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Investigation of the Fiber Length and the Mechanical Properties of Waste Recycled from Continuous Glass Fiber-Reinforced Polypropylene

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Abstract: This paper explores the mechanical recycling of continuous fiber-reinforced thermoplastics (CFRTPs) waste into injection molded products, focusing on the influence of recycling parameters on fiber length and mechanical properties. CFRTPs are gaining attention for their promising attributes, including weight-specific mechanical properties, short cycle times, storability, and recyclability, making them suitable for diverse applications. However, as CFRTP production rates rise, recycling strategies become crucial for sustainability. This study investigates the processability of CFRTP waste, defines size reduction conditions, and evaluates the impact of various compounding parameters such as temperature, screw speed, and fiber volume content during extrusion. The research findings indicate that higher screw speeds lead to fiber length reduction, whereas elevated temperatures result in longer fibers. Increased fiber volume intensifies interactions, resulting in shorter lengths. Additionally, the study examines the influence of injection molding parameters such as back pressure, screw speed, and initial fiber length on the resulting fiber length and mechanical properties of injection molded specimens, emphasizing the need for precise parameter control to optimize performance in recycled CFRTPs. Key findings are that increasing the initial fiber length from 260 µm to 455 µm results in an average fiber length after injection molding of 225 µm and 341 µm, respectively. This implies that longer initial fibers are more prone to breakage. Regarding the mechanical properties, increasing back pressure from 20 bar to 60 bar results in a reduction in Young's modulus of approximately 40 MPa. Higher screw speed also reduces modulus by approximately 70 MPa due to intensified fiber–screw interactions. However, back pressure and screw speed have neutral effects on the tensile strength and the elongation at break.

Keywords: continuous fiber-reinforced thermoplastics; recycling; fiber length; mechanical properties

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1. Introduction

Recently, fiber-reinforced composites with thermoplastic matrix materials have been receiving increasing attention due to their potential advantages such as excellent weight-specific mechanical properties, short cycle times, storability, repeated meltability, recyclability, good formability, and the use of alternative joining processes enabling automated large-volume manufacturing processes. These exceptional features render these materials widely applicable across a spectrum of industries, encompassing electronics, aerospace, automotive, transportation, military, energy, marine, sports and leisure, construction, medical, agriculture, recreation, industrial equipment, furniture, etc. [1–5]. When looking at the leading industries using these composites, according to a study by JEC, they are transportation (28%), construction (20%), electronics (16%), and piping and tanks (15%) [6].

As the production of continuous fiber-reinforced thermoplastics (CFRTPs) increases, so does the amount of waste to be disposed of, for which recycling strategies need to be established to ensure the sustainability of CFRTP. Hence, these recycling strategies must be developed, and economically and ecologically evaluated, to close the loop and achieve a circular economy to process recycled fiber-reinforced pellets from CFRTP waste to valuable products, e.g., by injection molding. Traditional disposal methods such as incineration and landfilling are becoming increasingly restricted [7]. Fiber-reinforced composite waste is generated not only after the use of fiber-reinforced plastics, but also during the manufacturing and processing of these products. Even if efforts are taken to minimize production waste during manufacturing, there is still a clear need to recycle CFRP material to prevent other, non-environmentally friendly options from being taken.

Depending on the matrix used, there are a variety of methods for recycling polymer composites. Thermoplastic composites can be sorted into three different categories including chemical, thermal, and mechanical processing. In chemical recycling, the matrix of solid composites is removed using reactive solvents breaking the covalent bonds of the matrix. The resulting base chemicals can be utilized as raw material or fuels to produce composites or in other industries, while the reinforcing materials and filler particles remain. As chemical recycling is less invasive than mechanical and thermal recycling, the length and homogeneity of recycled composite fibers are much greater; however, chemicals such as acids, bases, solvents, and washing liquids are consumed in this process, which may not be environmentally friendly [8]. The second recycling option for CFRTP is thermal recycling, which has been developed and applied to fiber-reinforced composites in various methods including combustion, fluidized-bed combustion (FBC), and pyrolysis. In thermal processing, external heat is applied in the absence of oxygen, usually in ovens with inert gas or under a vacuum, which decomposes the composites into different products. For instance, the matrix is volatilized into lower-weight molecules and gases such as CO_2, methane, and hydrogen. Most processes operate at temperatures between 450 and 700 °C depending on the polymer. The composite waste can also be converted into heat to produce electricity [8]. The mechanical recycling option starts with cutting and grinding the end-of-life composite materials into smaller pieces, which simplifies the separation from other components. After pre-shredding the CFRTPs, they are mechanically chopped in a cutting mill. With the resulting recycled material, fiber-plastic granules are produced using twin-screw extrusion with the addition of virgin polymer. Then the fiber-plastic granulates can be transferred into an injection molding machine or an extruder to produce new products [9]. It is worthwhile to note that the advancement in 3D printing technology has led to a sustainable approach to recycling high-performance CFRTPs. Innovations in 3D printing of CFRTPs have revolutionized complex composite structures, offering high performance at a low cost. This technology acts as a bridge between advanced materials and innovative structures; however, it should address correlations between materials, structure, process, and performance [10–12].

Several studies have investigated the influence of different parameters and manufacturing conditions during mechanical recycling of fiber-reinforced thermoplastics on the final product properties. Ogi et al. investigated the mechanical properties of ABS filled with various contents of recycled CFRP and found that tensile strength increases with increasing CFRP content, while the shear strength decreases [13]. Kouparitsas et al. explored the possibility of reusing short fibers from recycled composites to develop new composites. In their research, glass fibers (GFs) were first recovered from glass–polyester composites by mechanical shredding, then the recycled glass fibers were integrated into polypropylene (PP) at a level of 40% w/w (vf: 12%). The results of the mechanical tests proved that the new composites (PP + GF) made with recycled fibers showed mostly similar mechanical properties as those of the virgin fiber composites [14]. In research conducted by Palmer, the single fiber tensile test was conducted to compare the mechanical properties of both virgin and recycled fibers. The recycling method used was mechanical recycling of injection molded parts. According to the results, it was shown that the strength of the recovered glass fiber significantly decreased (between 18% and 30%) when compared to the virgin fibers [15]. According to a study by Anandakumar et al., low strength and stiffness are two major limitations of short glass fiber-reinforced thermoplastics, which can be surpassed by adding continuous fibers along the critical sections of the composites [16]. Another approach to the length reduction challenge is the production of fiber–hybrid composites, which was investigated by Hassan et al. According to the results, by combining a mixture of waste carbon and polyamide 6 fibers with 6 vol.% of continuous glass fibers, the impact strength of the hybrid composite could be increased by 50.5% [17]. To investigate the effects of mechanical recycling on the mechanical behavior of an injection molded glass fiber-reinforced polyamide 6,6 composite, the tensile test was performed by Bernasconi et al. and it was found that the tensile strength of the recycled fiber composites dropped since the recycled fibers were shortened and distributed randomly in the new composites, while the elongation increased slightly depending on the recycled fibers in the composites [18]. In a study by Sam-Daliri et al., glass fiber-reinforced polypropylene waste and domestic packaging polypropylene were recycled using closed-loop material extrusion (MEX) recycling. Filaments with varying glass fiber content were tested, revealing optimal strength and stiffness at 30%. Excessive fiber beyond this point caused brittleness and defects in 3D prints [19,20].

