibers as shown in Fig. 5e. A normal distribution with an average diameter of 12.5 μm was observed for these fibers. The shredding and grinding procedures used during mechanical recycling can account for the majority of the short lengths that were seen. The PSD based on this sieving analysis is presented in Fig. S4. It was observed that the level of glass fiber concentration increased as the sieve size decreased, a correlation also evident in the XRF analysis.

SEM analysis of the raw material (Fig. 6a&b) revealed the recycled fiber's morphology, which contains short glass fibers along with some bundles of long glass fibers and pieces of thermoset matrix. Due to the

Table 2
Oxide composition of SWTB samples.

Size	Al_2O_3	SiO_2	CaO	Others	LOI
400 μm	9.59	31.17	13.63	2.21	43.38
150 μm	9.60	37.15	15.28	2.27	35.68
PAN	13.32	40.21	16.93	2.52	26.99

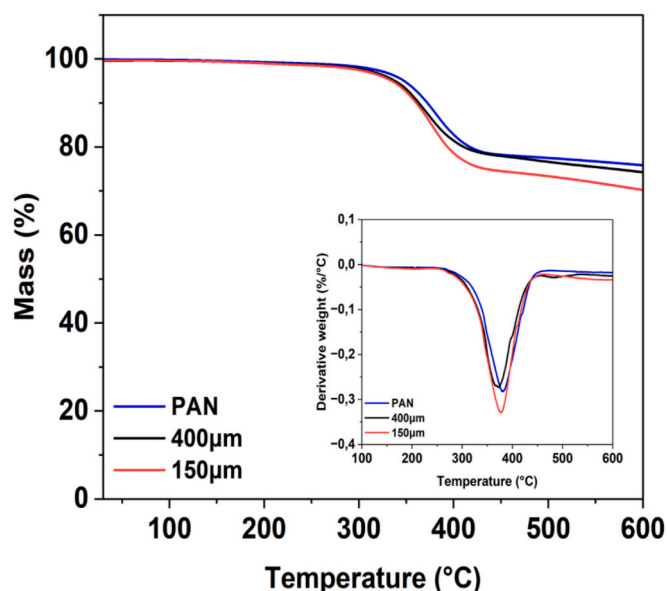


Fig. 4. TGA and DTG curves for different size fractions of SWTB.

comminution used during the recycling process, loose fibers get detached from the thermoset matrix. Fig. 5c clearly shows the presence of thermoset residue on the glass fiber surface. Fig. 6d illustrates how the integrity of the surface and the length of the fibers are compromised when wind turbine blades are mechanically shredded. Similar observations were also made by Beauson et al. [40].

3.2. Characterization of secondary composites

3.2.1. FTIR

FTIR spectra were used to analyze potential chemical structural changes in the composites for various reprocessing cycles, and a spectrum of only one cycle is represented in Fig. 7a. The medium CH_2 bending vibration was detected at 1457 cm^{-1} in all PP reprocessing

cycles, while the absorption band at 2950 cm^{-1} represents the C–H stretch bond. Additionally, CH_3 bending vibrations were detected at around 1375 cm^{-1} [31]. Touati et al. observed a weak carbonyl bond indicative of the MAPP compatibilizer around 1720 cm^{-1} [30]; however, the recycled composites without a coupling agent also exhibited a carbonyl bond, which indicates the presence of esters, as seen in Fig. 7b. FTIR spectra of pure PP and virgin composites did not exhibit this carbonyl bond. The peak at 1100 cm^{-1} is due to the stretching vibration of the Si–O bonds inside SiO_2 [24]. Several researchers obtained the same results, indicating that no substantial structural alterations, such as oxidative degradation, occurred even after numerous reprocessing cycles of reinforced polypropylene composites [30,31,41]. Therefore, from these observations, it was understood that there were no significant effects of reprocessing on the chemical structural change of all the composites.

3.2.2. Thermal properties

3.2.2.1. TGA. TGA and DSC were carried out to assess the effects of reprocessing on the thermal properties of the composites. Fig. 8 presents the TG and DTG curves of all the composites at different reprocessing cycles. At first, thermal analysis was done on 75PP25RM and 50PP50RM samples to determine the amount of glass fiber in them. Based on the average values obtained as shown in Table S1, it was found that 75PP25RM and 50PP50RM contained approximately 10 wt% and 15 wt% of glass fibers, respectively, and the remaining amount was considered as thermoset residue and PP. Additionally, slight variations in glass fiber content were noted in these composites, potentially due to two factors: (1) although an automatic feeding system with a 35 % feed rate was employed for SWTB, manual assistance was occasionally necessary during extrusion to prevent the clogging of fibrous materials; (2) as indicated by Chiou and Lin [42], the shredding of WTb results in the glass fibers acquiring an electrostatic charge, causing them to adhere to the walls of the twin screw extruder and ultimately hindering their uniform integration with PP. Therefore, for fair comparison, 10 wt% and 15 wt% of virgin glass fibers were used as reinforcement in virgin composites (90PP10VF and 85PP15VF). In the following sections, comparisons are made between 25 wt% SWTB and 10 wt% VF

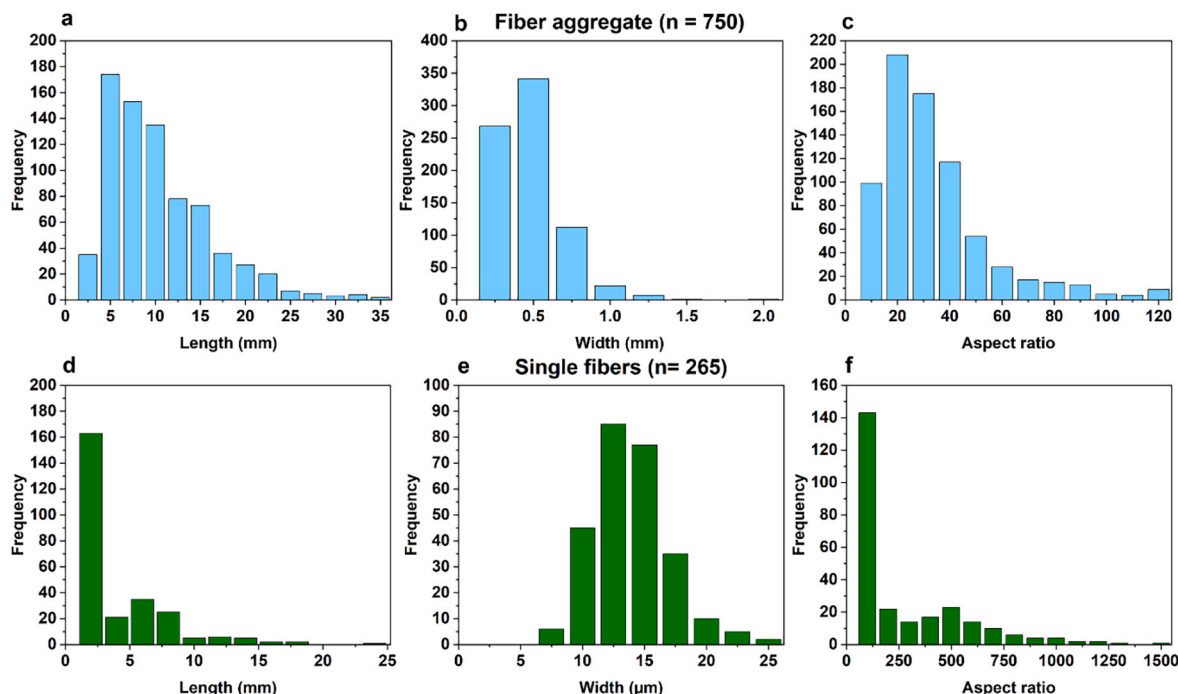


Fig. 5. Frequency distribution of length, width, and aspect ratio for as-received 20 mm SWTB fiber aggregates (a-c) and single fibers (d-f).