The objective of this paper is essentially the quantitative representation of the fiber shortening along the recycling process chain of continuous fiber-reinforced thermoplastics. The focus here is on the influence of different processing parameters on fiber length and the investigation of the mechanical properties of recycled CFRTP waste under different conditions.

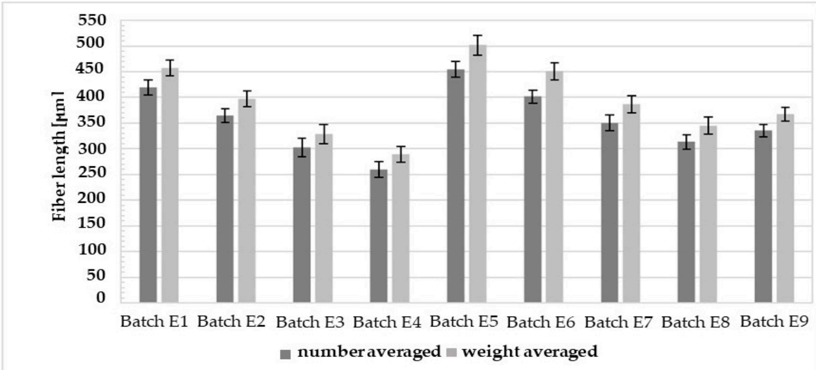
2. Results

The fabrication process of the samples involves three steps: shredding, compounding, and injection molding, with the resulting test specimens enabling the determination of the fiber length. The research aims to comprehensively understand the recycling process of CFRTP sheets. This involves establishing robust process windows for shredding, examining injection-moldable granule production, and investigating the impact of process parameters on reinforcing fiber shortening. Through statistical analysis, relationships are established that not only link process parameters with anticipated fiber length after twin-screw extrusion and injection molding, but also investigate the influence of various process parameters on the mechanical properties of the test specimen. This quantitative framework enhances process transparency and predictability, fostering material reuse for substantial resource conservation and cost savings.

2.1. Fiber Length Distribution Assessment following Compounding

Using an optical microscope, the evaluation of the fiber length distribution was conducted according to the methodology outlined in Section 4.2.4. During the processing of fiber-reinforced plastic, various damage mechanisms cause the fiber length to shorten, resulting in many short fibers. However, since the mechanical properties are determined by the long fiber portions, the longer fiber portions are increasingly included in the calculation of the weight-average fiber length [21,22]. Figure 1 displays the average fiber lengths, considering both number and weight average, alongside the deviations observed among individual batches. The deviations indicate the scatter between the evaluated images and are based on the mean values obtained from each evaluated image.

The measured values reveal a consistent trend where the weight-average fiber length surpasses the number-average fiber length across all batches. The batch with the smallest deviation is E3, exhibiting a percentage deviation of 7.8%. Conversely, the largest deviation is observed in batch E6, with a value of 10.9%. Batch E5 exhibits the longest fiber length in terms of both number and weight average, of 455 and 500 µm, respectively, whereas batch E4 illustrates the shortest fiber length, of 260 and 290 µm, for the number average and weight average, respectively. Generally, it can be observed that with constant processing temperature T and constant fiber volume content φ_f, but increasing screw speed n_s, the fiber length decreases. As an example, for batches E1 and E2, it is observed that at the same processing temperature of 210 °C and same fiber volume content of 9%, when screw speed is increased from 318 to 456 1/min, the final fiber length decreased from almost 420 to 370 µm for the number average. Furthermore, it is noticeable that increasing the processing temperature at constant fiber volume content and constant screw speed increases the fiber length (e.g., batch E1 vs. batch E5). An increased fiber volume content at constant screw speed and processing temperature decreases the fibers' length (e.g., batch E1 vs. batch E3). The percentage deviations consistently demonstrate a stable pattern across all batches, indicating a high level of consistency. As a result, only the number-average fiber length is considered for further analysis. When examining the number-average fiber lengths, regardless of the chosen process parameters, the resulting lengths range between 260 µm (batch E4) and 455 µm (batch E5).



T [°C]	210	210	210	210	250	250	250	250	250
φ_f [%]	9	9	19	19	9	9	19	19	14
n_s[min^{-1}]	318	456	318	456	318	456	318	456	387

Figure 1. Analysis of fiber lengths: number and weight average with deviations among extrusion batches and process parameters.

Figure 2 illustrates the fiber length distribution of all batches after the extrusion process.

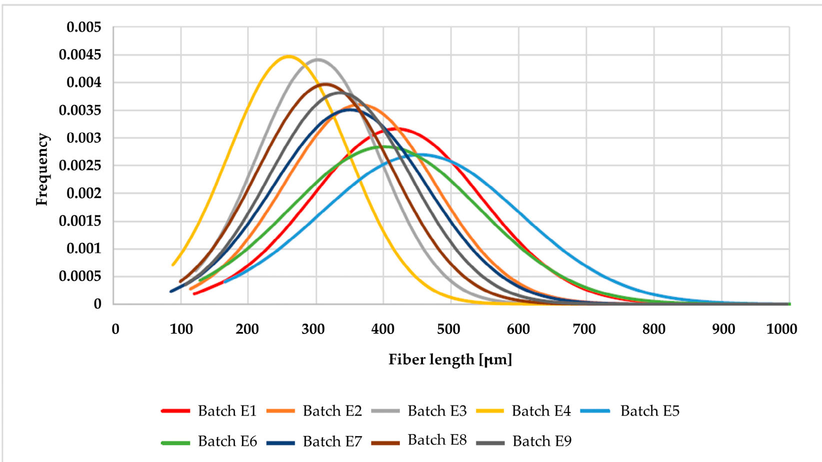


Figure 2. Histogram of the fiber length distribution after the extrusion process.

The frequency distribution reveals that the peak of each curve corresponds to the mean value of its respective batch. This observation indicates that curves with higher maximum values exhibit a flatter progression. This relationship becomes particularly evident when comparing batch E4, with a number-average fiber length of 260 µm, to batch E5, with a number-average fiber length of 455 µm. The longer fiber length in batch E5 results in a broader distribution range, covering a larger area compared to the shorter fiber length in batch E4.

2.2. Parameter Influences on Fiber Length following Compounding

To illustrate the effects of extrusion process parameters on the resulting fiber length, the main effect diagrams are presented in Figure 3. Each data point represents the average fiber length associated with different values of the process parameters. On the left side of the diagram, the processing temperature is depicted. The mean fiber length at a processing temperature of 210 °C is 337 µm, while at 250 °C, it increases to 380 µm. The fiber volume content exerts the most significant influence on the resulting fiber length. A low fiber volume content results in a higher fiber length after extrusion: at a fiber volume content of 9%, the average fiber length measures 410 µm, while it reduces to 307 µm at a fiber volume content of 19%. On the right, the screw speed is presented. The average fiber length at a screw speed of 318 rpm is 382 µm, whereas, at a speed of 456 rpm, it decreases to 335 µm. Hence, it can be concluded that a higher screw speed leads to a shorter fiber length.

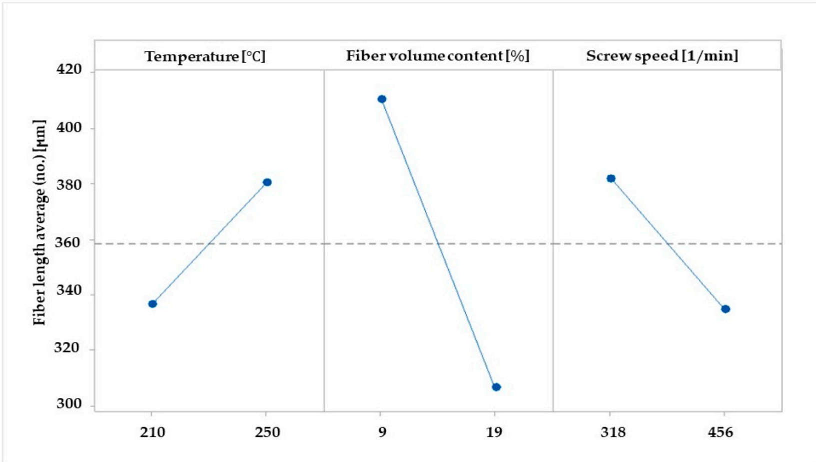


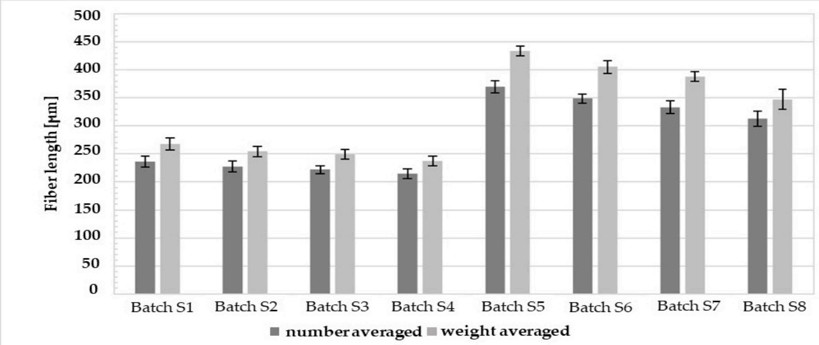
Figure 3. Main effects diagram of the parameter influences of the extrusion process.

2.3. Fiber Length Distribution Assessment following Injection Molding

In addition to investigating compounding in a twin-screw extruder, this study also considered the influence of different process parameters of the injection molding process. For this purpose, the granules produced by extrusion were utilized to create fiber-reinforced test specimens using an injection molding machine. More specifically, batches E4 with the shortest fiber length and E5 with the longest fibers after compounding were used for molding test specimens. During the production of the test specimens, the fiber volume content was investigated with the initial fiber length l_a, back pressure p, and screw speed n_s, resulting in eight distinct batches. To accurately assess the fiber volume content, samples were calcinated.

Similar to the extrusion process, the fiber length distribution was assessed after injection molding using an optical microscope (see Section 4.2.4). Figure 4 illustrates the number- and weight-average fiber lengths, including deviations observed across the eight injection molding test specimen batches. The deviation reflects the scatter between the evaluated images and is based on the mean values obtained from those evaluations.

The observed data indicate that the weight-average fiber length consistently exceeds the number-average fiber length across all batches. The smallest percentage deviation is observed in batch S8, with a deviation of 9.8%. On the other hand, batch S5 exhibits the largest percentage deviation, with a value of 14.8%. Batch S5 stands out with the longest fiber length in terms of number and weight averages, which measure nearly 370 µm and 435 µm, respectively. On the contrary, batch S4 exhibits the shortest fiber length, with number and weight averages of 220 µm and 240 µm, respectively. Moreover, a general trend can be noticed: when the screw speed increases for the same initial fiber length and constant back pressure, the resulting test specimens tend to have a shorter fiber length. For instance, comparing batches S1 and S2, at the same initial fiber length of 260 µm (fiber volume content of 19%) and the same back pressure of 20 bar, increasing the screw speed from 100 to 200 1/min leads to a decrease in the fiber length from approximately 240 µm to 230 µm for the number average. Furthermore, it becomes evident that raising the back pressure for batches with the same initial fiber length and constant screw speed results in shorter fibers in the test specimens (e.g., batch S1 vs. batch S3). Increasing the initial fiber length, at constant screw speed and back pressure, results in longer fibers in the test specimens (e.g., batch S1 vs. batch S5).



l_a[µm] / φ_f [%]	260 / 19	260 / 19	260 / 19	260 / 19	455 / 9	455 / 9	455 / 9	455 / 9
p[bar]	20	20	60	60	20	20	60	60
n_s[min^{-1}]	100	200	100	200	100	200	100	200

Figure 4. Analysis of fiber lengths: number and weight average with deviations among injection molding batches and process parameters.

The fiber length frequency distribution is depicted in Figure 5.

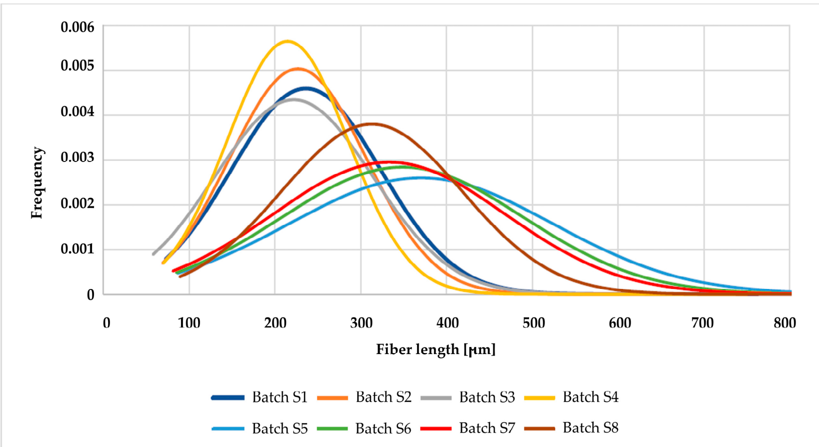


Figure 5. Histogram of the fiber length distribution after the injection molding process.

The fiber length frequency distribution after injection molding reveals that the local maximum corresponds to the number-averaged fiber lengths. As observed in the extrusion process, the curves demonstrate distinct frequency distributions. Batches with lower mean values demonstrate a higher concentration of reinforcing fibers within a specific length range. For instance, batch S4 exhibits the sharpest peak and the lowest mean value of approximately 220 µm in fiber length among all the batches. Conversely, batches with higher mean values display a broader distribution of fiber lengths, resulting in flatter curves. This is evident in batch S5, which features the broadest curve and a mean value of around 370 µm for fiber length.

2.4. Parameter Influences on Fiber Length following Injection Molding

Given the significant impact of the initial fiber length on fiber deterioration, only the initial fiber length is discussed in the following, while acknowledging that the fiber volume content also varies among these batches. However, since the initial fiber length holds greater importance in influencing the results, further details regarding the fiber volume content are not elaborated upon. Figure 6 illustrates the initial fiber lengths and the resulting fiber lengths, revealing a notably greater reduction in fiber length for batches S5 to S8 compared to batches S1 to S4 since they have longer initial fiber lengths. Additionally, the starting fiber length for batches S5 to S8 is 195 µm longer than that of batches S1 to S4.