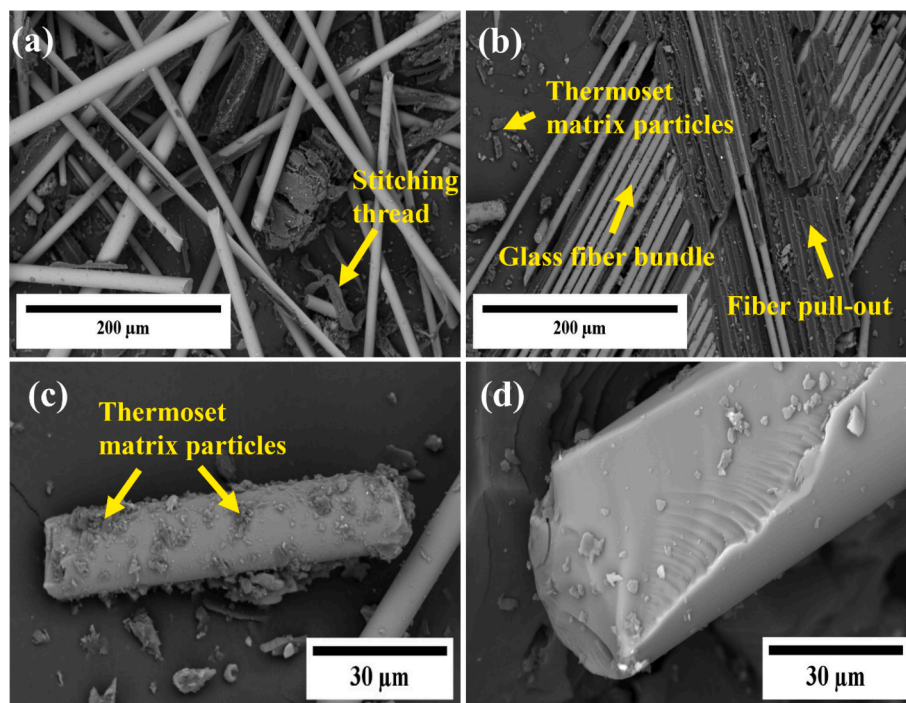


Fig. 6. SEM images of (a, b) raw material containing glass fiber bundles, stitching thread, and thermoset residue particles; (c) a single glass fiber with thermoset residue attached to the surface; (d) fiber deformation occurred during the shredding process.

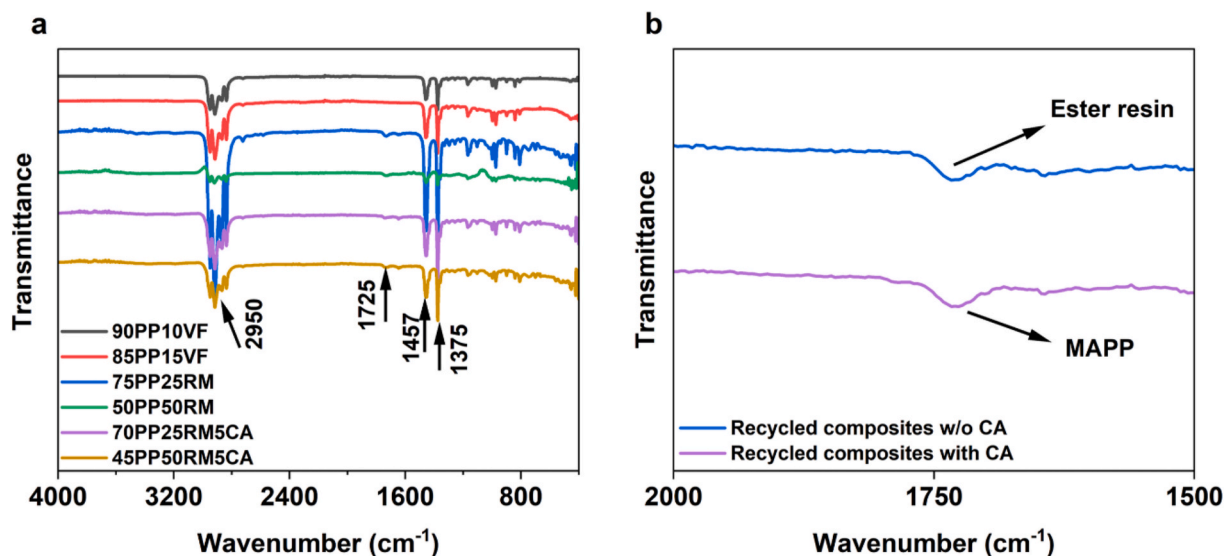


Fig. 7. FTIR bands of PP/VF and PP/SWTB composites (a); presence of carbonyl bond in recycled composites with and without CA (b).

composites and similarly between 50 wt% SWTB and 15 wt% VF.

In all the reprocessing cycles, it could be observed that recycled composites, compared with 90PP10VF and 85PP15VF, exhibited two thermal weight loss stages. The first one occurred in the range of 280–340°C, which mainly comprises thermoset residue such as an epoxy or polyester matrix. Subsequently, between 400 and 460°C, a second stage of thermal decomposition occurred, which was mainly attributed to the PP matrix. As presented in Table 3, during reprocessing cycles, the degradation temperature (T_d), the peak shown in the DTG curve, of 90PP10VF and 85PP15VF showed an increase in the second cycle followed by a decrease in the third cycle. Although recycled composites showed a similar pattern, their T_d showed a significant improvement of approximately 5–12°C over virgin composites in all the cycles, thus

exhibiting good thermal stability. The aforementioned trends were also observed for onset temperatures in all the composites (Table S2). The glass fibers present in both virgin and recycled composites, due to their strong thermal stability, can absorb a significant amount of heat, slowing down the decomposition of the PP matrix. Additionally, in SWTB/PP composites, at high temperatures, thermoset residues do not fully volatilize; instead, they may undergo a carbonization process and form a partial char layer on the glass fibers, which enhances the thermal stability of the composites, as explained by Chen et al. [43]. Furthermore, the amount of residue after complete degradation was almost similar in all reprocessing cycles, with slight variations (Table 3). Therefore, recycled composites, both compatibilized and uncompatibilized, showed good thermal performance even after three reprocessing cycles

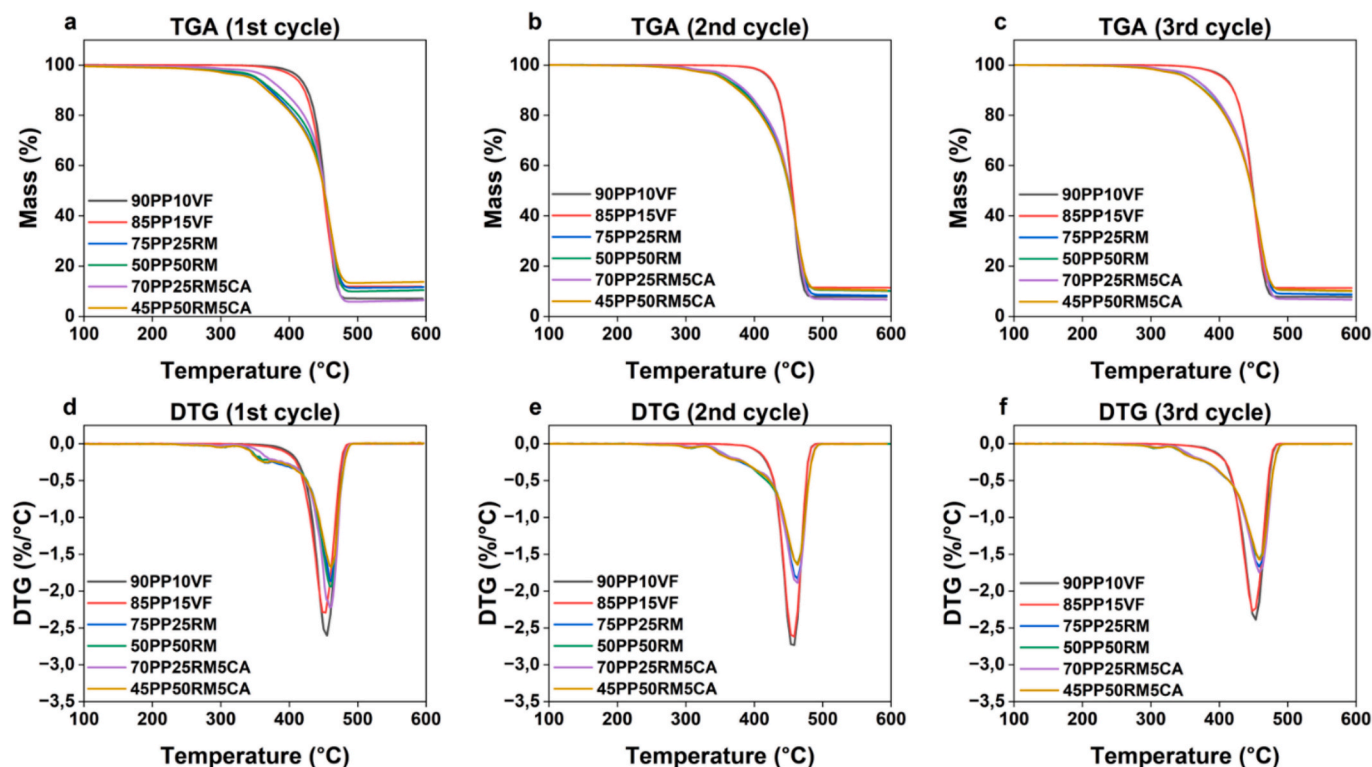


Fig. 8. Schematic illustration of nucleation-inducing behavior of virgin fibers (a) in virgin composites; glass fibers and thermoset residue (b) in recycled composites.

Table 3

Degradation temperature of all the composites calculated by the DTG curves and residual fiber content.

Samples	T_d (°C) (1 st cycle)	T_d (°C) (2 nd cycle)	T_d (°C) (3 rd cycle)	Residue (%) (1 st cycle)	Residue (%) (2 nd cycle)	Residue (%) (3 rd cycle)
90PP10VF	455	456.3	450.1	7.06	7.77	7.79
85PP15VF	450.2	456.4	448	11.86	11.41	11.30
75PP25RM	460.3	464.3	460.2	8.83	8.23	8.68
50PP50RM	461.1	463.5	459.6	10.48	10.13	10.07
70PP25RM5CA	460.4	463.7	460.6	6.47	6.66	6.62
45PP50RM5CA	461.1	463.4	460.2	13.80	10.39	10.20

compared to virgin composites.

3.2.2.2. DSC. The melting and cooling curves of all the extruded samples as a function of various reprocessing cycles are represented by the DSC thermograms in Fig. 10. Table S3 summarizes the melting and crystallization temperatures and degree of crystallinity at each reprocessing cycle. The melting temperature (T_m) of the composites 90PP10VF, 85PP15VF, 75PP25RM, and 50PP50RM slightly increased to around 164–165°C from 162°C (for neat PP). This might be due to the presence of thermally stable virgin glass fibers and SWTB [42,44]. However, T_m values of 70PP25RM5CA and 45PP50RM5CA slightly decreased compared to the uncompatibilized composites. Luo et al. indicate that an increased MAPP content results in a slight reduction in the T_m in compatibilized composites, mostly due to MAPP's lower melting point [45]. The T_m of all the composites remained stable during all the reprocessing cycles. Moreover, the T_m of each sample exceeded 160°C, indicating the presence of α -form crystals, as evidenced by XRD measurements conducted by Pu et al. [24]. The research by G. Luo et al. further substantiates the existence of α -form crystals within the temperature range of 160–165°C, while it has also been demonstrated that β -form crystals exist between 151 and 152°C [45]. In light of these findings and the consistency of the material system, additional XRD characterization was not conducted in the present study.

Meanwhile, in the first cycle, the crystallization temperature (T_c) of

75PP25RM and 50PP50RM rose to 129°C. However, 90PP10VF and 85PP15VF showed a T_c of 124.26°C and 125.13°C, respectively, which are comparatively lower than their recycled counterparts. Generally, the T_c of neat PP is around 120°C. This clearly shows the positive impact of adding highly thermally stable reinforcements such as glass fibers. However, recycled composites compatibilized with MAPP showed a slight decrease in T_c compared to counterparts without MAPP. Similar observations were made by G. Luo et al., where increasing MAPP over 2 wt.% resulted in lower T_c , which is attributed to the lower nucleating ability of the compatibilizer, but an optimal MAPP content in the matrix or attached to the surface of the glass fiber is essential for the composites' enhanced mechanical properties [45]. Upon reprocessing, the T_c of uncompatibilized and virgin composites decreased by approximately 2°C; however, the T_c of compatibilized composites remained almost similar across all the reprocessing cycles.

The crystallinity index (X_c), on the other hand, for 90PP10VF and 85PP15VF was 46.27 % and 46.76 %, respectively. This can be attributed to virgin glass fibers, which act as a heterogeneous nucleating agent, as shown in Fig. 9a. These fibers provide enough surface area for PP crystals to grow, which enhances X_c of these composites. Upon reprocessing, the crystallinity remained nearly unchanged; i.e., X_c of 90PP10VF and 85PP15VF in the third cycle was 47.32 % and 46.28 %, respectively. Due to intense shear in the extruder, fiber breakage might occur, which further increases the total number of nucleating sites.

In contrast, 75PP25RM and 50PP50RM composites exhibited a

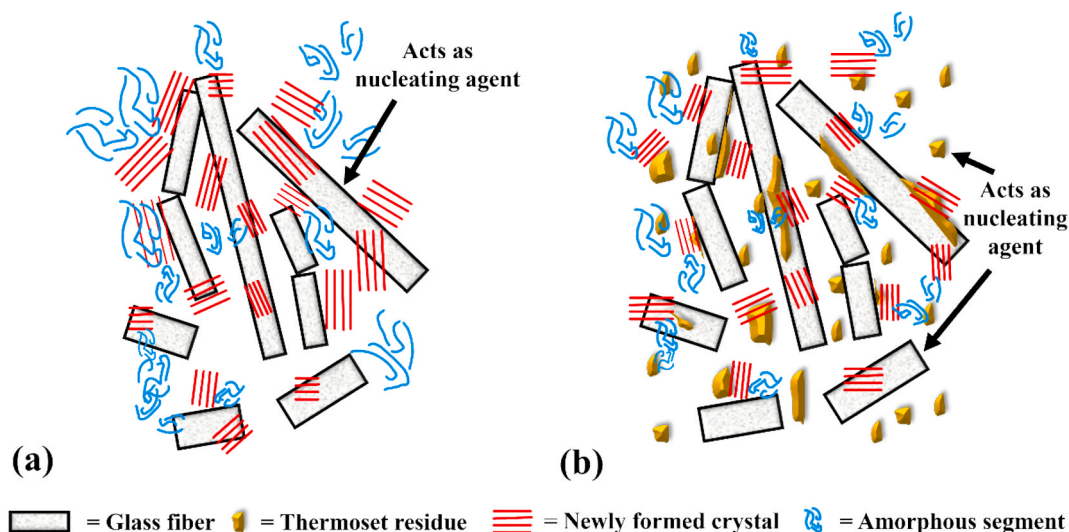


Fig. 9. Schematic illustration of nucleation-inducing behavior of virgin fibers in virgin composites (a); glass fibers and thermoset residue in recycled composites (b).

higher X_c of 59.33 % and 79.87 %, respectively, compared to virgin composites. This enhancement is attributed to the combined nucleating effect of glass fibers and thermoset residue particles (Fig. 9b), which further promotes crystal formation within the composites [24]. However, upon reprocessing, a reduction in X_c was observed, likely due to thermal degradation of thermoset residue, which forms charred impurities. This can eventually hinder the PP chains from organizing into crystalline lamellae. In addition, the weak interface between the contaminated recycled material and the PP matrix in the absence of a coupling agent makes the crystallinity more vulnerable to the detrimental effects of degradation, which led to the decrement of their X_c in

the second and third cycles.

In 70PP25RM5CA and 45PP50RM5CA, the presence of MAPP improved interfacial adhesion between PP and recycled materials, promoting faster crystallization of PP chains [46]. This improved adhesion helped to maintain similar crystallinity across all cycles despite the thermal degradation of thermoset residue particles. Furthermore, in composites with a higher amount of recycled materials, the nucleation-inducing effect of SWTB augments the degree of crystallinity. However, at lower content of SWTB, a notable decrease in X_c was observed. However, Pu et al. reported the contrary of this result, which suggested that a lower amount of SWTB improved X_c of the composite [24].