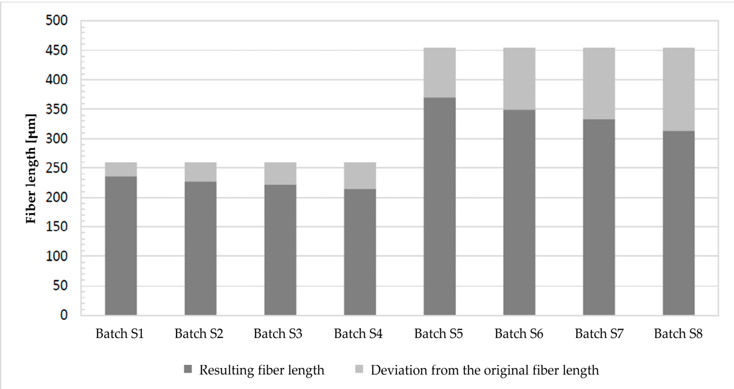


Figure 6. Comparison of the initial fiber length and the resulting fiber length after the injection molding process of all batches.

In the injection molding process, similar to the observations in the extrusion process, individual influences of the process parameters on the resulting fiber length are examined using a main effect diagram (Figure 7). The data points in the diagram represent the mean values of the batches with different process parameters. The left section of the diagram illustrates the initial fiber length, which has the most significant influence on the resulting fiber length. For instance, with an initial fiber length of 260 µm, the resulting fiber length is 225 µm, whereas increasing the initial fiber length to 455 µm results in an average fiber length of 341 µm. In the middle of the diagram, the influence of the back pressure can be observed. At a back pressure of 20 bar, the mean fiber length is 295 µm, while at 60 bar, it decreases to 270 µm. Thus, it can be generally concluded that higher back pressure leads to shorter fiber length. Finally, the resulting fiber length at a screw speed of 100 rpm is 290 µm. If the screw speed is increased to 200 rpm, the fiber length reduces to 276 µm. Hence, increasing the screw speed in the injection molding process results in a reduction in the resulting fiber length.

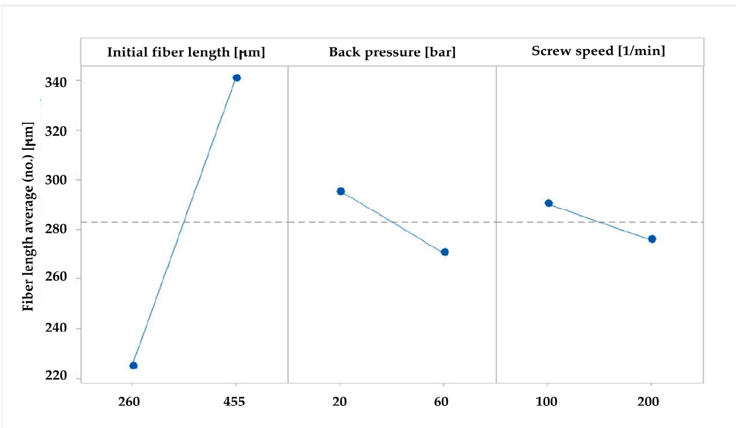


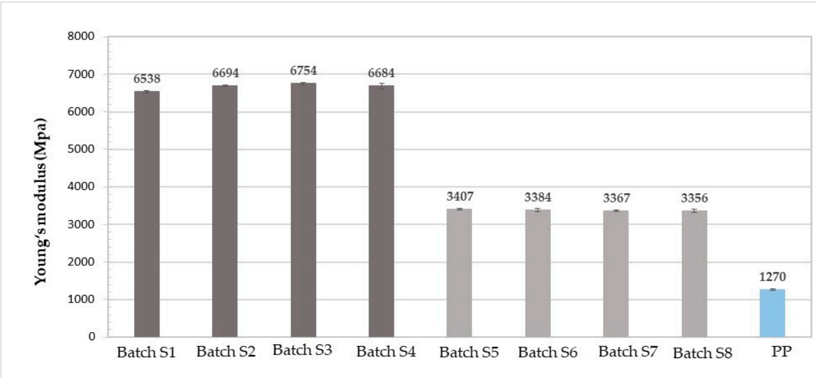
Figure 7. Main effects diagram of the parameter influences of the extrusion process.

2.5. *Influence of Process Parameters on Mechanical Properties*

As demonstrated in the preceding sections, the process parameters exert an influence on the fiber length, and it is anticipated that the fiber length, in turn, impacts the properties of the end product. Evaluating the properties of the final recycled product that is going to be reused is of utmost importance. Thus, the mechanical properties were examined through tensile tests.

2.5.1. Influence of Various Process Parameters on Tensile Modulus

The tensile modulus for all batches subsequent to the injection molding process under different process parameters is presented in Figure 8. It can be observed that the modulus of neat polypropylene is 1270 MPa. With the addition of fibers, the modulus increases significantly. Comparing batches S1 and S5 under identical process conditions, batch S1, with 19% fiber content, achieves a modulus of 6537 MPa, whereas batch S5, with 9% fiber content, reaches a modulus of 3406 MPa. As expected, a higher fiber content results in an increased modulus. The investigation of the influence of the back pressure, exemplified by the comparison between batch S5 and batch S7, reveals that with a constant fiber volume of 9% and a constant screw speed of 100 rpm, an increase in back pressure from 20 bar to 60 bar results in a decrease in modulus of approximately 40 MPa, shifting from 3406 MPa to 3366 MPa. The findings indicate that the increase in back pressure has a detrimental effect on the modulus. To examine the impact of screw speed on the modulus, a comparison between batch S3 and batch S4 demonstrates the influence of increasing screw speed at a constant fiber volume content of 19% and a constant back pressure of 60 bar on the investigated mechanical properties. Furthermore, the results indicate that when the fiber length is shorter (with a higher fiber volume content), increasing the screw speed exerts a more pronounced negative influence on the modulus as compared to longer fibers with less volume. In contrast, when shorter fibers are present with a higher volume content, increasing the back pressure exhibits a reduced negative influence on the final product modulus in comparison to when longer fibers with lower volume are present.

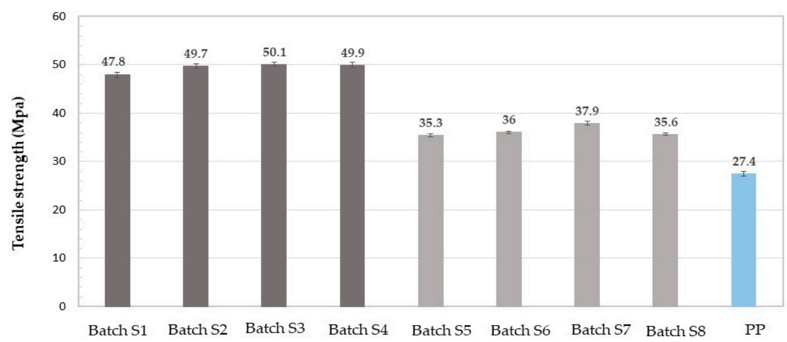


	Batch S1	Batch S2	Batch S3	Batch S4	Batch S5	Batch S6	Batch S7	Batch S8	PP
l_a[μm] / φ_f [%]	260 / 19	260 / 19	260 / 19	260 / 19	455 / 9	455 / 9	455 / 9	455 / 9	-
p[bar]	20	20	60	60	20	20	60	60	20
n_s[min^{-1}]	100	200	100	200	100	200	100	200	100

Figure 8. Modulus diagram of different batches under the influence of injection molding parameters.

2.5.2. Influence of Various Process Parameters on the Tensile Strength

Figure 9 presents the tensile strength of all batches following the injection molding process under different process parameters. Neat polypropylene exhibits a tensile strength of 27.4 MPa. The introduction of fibers leads to a notable increase in tensile strength. Comparing batches S1 and S5 under identical process conditions, it is evident that batch S1, with 19% fiber content, achieves a tensile strength of 47.8 MPa, while batch S5, with 9% fiber content, reaches a tensile strength of 35.3 MPa. This trend is consistent across all batches. Further investigations of the influence of the back pressure, exemplified by the comparison between batch S6 and batch S8, reveal that with a constant fiber volume of 9% and a constant screw speed of 200 rpm, an increase in back pressure from 20 bar to 60 bar results in a slight decrease in tensile strength of 0.4 MPa. This small change is consistent across all other batches, suggesting that an increase in back pressure has no significant effect on tensile strength. To examine the impact of the screw speed on the tensile strength, a comparison between batch S3 and batch S4 demonstrates that at a constant fiber volume of 19% and constant back pressure of 60 bar, increasing the screw speed from 100 rpm to 200 rpm leads to a reduction in tensile strength of approximately 0.2 MPa. Again, this shows that screw speed exerts no significant influence on the tensile strength of the test specimen. However, it is worth noting that when the initial length of the fibers and the back pressure is more distinct, an increase in screw speed has a more pronounced effect on the tensile strength, as evident from batches S7 and S8.

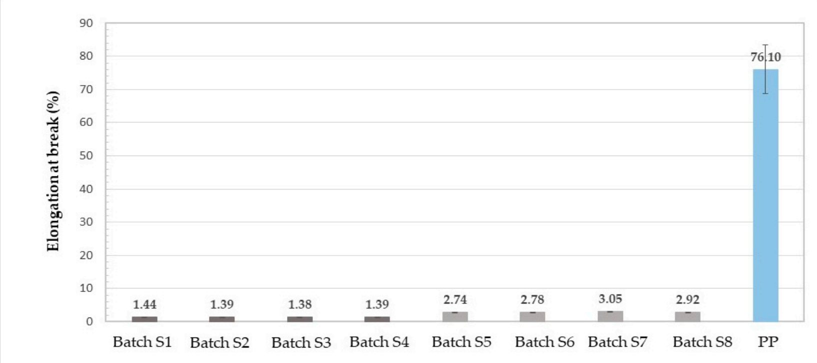


	Batch S1	Batch S2	Batch S3	Batch S4	Batch S5	Batch S6	Batch S7	Batch S8	PP
l_a[µm] φ_f [%]	260 / 19	260 / 19	260 / 19	260 / 19	455 / 9	455 / 9	260 / 19	455 / 9	-
p[bar]	20	20	60	60	20	20	60	60	20
n_s[min^{-1}]	100	200	100	200	100	200	100	200	100

Figure 9. Tensile strength of different batches under the influence of injection molding parameters.

2.5.3. Influence of Various Process Parameters on the Elongation at Break

Figure 10 depicts the elongation at break of all batches after injection molding, for different process parameters. Neat polypropylene exhibits an elongation at break of 76%. Upon the addition of fibers, the elongation at break decreases significantly. When comparing batches S1 and S5 under identical process conditions, batch S1, containing 19% fiber content, achieved an elongation at break of 1.44%, whereas batch S5, with 9% fiber content, reached an elongation at break of 2.75%. This pattern is observed consistently across all batches. The investigation of the influence of the back pressure, exemplified by the comparison between batch S1 and batch S3, reveals that with a constant fiber volume of 19% and a constant screw speed of 100 rpm, an increase in back pressure from 20 bar to 60 bar results in a small change in the elongation at break of 0.06%. This trend holds true for all batches, suggesting that an increase in back pressure has no significant effect on the elongation at break. However, it is important to note that when dealing with longer fibers in comparison to shorter fibers, an increase in back pressure at the same screw speed has a greater influence on the final product's elongation at break. Examining the impact of the screw speed on the elongation at break by comparing batch S3 and batch S4, it can be observed that at a constant fiber volume content of 19% and a constant back pressure of 60 bar, increasing the screw speed from 100 rpm to 200 rpm results in no significant change in the elongation at break. Thus, it is evident that screw speed exerts a negligible influence on the elongation at break.



	Batch S1	Batch S2	Batch S3	Batch S4	Batch S5	Batch S6	Batch S7	Batch S8	PP
l_a[µm] / φ_f [%]	260 / 19	260 / 19	260 / 19	260 / 19	455 / 9	455 / 9	260 / 19	455 / 9	-
p[bar]	20	20	60	60	20	20	60	60	20
n_s[min^{-1}]	100	200	100	200	100	200	100	200	100

Figure 10. Elongation at break of different batches under the influence of injection molding parameters.

3. Discussion

3.1. Fiber Length Assessment Post-Compounding: Summary of Key Findings and Insights

Based on the data provided in Section 2.1, it can be observed that the following factors influence the fiber length in the compound:

Screw speed: When the screw speed increases under the same process conditions of temperature and fiber volume content, the resulting compound exhibits a shorter fiber length. This is attributed to higher fiber–screw interactions and shear at higher screw speeds, leading to increased fiber damage, which ultimately results in the shortening of fiber length.

Process temperature: Enhancing the process temperature for all batches under the same conditions leads to a longer fiber length in the compound. This is because the higher temperature results in a better molten polymer matrix, which reduces the interaction between the fiber and the matrix and shear. As a result, the fibers are less damaged, and their lengths are retained more effectively in the compound.

Fiber volume content: When the fiber volume content increases to a higher amount at constant screw speed and process temperature, the final compound tends to have shorter fibers in length. This is due to the greater fiber–fiber interactions caused by the higher fiber volume, which results in more severe fiber breakage and a reduction in fiber length.

It is essential to consider these factors in the process to control and optimize the fiber length in the final compound, as they can significantly impact the mechanical properties and performance of the composite material. Regarding the fiber length distribution, the analysis indicates that the frequency distribution curves demonstrate a distinct peak, which corresponds to the mean value of each respective batch. This observation suggests that curves exhibiting higher maximum values display a flatter progression, mainly attributed to the presence of fibers with longer lengths. The relationship between the maximum values and the fiber length becomes particularly evident when comparing batch E4, which possesses a number-average fiber length of 260 µm, with batch E5, characterized by a number-average fiber length of 455 µm. The longer fiber length in batch E5 contributes to a broader distribution range, covering a significantly larger area compared to the shorter fiber length in batch E4. These findings highlight the importance of fiber length control and its impact on the overall distribution pattern. Understanding this relationship is essential for optimizing the properties and performance of composite materials, as the fiber length distribution significantly influences the mechanical characteristics and structural integrity of the final product.