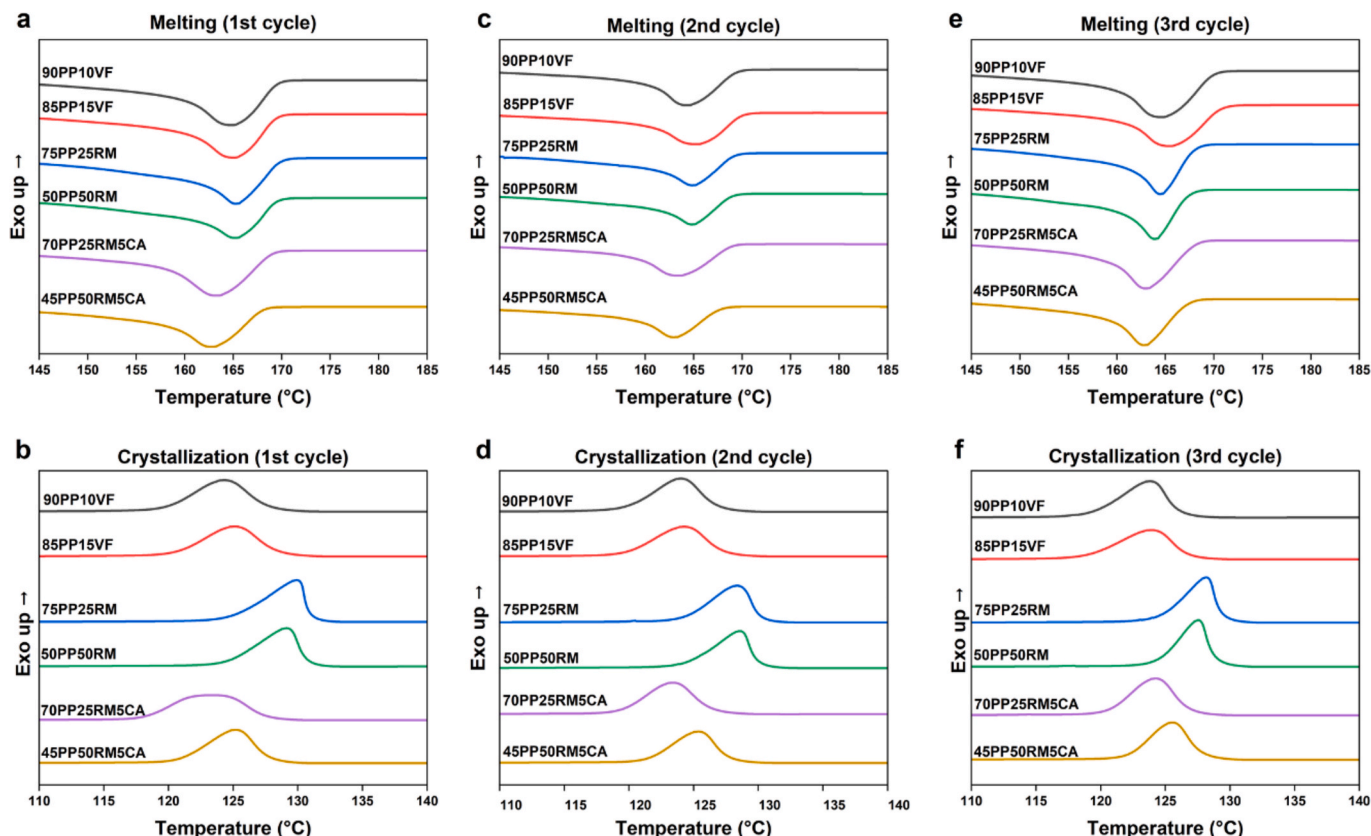


Fig. 10. DSC thermograms of all the composites at different reprocessing cycles: (a, c, e) melting; (b, d, f) crystallization.

Therefore, these results demonstrated that (i) compatibilization is essential to maintain crystallinity during reprocessing of recycled composites and (ii) SWTB-derived glass fibers and thermoset residue act as effective nucleating agents and improve crystallization. A detailed discussion on the nucleating ability of glass fibers and thermoset residue particles is presented in [section 3.2.4](#).

3.2.3. Static and dynamic mechanical properties

3.2.3.1. Tensile test. Mechanical testing under static and dynamic conditions was conducted on all the samples. The tensile and flexural properties of all the samples at different reprocessing cycles are shown in [Fig. 11](#). The comparison in mechanical properties, especially between uncompatibilized, compatibilized recycled composites and virgin composites, was done based on their glass fiber percentage as discussed in the previous section. Tensile properties of 45PP50RM5CA (1st cycle) were determined based on 4 samples due to an outlier that exceeded 3 times the standard deviation.

Higher tensile properties were observed in VF/PP composites due to the addition of virgin glass fibers, which had uniform length and dispersion within the PP matrix. On the other hand, when recycled materials from SWTB were incorporated into the PP matrix, the tensile strength decreased due to poor adhesion between the recycled glass fiber and the PP matrix, although tensile modulus showed an increase due to the addition of high-modulus glass fibers present in SWTB. With the introduction of the MAPP coupling agent, the tensile strength of SWTB/PP composites escalated to 32.50 MPa (70PP25RM5CA) and 31.54 MPa (45PP50RM5CA), and consequently the tensile modulus also showed an improvement as the SWTB content increased from 25 wt.% to 50 wt.%. This behavioral divergence is statistically substantiated by the 2-way ANOVA, where the analysis of tensile strength performance revealed that composition type is the dominant governing factor with $p < 0.05$ (Tables S4 and S8) in all the composites. This demonstrates the reinforcing effect of SWTB and MAPP in recycled composites. The difference between uncompatibilized and compatibilized composites was also characterized by SEM micrographs, as shown in [Fig. 12a&b](#), which

clearly show the positive impact of MAPP in improving adhesion between uncompatibilized and compatibilized composites. Pu et al. also reported similar improvements in tensile properties after the addition of MAPP into SWTB/PP composites [24]. Despite these improvements in both 70PP25RM5CA and 45PP50RM5CA composites, they were able to achieve only 85 % of the tensile strength of virgin composites in the first cycle. It was also observed that the tensile modulus of the composites increased with the increase in glass fiber loading, which shows the high stiffness provided by glass fibers. The ANOVA analysis showed that the aforementioned increase in tensile modulus in higher glass fiber loaded composites (85PP15VF, 50PP50RM, and 45PP50RM5CA) is statistically significant and is mainly affected by the type of composition ($p = 0.001$) and the reprocessing cycle ($p = 0.024$) ([Table S9](#)). This can be attributed to the proper fiber dispersion happening during the reprocessing, which is discussed in [Section 3.2.3.3](#).

Furthermore, the tensile strength of compatibilized SWTB/PP composites showed an increase after the second and third cycles of reprocessing. After three reprocessing cycles, the tensile strength of 45PP50RM5CA increased to 33.19 MPa, which is almost equivalent to the tensile strength of the 85PP15VF composite. Noticeably, in [Table S8](#), the interaction effect (composition type $\times$ cycle) showed statistical significance ($p < 0.05$) in higher fiber-loaded composites (85PP15VF, 50PP50RM, and 45PP50RM5CA). This result demonstrates the excellent retention and recovery of mechanical performance in the compatibilized recycled composite despite replacing virgin glass fibers with recycled wind turbine blade waste.

3.2.3.2. 3-point bending test. The flexural strengths of 70PP25RM5CA and 45PP50RM5CA after the first cycle were 47.45 MPa and 51.13 MPa, respectively. Their virgin counterparts, 90PP10VF and 85PP15VF, exceeded them by 9 % and 2 %, respectively. A similar trend was noticed in the flexural moduli of these composites. Although the flexural strengths of the virgin composites were initially above 51 MPa, they decreased by approximately 6 % (90PP10VF) and 4 % (85PP15VF) after three cycles. Compatibilized composites, however, outperformed both virgin and uncompatibilized systems after reprocessing. Notably,

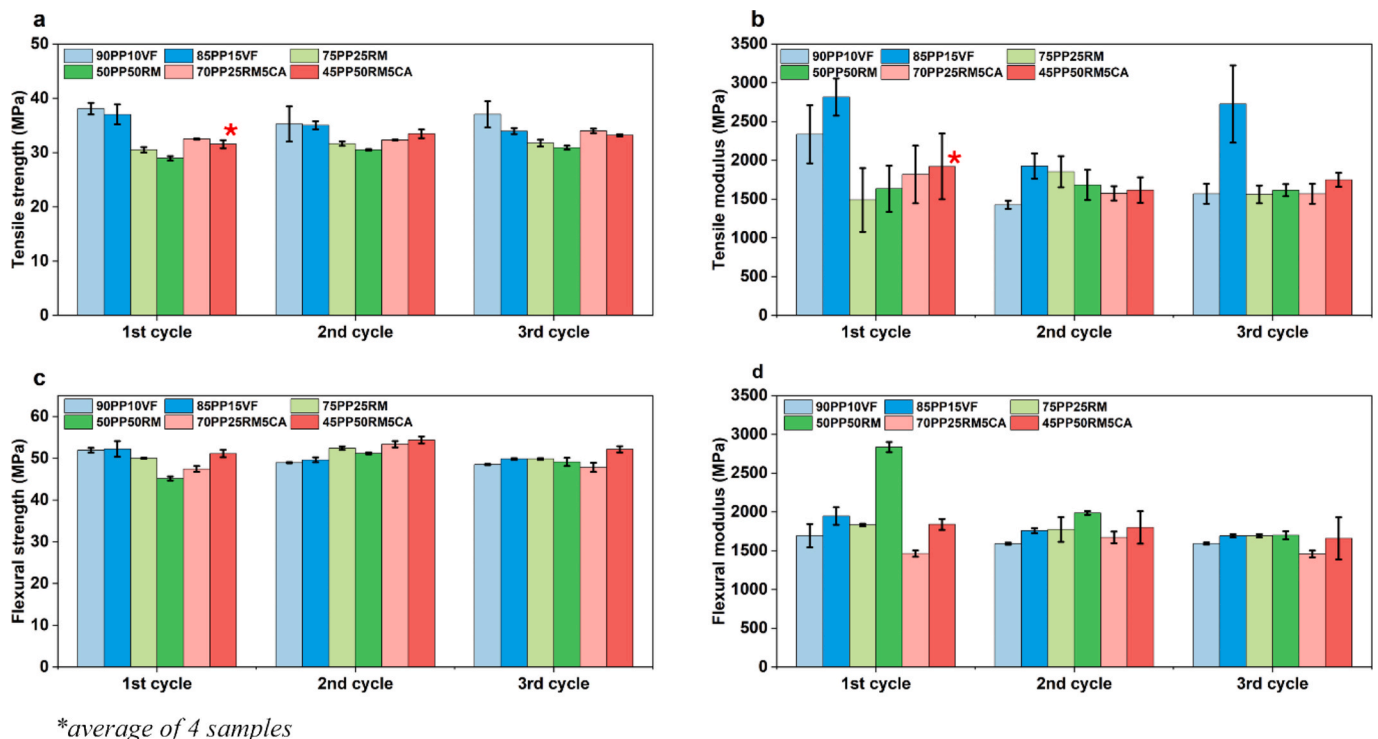


Fig. 11. Tensile and flexural properties of PP/VF and PP/SWTB composites during three reprocessing cycles.

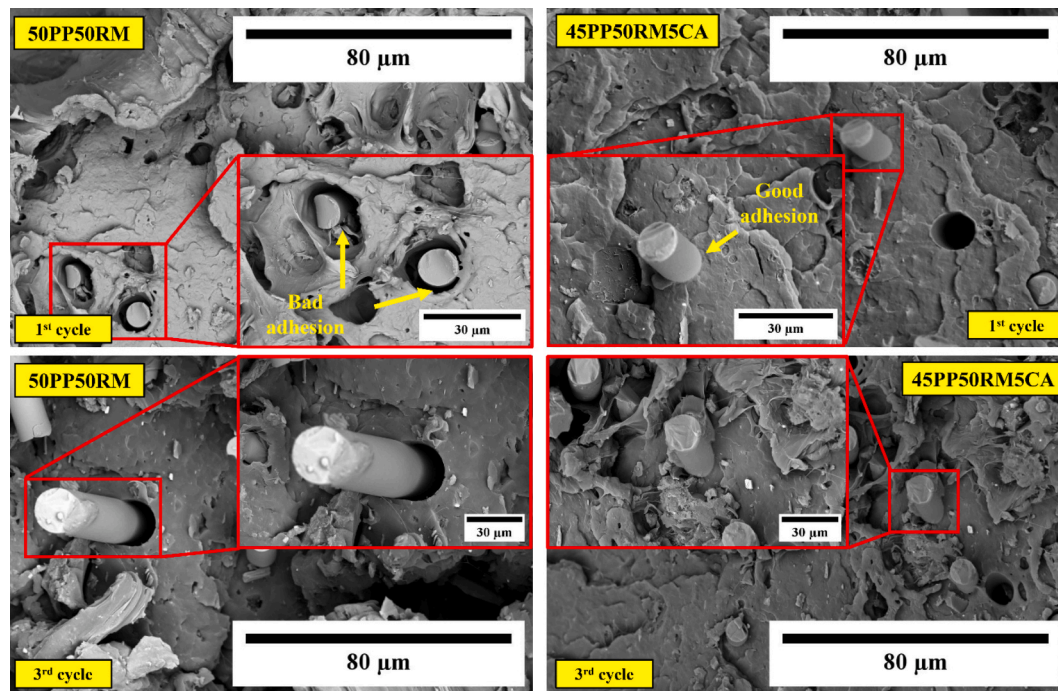


Fig. 12. SEM micrographs of tensile fractured surfaces of 50PP50RM and 45PP50RM5CA at first and third reprocessing cycles, representing the effectiveness of CA in secondary composites.

45PP50RM5CA reached 52.15 MPa after the 3rd cycle, exceeding the flexural strength of its virgin counterpart 85PP15VF, by approximately 5 %. The ANOVA analysis, as seen in Tables S6, S7, S10, and S11, confirmed that flexural strength and modulus are statistically significant, where the type of composition, reprocessing cycles, and interaction between them are below the 95 % confidence interval. This highlighted the strong effect of compatibilization under flexural loading, where crack initiation and propagation were effectively suppressed. Nonetheless, uncompatibilized composites exhibited higher flexural modulus across all reprocessing cycles; this increase did not translate into improved mechanical performance; instead, it represented higher brittleness within the composite. In contrast, compatibilized composites displayed slightly lower flexural modulus but superior strength retention and stability over multiple reprocessing cycles, indicating a more homogeneous microstructure and effective load transfer.

3.2.3.3. Effect of SWTB and reprocessing cycles on mechanical properties.

According to Rahimizadeh et al., this discrepancy in tensile and flexural behavior in uncompatibilized recycled composites after the first cycle can be attributed to the local stress concentration regions developed due to improper dispersion of fibers within the PP matrix, which leads to lower mechanical properties of uncompatibilized recycled composites. The resin particles and fibers below critical length increase the likelihood of microcrack development. Additionally, non-uniform distribution of thermoset residue on the fiber surface might also reduce the ultimate tensile strength of the composites [47]. Furthermore, the absence of a coupling agent restricts stress transfer at the fiber-matrix interface, resulting in fiber pull-out and interfacial debonding under load.

However, compatibilized composites (with MAPP) exhibited a constant improvement in mechanical properties after reprocessing. Correa-Aguirre et al. made similar conclusions, where silane-treated bagasse-PP composites showed similar improved adhesion during all 5 reprocessing cycles [48]. Huang et al. primarily ascribed this enhancement in mechanical properties to processing parameters in injection molding, including reduced screw speed (100 rpm) and lower melt temperature (190°C). Reduced damage to the PP polymer chains led to elevated

molecular densities, thereby enhancing the tensile strength of reprocessed composites. Also, at reduced melt temperatures, the configuration of molecular chains remained intact, leading to enhanced tensile strength [49]. Even this study employs lower screw speed and melt temperature, as discussed in Section 2.2.2, which further bolsters this argument.