3.2. Impact of Parameters on Fiber Length Post-Compounding: A Comprehensive Discussion with Relevant Literature

Considering the impact of process parameters on the fiber length according to Section 2.2., it can be observed that an increased fiber volume content generally results in a decrease in fiber length. This phenomenon can be attributed, in part, to the intensified interaction between fibers. These findings align with the research conducted by Brast and Albrecht [23,24], which also emphasized the presence of elevated fiber-to-fiber interaction in regions characterized by a high fiber volume content. Moreover, an elevation in the processing temperature yields a greater average fiber length. This outcome is attributed to the accelerated polymer melting process during compounding. Consequently, there is a decrease in the fiber–matrix interaction, where reinforcing fibers are embedded in the solid matrix part while the polymer melt flows around them, which is diminished in duration. These findings align with the insights presented by Brast, as he suggests that lower barrel and material temperatures result in a larger melting zone. Given that fiber damage predominantly occurs within the melting zone, this leads to a notable reduction in fiber length [23]. Consequently, it can be concluded that the influence of processing temperature on the resulting fiber length increases with quick processing. From the collected data, it is observed that an elevation in screw speed decreases the average fiber length. This phenomenon can be attributed to several factors. Firstly, higher screw speeds contribute to increased interaction between the fiber and the extruder, thereby resulting in a reduction in fiber length. Furthermore, the movement experienced by the fiber components within the polymer intensifies, leading to enhanced fiber-to-fiber interaction. Additionally, the higher screw speed causes an increase in shear rate, which further enhances the interaction between the fiber and the surrounding matrix. These findings align with the observations of Yilmazer and Cansever. Their studies demonstrated that increasing the screw speed from 250 rpm to 350 rpm during twin-screw extrusion led to a reduction in fiber length. Specifically, with a 100 rpm increase in screw speed, there was a percentage reduction in fiber length of 7.09% at a throughput of 70 kg/h and 9.21% at a throughput of 80 kg/h [25].

3.3. Fiber Length Assessment Post-Injection Molding: Summary of Key Findings and Insights

The findings presented in Section 2.3 shed light on several critical factors influencing the fiber length during injection molding. The discussion revolves around three key parameters: screw speed, back pressure, and initial fiber length. Firstly, it is evident that an increase in screw speed under constant process conditions of temperature and fiber volume content leads to a reduction in the resulting fiber length. This phenomenon is attributed to the intensified fiber–screw interactions and shear at higher screw speeds, causing an escalation in fiber damage, ultimately leading to a decrease in fiber length within the compound. Secondly, the effect of back pressure on fiber length is observed. Elevating the back pressure for all batches under identical conditions results in a shorter fiber length at the end of the compound. The higher back pressure induces more pronounced fiber–fiber, fiber–matrix, and fiber–screw interactions, all of which contribute to increased fiber damage and a subsequent decrease in fiber length within the compound. Lastly, the influence of the initial fiber length on the final fiber length is examined. Despite a higher degree of fiber damage caused by greater buckling length in a compound with longer initial fiber lengths, the results demonstrate that longer fibers are achieved compared to compounds with shorter initial fiber lengths. These findings emphasize the intricate interplay of process parameters and their impact on fiber length during injection molding. Understanding and controlling these factors are crucial for optimizing the production of composite materials with desired mechanical properties and performance characteristics. Furthermore, these insights contribute to the advancement of composite material processing techniques and enable manufacturers to tailor composite materials for specific applications. The investigation of fiber length distribution reveals similarities with the extrusion process, where curves demonstrating higher maximum values exhibit a more flattened progression. This distinct behavior is primarily attributed to the presence of longer fibers within those batches. A notable illustration of this relationship is apparent when comparing batch E4, with a number-average fiber length of 220 µm, to batch E5, featuring a number-average fiber length of 370 µm. The longer fiber length in batch E5 significantly influences the distribution range, resulting in a broader spread that covers a larger area in comparison to the distribution observed in batch E4, which comprises shorter fibers.

3.4. Impact of Parameters on Fiber Length Post-Injection Molding: A Comprehensive Discussion with Relevant Literature

When comparing batches with varying combinations of fiber volume content and initial fiber length, a slight shortening of fibers is noticeable with a high fiber volume content (19%) and short fiber length (260 µm). Conversely, significant fiber damage occurs with low fiber volume content (9%) and a large initial fiber length (455 µm). This finding contradicts the influence of fiber volume content observed in the extrusion process. It is important to note that, apart from fiber volume content, the initial fiber length also differs among individual batches. The increased fiber damage can thus be attributed to the larger initial fiber length, as longer fibers are more prone to break under lower mechanical loads due to their greater buckling length [23,26]. Gupta and fellow researchers studied fiber length reduction in extrusion and injection molding with two polypropylene products (30% fiber content). They used glass fibers with varying initial lengths for reinforcement. Long fibers (starting around 9000 µm) experienced an 88.9% reduction to around 1000 µm. Short fibers (starting around 550 µm) reduced by 27.3% to 400 µm. Longer fibers had a more significant reduction but resulted in a greater final length compared to short fibers [27]. Moritzer, Heidrich, and Hirsch created a calculation model for injection molding of fiber-reinforced plastics. They tested various parameters and fibers, finding that initial fiber length affected the resulting length. Over time, the length stabilized, influenced by shear stress, fiber content, and fiber stiffness [28]. In another study, Seong and colleagues studied a composite of polypropylene with graphite and glass fibers. They varied initial fiber lengths (1840 µm and 10,970 µm) and found shorter initial lengths resulted in 1380 µm fibers, while longer initial lengths led to 7540 µm fibers. Longer lengths caused more damage but resulted in greater component fiber length [29]. Regarding the influence of dynamic pressure, higher dynamic pressure generally leads to a reduction in fiber length. The elevated dynamic pressure ensures thorough mixing of the fiber-plastic melt, resulting in increased fiber–fiber, fiber–matrix, and fiber–screw interactions. This observation is consistent with the literature. Goris and other researchers developed a novel measuring method to analyze fiber length in composites. In their study, glass fiber-reinforced polypropylene was processed using an injection molding machine, and various process parameters, including back pressure, were altered. As back pressure opposes dynamic pressure, an increase in counter pressure results in a corresponding rise in dynamic pressure [30]. Their research indicated that raising back pressure from 13 bar to 50 bar reduced the resulting fiber length from 3210 µm to 2540 µm [31]. Additionally, Huang, Peng, and Hwang investigated the fracture behavior and fiber length distribution of polypropylene with glass fibers during injection molding, utilizing glass fibers with a length of 25 mm. They found that increasing the screw speed contributed to the shortening of the reinforcing fibers [32]. Furthermore, Goris, Back, and Yanev studied the influence of screw speed in addition to back pressure. Their research indicated that increasing the screw speed from 27 rpm to 35 rpm resulted in a reduction in fiber length from 2530 µm to 1720 µm [31].

3.5. Influence of Process Parameters on Mechanical Properties

3.5.1. Influence of Various Process Parameters on Tensile Modulus

The analysis reveals that the tensile modulus of neat polypropylene exhibits the lowest value among all batches. However, upon the incorporation of fibers in all batches, a significant increase in the modulus is observed. This enhancement can be attributed to the reinforcing role played by the added fibers. As the fiber content in the composite increases, it restricts the mobility of the matrix, leading to a stiffer composite and, consequently, a higher tensile modulus [33,34]. A noteworthy comparison between two batches, S1 and S5, under identical process conditions, further exemplifies this trend. Batch S1, with 19% fiber content, achieved a modulus of 6537 MPa, whereas batch S5, with 9% fiber content, attained a modulus of 3406 MPa. This trend is consistent across all batches, highlighting the clear positive correlation between fiber content and the modulus in the tested samples. Overall, the findings underscore the significant influence of fiber reinforcement on enhancing the mechanical properties of the composite. The investigation of the influence of back pressure on the tensile modulus, illustrated by the comparison between batch S5 and batch S7, yields noteworthy insights. Under constant conditions of 9% fiber volume and a steady screw speed of 100 rpm, an increase in back pressure from 20 bar to 60 bar results in a moderate decrease in modulus, of approximately 40 MPa. This decrease in tensile modulus can be attributed to the adverse effect of high back pressure, as discussed in previous sections, on the fiber length, leading to fiber shortening. It is essential to emphasize that the existing literature corroborates a direct relationship between fiber length and stiffness [35]. As fiber length decreases, the modulus exhibits a corresponding decrease as observed for high back pressure. These findings underscore the critical role of back pressure in influencing the mechanical properties of the composite, specifically in terms of modulus. Proper consideration and control of back pressure are crucial aspects to ensure the desired mechanical performance of the final product, in alignment with the principles established in the literature. Regarding the influence of screw speed on the modulus, exemplified by the comparison between batch S3 and batch S4, under identical conditions it was observed that increasing the screw speed from 100 1/min to 200 1/min resulted in intensified fiber–screw interactions. This led to a reduction in fiber length and, subsequently, a decrease in the modulus of the composite material by 70 MPa. This observation further underscores the negative impact of screw speed on the modulus of the final product. These findings highlight the significance of controlling screw speed during the injection molding process to optimize the mechanical properties of the composite material.

3.5.2. Influence of Various Process Parameters on Tensile Strength

Neat polypropylene exhibits the lowest tensile strength among all batches; however, with the incorporation of fibers into the composite, a notable enhancement in tensile strength is observed, attributable to the reinforcing effect of the added fibers. By comparing different batches with varying fiber volume content under the same process conditions, for instance, batch S1 with 19% and S5 with 9% fiber volume content, a clear pattern emerges. Batch S1 achieves a significantly higher tensile strength of 47.8 MPa, whereas batch S5 reaches a lower value of 35.3 MPa. The observed increase in tensile strength is attributed to the greater amount of fibers present in batch S1 [33,34]. This highlights the significance of optimizing the fiber volume content to achieve superior mechanical properties in composite materials, particularly concerning tensile strength. As already mentioned in Section 2.5.2, no significant changes can be observed regarding the effect of two other process parameters, namely back pressure and screw speed, on tensile strength. This indicates that both screw speed and back pressure have a neutral effect on the tensile strength of the final product.

3.5.3. Influence of Various Process Parameters on Elongation at Break

Neat polypropylene displays the highest elongation at break, of approximately 76%, among all batches. However, upon the introduction of fibers in all batches, a substantial reduction in elongation at break is observed, attributed to the presence of fibers that decrease the ductility of the composite. The decrease in elongation at break is consistently observed with an increase in fiber content. For instance, when comparing batch S5 and batch S1, with 9% and 19% fiber content, respectively, batch S1 achieves an elongation at break of 1.4%, while batch S5 reaches an elongation at break of 2.75%. This consistent pattern across all batches points to a clear negative correlation between the fiber reinforcement content and the elongation at break in the tested samples. This is because the higher number of fibers leads to a more rigid composite, limiting the stretching capability and resulting in lower deformation during fracture. Such behavior is well documented in the literature [36]. Overall, the findings underscore the importance of carefully considering the fiber content in composite materials to strike a balance between mechanical properties, such as tensile strength and elongation at break, for specific application requirements. As discussed in Section 2.5.3, it is evident that two other process parameters, namely back pressure and screw speed, do not yield significant changes in the elongation at break. The lack of a substantial impact of both screw speed and back pressure implies that these factors have a neutral effect on the elongation at the break of the final product.

4. Materials and Methods

4.1. Materials

4.1.1. Matrix

The polymer chosen as the matrix material was Ducor DuPure® SR76 polypropylene, which is widely utilized for injection molding and has a reasonably good melt flow behavior. To determine the melting and crystallization temperature of this material, Differential Scanning Calorimetry (DSC 204 F1 Phoenix, NETZSCH-Gerätebau GmbH, Selb, Germany) was applied with a heating rate of 20 K/min. To evaluate the flow behavior, a rotational rheometer (Modular Compact Rheometer MCR 302, Anton Paar GmbH, Graz, Austria) with a cone-plate design was utilized. Table 1 depicts the features of the polymer used and Figure 11 illustrates the viscosity versus different temperatures. It appears from the results that this polymer has shear thinning behavior at higher shear rates.

Table 1. Overview of the polymer used in this research.

Ducor DuPure® SR76	
Melt flow rate (230 °C/2.16 kg)	15 g/10 min
Melting temperature	176.4 °C
Crystallization temperature	110.3 °C

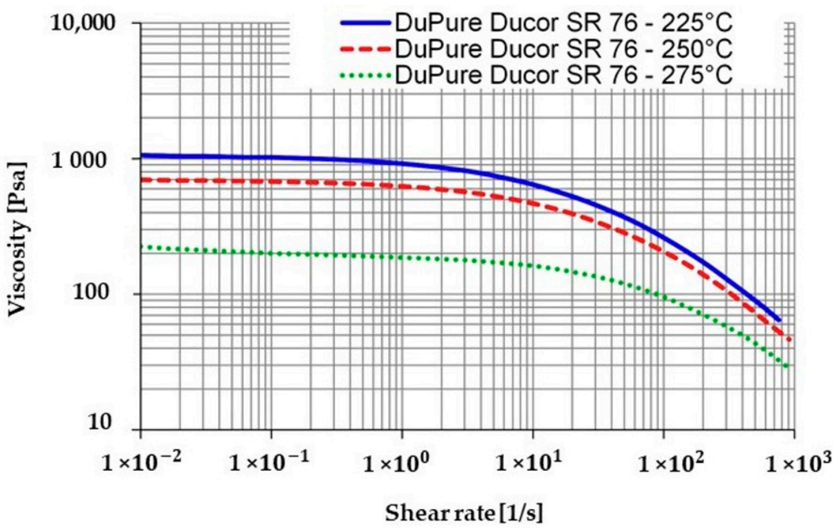


Figure 11. Data on viscosity for various temperatures of the polymer used.

4.1.2. Reinforcement

A fiberglass fabric in a plain weave with a fabric weight of 390 g/m^2 supplied by Porcher Industries Germany GmbH was utilized as the reinforcement. The fabric filaments with a diameter of 9 µm were made of E-glass filaments. The fabric was treated with 0.08 to 0.28% Volan chromium complex finish (FK144).

4.2. Methods

To evaluate the influence of different process parameters on the fiber shortening during the mechanical recycling process and investigate the influence of fiber shortening on the final product properties, the samples were fabricated by following three main steps: shredding, compounding, and injection molding. The fiber length could then be determined from these test specimens. The recycling process chain, encompassing the stages of CFRTP waste size reduction, compounding via extrusion, and injection molding, is illustrated in Figure 12.