Furthermore, Fig. 13 shows two more plausible reasons for such a stable improvement in the compatibilized composites. Firstly, repeated extrusion enhanced fiber dispersion within the PP matrix by breaking the fiber agglomerates. While fiber breakage occurred during reprocessing, the initially long length of fibers in SWTB (≤ 20 mm) compared to virgin fibers (4 mm) helped to retain sufficient length to remain above the critical fiber length required for effective stress transfer. Correa-Aguirre et al. made analogous observations, noting that fiber dispersion improved following reprocessing, whereas fiber length retention depended upon the initial fiber length [48]. Consequently, the reduction in fiber length does not significantly compromise the reinforcement effect within the studied number of cycles. Due to these effects, stress concentration regions, which were discussed earlier in the section, would be minimized. On the other hand, both 90PP10VF and 85PP15VF showed a logarithmic decrease in their tensile ($R^2 = 0.999$ for 85PP15VF) (Fig. S3) and flexural ($R^2 = 0.936$ for 90PP10VF, $R^2 = 0.816$ for 85PP15VF) (Figs. S4a and S5a) strengths for increasing reprocessing cycles. A similar trend was observed for flexural modulus, as shown in Figs. S4b and S5b ($R^2 = 0.859$ for 90PP10VF, $R^2 = 0.986$ for 85PP15VF). This trend in virgin composites was also observed by Sergi et al., who attributed it to fiber length reduction in each reprocessing cycle [45].

Secondly, partial thermal degradation of thermoset residue or original sizing agent that was present in SWTB leads to the accessibility of a larger fiber surface for the coupling agent and augments the interfacial adhesion between the fiber and the PP matrix. Previous studies reported that the presence of thermoset residue on the fiber surface increases the interfacial strength by allowing fibers to interact mechanically and chemically; rough fiber surfaces cause the former, while the latter is caused by hydrogen bonds [47]. Despite uncompatibilized composites undergoing similar mechanisms, the absence of MAPP made them

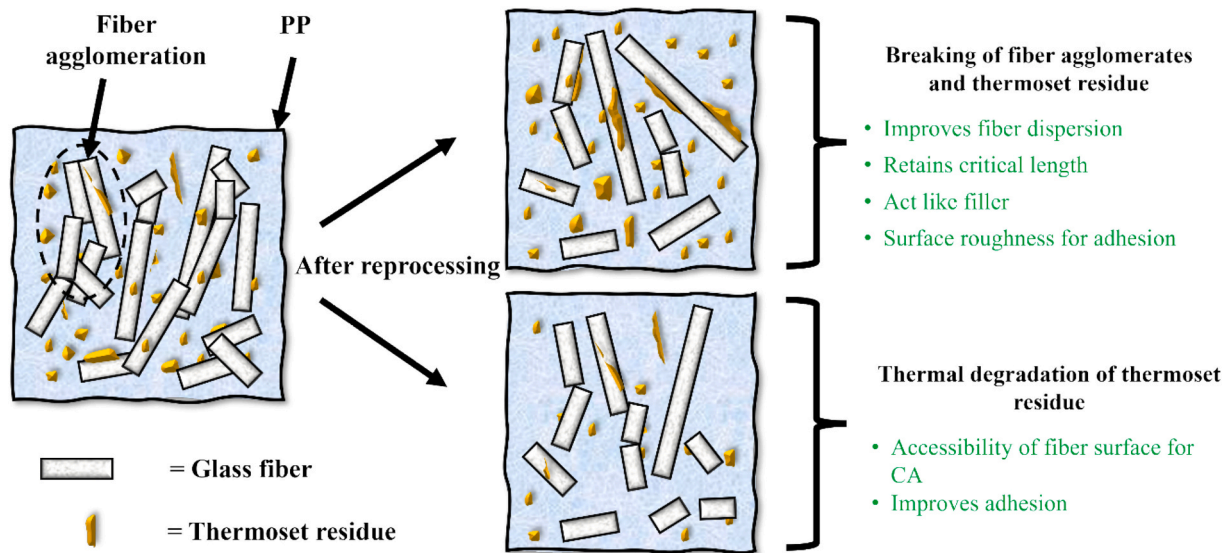


Fig. 13. Schematic illustration of the effects of reprocessing on recycled composites.

underperform in both tensile and flexural tests. SEM observations (Fig. 12a&c) supported these interpretations, where uncompatibilized composites exhibited increased fiber pull-out, lower fiber-matrix adhesion, and increased interfacial voids across the reprocessing cycles.

Overall, the interaction of fiber length reduction, interfacial modification, dispersion improvement, and thermoset residue evolution regulates the mechanical behavior of SWTB/PP composites during reprocessing. The consistency in mechanical performance over several recycling cycles was observed, as the advantages of improved interfacial adhesion and dispersion in compatibilized systems outweigh the drawbacks of fiber shortening.

3.2.3.4. DMA. The storage modulus and glass transition temperature

(T_g) of the composites as a function of the number of reprocessing cycles were studied through DMA as shown in Fig. 14. It was evident that the recycled composites, both uncompatibilized and compatibilized, showed a substantial enhancement in the storage modulus (G') in all the cycles. The G' values of virgin composites were lower than or equal to those of recycled composites, except for 90PP10VF during the second cycle, whose G' was as low as 2527.68 MPa (Fig. 14b). Also, it was shown that the addition of SWTB augments the rigidity of the composites, similar to virgin composites, helping them to maintain their form and structural integrity even at as low as -50°C . The fundamental reason for this improvement in recycled composites is the effective transfer of stress between the glass fibers and the PP polymer chains [50]. The ratio of the loss modulus to the storage modulus was quantified as the

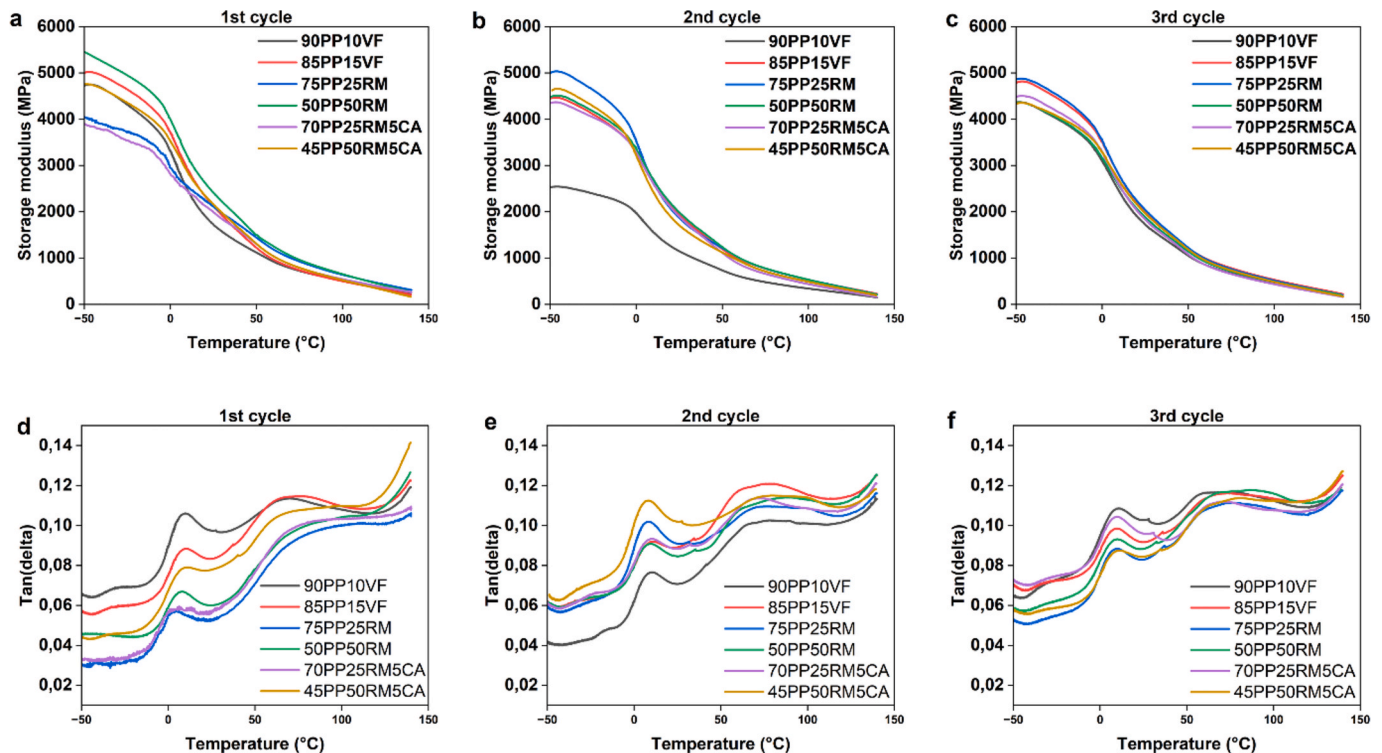


Fig. 14. Storage modulus (a, b, c) and $\tan \delta$ (d, e, f) curves of PP/VF and PP/SWTB composites during three reprocessing cycles.

damping factor ($\tan \delta$). As shown in Table S5, two different T_g values of all the composites were evaluated using $\tan \delta$ and G' as described by Sergi et al. [51]. During all reprocessing cycles, the T_g of all the composites, according to the $\tan \delta$ peak, was around 1.2 to 1.4°C, and as per G' , T_g was between -3 and -8°C. As already reported for TGA and DSC, mechanical reprocessing does not alter the glass transition temperature significantly. A second peak in $\tan \delta$ was observed at a higher temperature range between 60 and 90°C, as shown in Figs. 14d, e & f. A similar result was also reported by Pu et al. [24]. This phenomenon is mainly due to different segmental dynamics occurring near the interface between the glass fiber and polypropylene matrix. This was ascribed by Tsagaropoulos and Eisenberg to the glass transition of immobilized chains close to the particles [52,53]. According to Robertson et al., interactions with particles can also inhibit the terminal relaxation process (chain diffusion) of uncrosslinked polymers. This indicates that only chains that are unaffected by the particles move within the typical temperature range [54].

Overall, the mechanical and thermo-mechanical performance of compatibilized recycled composites improved in each reprocessing cycle and reached the same level as that of virgin composites at the end of the third cycle, thereby exhibiting the positive effect of reprocessing on SWTB composites. Thus, 10 to 15 wt.% of virgin fibers can be easily replaced by 25 to 50 wt.% of SWTB in secondary polymer composites without compromising on mechanical properties.

3.2.4. Nucleation and interfacial transcrystallinity

To further clarify whether the transcrystallinity occurs at the interface between glass fiber, thermoset particles, and the PP matrix during crystallization, polarized optical microscopy was used to capture the crystallization process of the pellet samples. In this test, virgin composites (90PP10VF) and compatibilized composites (70PP25RM5CA) were considered since it was more of a qualitative analysis. Additionally, for comparative purposes, the transcrystallinity of pure PP was examined. Fig. 15 compares the development of crystallization in pure PP and

near the fiber surface in virgin and recycled composites after the first cycle, which occurred between 140 and 120°C. Due to birefringence and degraded thermoset particles, it was difficult to make a sharp contrast distinction during initial crystallization in recycled composites. As can be seen after 240 s, the PP crystals nucleate randomly and grow into larger spherulites near the fiber surface in both virgin and recycled composites, except in pure PP, where nucleation occurs randomly, which in turn takes a long duration for crystals to grow into larger spherulites. After 500s, layers of oriented crystals surrounding the glass fibers developed rapidly in the case of virgin composites, and glass fibers and thermoset residue particles in recycled composites, which indicated the high nucleating ability of the glass fiber and thermoset residue. Further amalgamation of the transcrystalline interface and bulk PP spherulites also occurred at the later stage of crystallization. A similar observation on the nucleating ability of glass fibers was also reported by Luo et al. [45]. Furthermore, the time taken to crystallize for recycled composites was comparatively lower than for PP and virgin composites. Similarly, the corresponding crystallization temperature was also increased in recycled composites, proving the rapid crystallization capability of recycled glass fibers and thermoset particles. There were no significant differences in transcrystallinity after reprocessing. Thus, the presence of a nucleating agent in the form of glass fibers and thermoset particles helped the rate of crystallization.

3.2.5. MFR

The MFR of composites was determined in order to investigate how reprocessing affects flowability. The MFR of all the composites at different reprocessing cycles is shown in Fig. 16. In the first cycle, the values of MFR for 90PP10VF and 85PP15VF were the lowest of all at 10.28 g/10 min and 10.32 g/10 min, respectively. In recycled composites, both uncompatibilized and compatibilized, a higher melt flow was observed in comparison with virgin composites. Another noticeable observation was that MFR increased with the addition of MAPP. For instance, in the first cycle, MFR of 70PP25RM5CA and 45PP50RM5CA

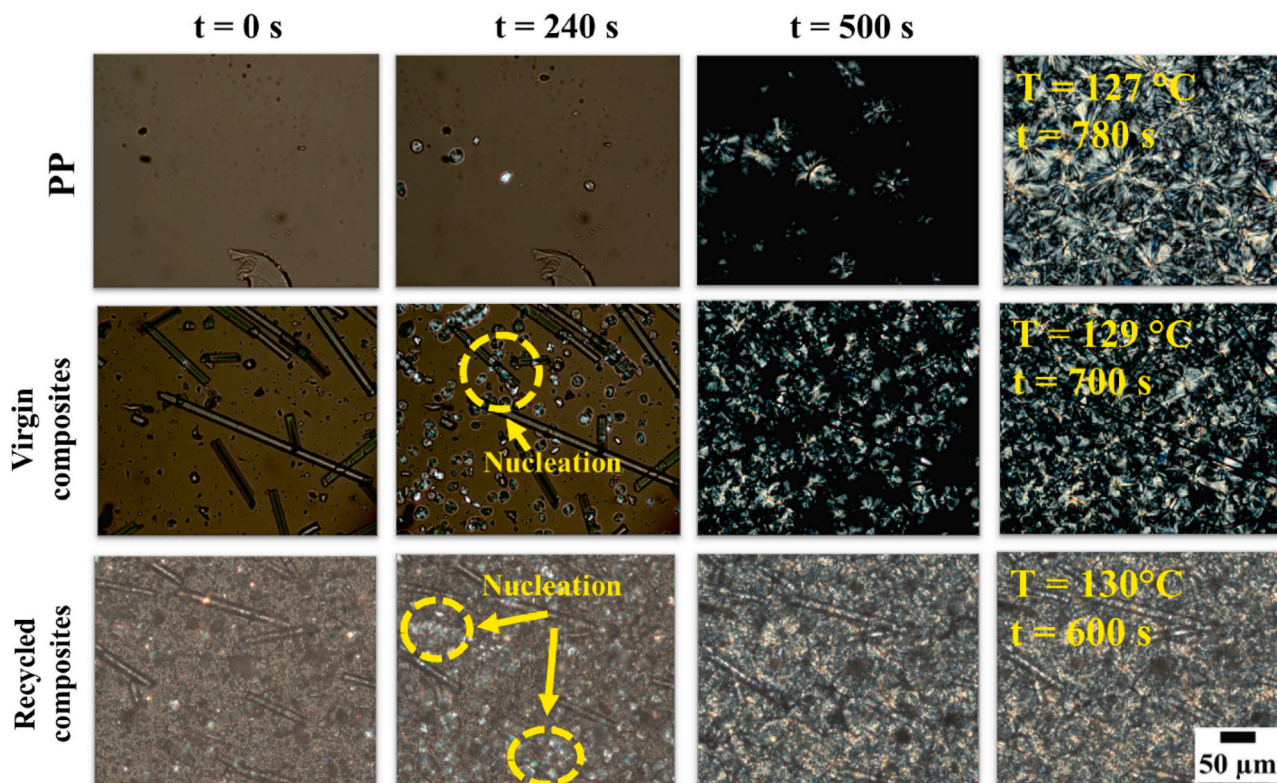


Fig. 15. In-situ polarized optical micrographs of different composites at $t = 0$, 240, and 500 s.

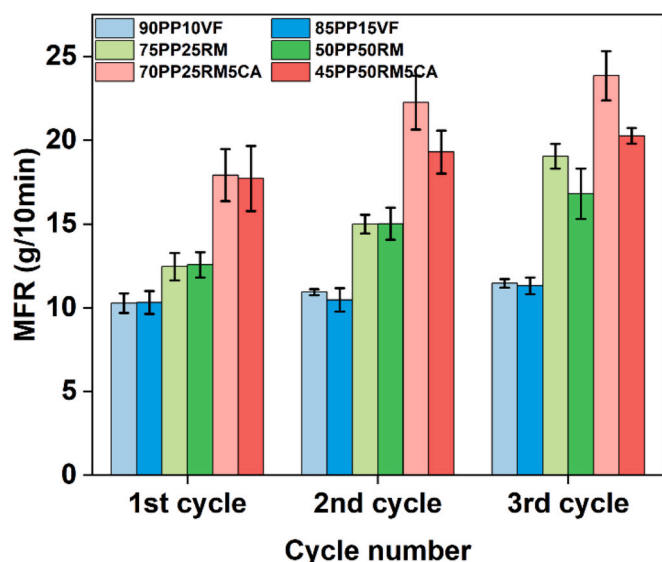


Fig. 16. Effect of reprocessing on the MFR of different composites.

increased by 44 % and 41 %, respectively, compared to their uncompatibilized counterparts, 75PP25RM and 50PP50RM. After the third cycle, MFR of 90PP10VF, 75PP25RM, and 70PP25RM5CA increased by 11 %, 53 %, and 33 %, respectively. However, 85PP15VF, 50PP50RM, and 45PP50RM5CA showed an increase of 9 %, 33 %, and 14 % in their MFR values after three cycles. This clearly shows that lower values of MFR were observed in those composites with higher glass fiber loading, and this can be attributed to the fact that when fillers such as glass fibers are added to a polymeric matrix, they function as barriers that alter the flow lines of the polymer and limit its chain mobility [55], increasing the melt viscosity [56]. However, the increase in the melt flow of recycled composites can also be attributed to the thermoset residue that might hinder the entanglement of PP chains and thereby decrease the viscosity of PP. It was observed that the MFR of all materials increased linearly after every reprocessing, as seen in Fig. 16. This outcome could be related to a gradual drop in the molecular weight of the polymer caused by the scission of macromolecules, which reduces the polymer length [57] and thereby lowers the viscosity of the polymer melt. This degradation can also be due to the combined effects of operating temperature and mechanical stresses during the extrusion and injection stages [58,59]. This was further proved by Spicker et al., who showed that PP subjected to ten reprocessing cycles had improved MFR and decreased average molecular weight and viscosity, all of which corresponded to the occurrence of β -scission reactions [60]. In addition, Sergi et al. [51] attributed this increase in flowability to another competing phenomenon, i.e., fiber length reduction that happened during reprocessing. This increase in MFR during reprocessing can also be correlated with the increase in crystallization rate as discussed in sections 3.2.2 and 3.2.4. Huang et al. also indicated that the progressive increase in material fluidity (up to three reprocessing cycles) significantly aided the mold filling process during injection molding, thereby increasing the tensile strength of the produced specimens [49]. Therefore, the increase in MFR of the composites eventually helps in achieving optimal parameters required for injection molding, provided reprocessing is limited to a maximum of three cycles.

4. Environmental performance outlook of SWTB/PP composites

Beyond the mechanical and thermal performance demonstrated in the previous sections, there are reasons to assume that the product system described could offer a favorable environmental profile. The following considerations arise from the architecture of the product system itself rather than from any assessment providing quantified

results, and as such, they are stated explicitly as hypotheses requiring further investigation.

First, the system substitutes two virgin materials simultaneously. The incorporation of SWTB displaces a share of virgin PP, a fossil-based polymer, while the glass fibers already embodied in the SWTB take over the reinforcing function otherwise served by virgin glass fibers, whose primary production is generally regarded as energy-intensive [61,62]. Cradle-to-gate production of virgin dry chopped strands of glass fibers in Europe typically contributes to an average total primary energy demand of 29.6 MJ (range 22.6–37.4 MJ/kg across eleven European production sites) and to an average total GWP100 value of 1.57 kg CO₂ eq./kg (range 0.96–2.26 kg CO₂ eq./kg across the same eleven production sites), reflecting the energy-intensive melting of raw materials at furnace temperatures of approximately 1500°C [63]. The total primary energy comprises non-renewable and renewable energy, including both the energy consumed by production processes (combustible energy) and the energy embodied in material outputs (material energy) [63]. This metric is broadly comparable to cumulative energy demand (CED) as reported elsewhere in the literature, though underlying calculation methods and system boundaries may differ between sources and are not independently verified here. The system thereby has the potential to avoid primary production burdens of both virgin PP and glass fibers, while diverting a composite waste stream from disposal, which has no established high-value recovery route.

Second, the processing route is comparatively simple. The SWTB enters the new product system carrying only the burdens of mechanical recycling, which is commonly reported as the least energy-intensive recovery route for fiber-reinforced composites when compared with thermal and chemical fiber reclamation [61,62]. Reported energy demands for reclaiming fibers from end-of-life fiber-reinforced composite waste range from 0.27 to 3.03 MJ/kg for mechanical recycling, compared with 3 to 30 MJ/kg for thermal and 63 to 91 MJ/kg for chemical recycling routes [18]. Upstream, the shredding process itself requires only electricity for operations, fuel for on-site machinery, and auxiliary consumables for equipment maintenance. Downstream, the incorporation of SWTB demands no chemical pretreatment, or purification beyond the conventional composite production process. This entails that no additional environmental burdens, apart from those associated with mechanical recycling, are introduced to the system as part of SWTB incorporation.

Third, the reprocessing results reported above suggest that the material can sustain multiple product lives. The compatibilized formulations retained and partially recovered their mechanical performance over three processing cycles, with no evidence of chemical degradation. If confirmed at product scale, this multi-cycle capability would allow the initial production burden to be distributed across several service lives.

The above could in principle lead to a favorable environmental performance analysis; however, quantified results to back up these expectations are not yet available. Moreover, a complete picture across all environmental impact categories is necessary to ensure that improvements in one category do not coincide with burden-shifting into others. A dedicated life cycle assessment of this product system, conducted in accordance with ISO 14040/14044 and encompassing the full cradle-to-gate system, including the upstream shredding process and the multi-cycle reprocessing loop, is therefore required and is the subject of ongoing work by the authors.

5. Conclusion

In this study, Polypropylene (PP) composites containing 25 and 50 wt% shredded wind turbine blade (SWTB) waste were produced and repeatedly reprocessed through three consecutive thermomechanical recycling cycles, each consisting of shredding, twin-screw extrusion, and injection molding, to systematically investigate the effects of repeated processing on the mechanical and thermal performance of secondary composites and their potential for multi-cycle circular utilization. Also, a

comparative study was done between secondary composites and virgin composites. The following conclusions can be drawn:

- Inclusion of 5 wt% MAPP (maleic anhydride-graft-polypropylene) was essential. SEM micrographs showed the improved adhesion between polypropylene and SWTB at the interface, ensuring the retention and recovery of mechanical properties over multiple reprocessing cycles.
- FTIR analysis verified that the chemical structure of the composites stays intact. No substantial oxidation or novel chemical peaks were detected after three reprocessing cycles, demonstrating that the degradation is mainly thermo-mechanical.
- Recycled composites (SWTB/PP) exhibited superior thermal stability compared to virgin glass fiber composites. The degradation temperatures (T_d) of SWTB/PP composites were approximately 5–12°C elevated relative to virgin composites across all reprocessing cycles.
- The glass fiber and thermoset residue in SWTB function effectively as nucleating agents. In comparison to virgin composites, the recycled composites exhibited elevated crystallization temperatures and a crystallinity index of up to 80 %. This indicates that waste materials possess a greater number of surfaces for polymer crystal growth compared to smooth virgin fibers.
- The mechanical properties showed that initial fiber length, reprocessing, and addition of MAPP led to retention of critical fiber length, improved fiber dispersion, and fiber-matrix interaction, respectively, in recycled composites. The mechanical properties of compatibilized recycled composites achieved a maximum point in their third cycle, achieving equivalent performance to virgin composites.
- The compatibilized recycled composites showed a higher MFR compared to other composites across all the reprocessing cycles, which exhibit lower molecular weight and decreased viscosity. This progressive increase in material fluidity significantly helps the mold filling process during injection molding.
- The product system's architecture, considering virgin material substitution, low-energy requirements of mechanical recycling, and the multi-cycle reprocessing capabilities, offers reasons to suggest a favorable environmental profile, though this remains to be confirmed through a dedicated life cycle assessment.

However, further upscaling of reprocessing of secondary composites could be done on a component level. Additionally, further studies should examine the impact of accelerated aging on the recyclability and property retention of these secondary composites to replicate real end-of-life scenarios more accurately.

CRedit authorship contribution statement

S. Tumkur Karnick: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **N. Lushnikova:** Writing – review & editing, Supervision. **David Hysi:** Writing – original draft. **H.J.H. Brouwers:** Writing – review & editing, Supervision. **F. Gauvin:** Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.compositesa.2026.110326>.

Data availability

All data are contained within the article and **supplementary material**

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