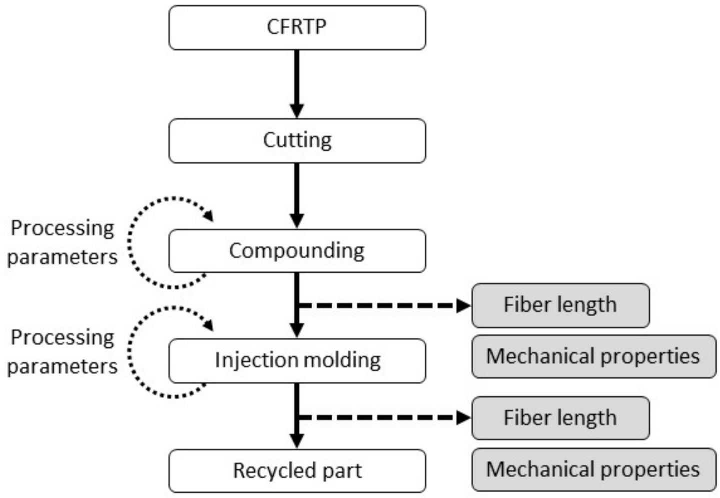


Figure 12. The recycling process chain demonstrating CFRTP waste size reduction, compounding, and injection molding stages.

The influence of the various process parameters on fiber length and the quantitative correlations were determined based on the measured values, and finally, an investigation of the influence of the fiber length on the final product's mechanical properties was necessary to determine the effect of the various processing parameters that significantly influence fiber length during manufacturing. These parameters fall into different categories. Material-related factors include fiber volume content, melt viscosity, fiber type, strength, melting temperature, and matrix crystallinity. The extrusion process is influenced by screw speed, processing temperature, back pressure, and screw configuration [23,37]. In injection molding, the plasticizing process is affected by screw speed, processing temperature, and back pressure. Meanwhile, the injection process is determined by component geometry, injection speed, and holding pressure [23,31,32]. External factors such as contamination, processing errors, and ambient temperature also play a crucial role. These parameters are detailed and categorized in Figure 13.

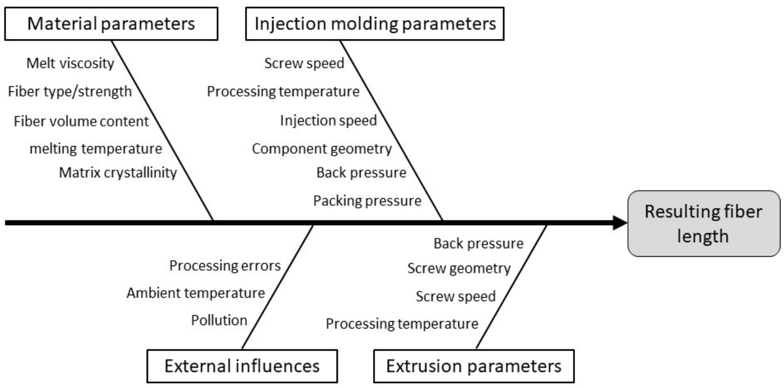


Figure 13. Fishbone diagram of various process parameters influencing fiber length.

The investigation into the effects of various parameters on fiber length in this study was narrowed down to specific variables, namely fiber volume content, processing temperature, and screw speed for extrusion, as they have been identified as key factors impacting fiber length during these processes. For injection molding, we concentrated on initial fiber length, back pressure, and screw speed to focus on the most significant and critical factors influencing fiber morphology and mechanical properties. By studying these parameters in depth, we aimed to gain comprehensive insights into the intricate relationships between processing conditions and fiber length, facilitating a more exhaustive understanding of the overall manufacturing process.

4.2.1. Shredding

The Rapid Granulator AB G200-24K cutting mill depicted in Figure 14 (left) was utilized for the mechanical shredding of the CFRTPs. Approximately 10 kg of recycled CFRTP material was produced. The material was pre-shredded by hand using scissors into approximately 10 cm × 10 cm blanks to ensure smooth processing. These blanks were placed in the opening of the cutting mill at constant time intervals and were comminuted by it for further particle size reduction. The diameter of the screen holes is 6 mm. After the material was shredded, the recycled material was collected (Figure 14 (right)). Finally, the range of particles was between 0.5 and 10 mm.

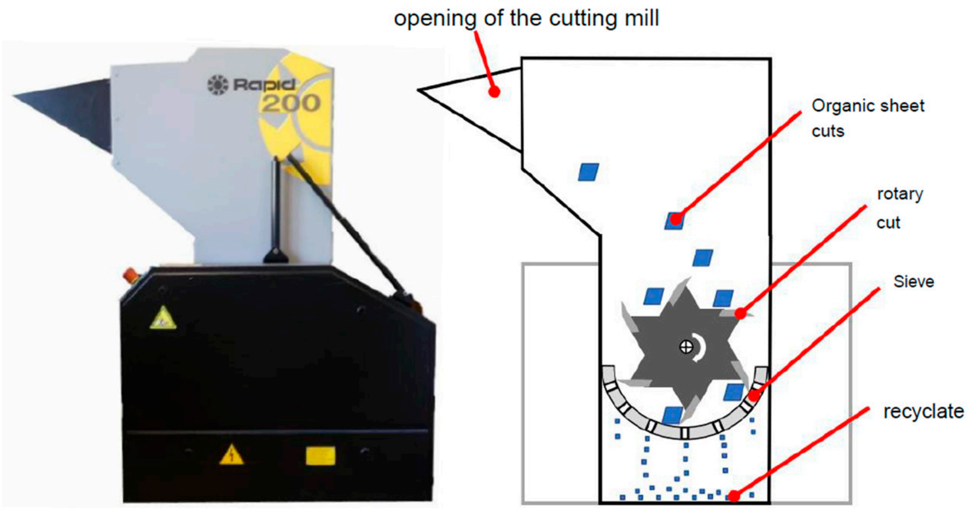


Figure 14. The cutting mill from Rapid Granulator AB (**left**); schematic representation of the cutting mill (**right**).

4.2.2. Compounding via Twin-Screw Extrusion

During compounding, the recycled material produced in the previous step was converted into a granulate using a twin-screw extruder. In addition to the recycled material, virgin polymer was added to dilute the high fiber volume content of the recycled material, also reducing the viscosity for processing. According to the literature, fiber volume content, processing temperature, and screw speed are three major parameters that have a significant influence on the resulting mean fiber length of the composites [38]. The processing temperature was set to 210 °C for batches E1 to E4 and to 250 °C for batches E5 to E8, with the average batch E9 being compounded at 230 °C. The fiber volume content was varied between 9%, 14%, and 19%. The screw speed was increased from 318 min^{-1}, to 387 min^{-1}, and up to 456 min^{-1} (Table 2).

Table 2. Overview of the twin-screw extruder batches including processing parameters.

	Fiber Volume Content	Processing Temperature	Screw Speed
Batch E1	9%	210 °C	318 rpm
Batch E2	9%	210 °C	456 rpm
Batch E3	19%	210 °C	318 rpm
Batch E4	19%	210 °C	456 rpm
Batch E5	9%	250 °C	318 rpm
Batch E6	9%	250 °C	456 rpm
Batch E7	19%	250 °C	318 rpm
Batch E8	19%	250 °C	456 rpm
Batch E9	14%	230 °C	387 rpm

4.2.3. Injection Molding

Two different batches from the previous step were selected to produce test specimens by injection molding under various process conditions. The injection molding machine used was from KraussMaffei Technologies GmbH with the model designation CX 80-380. A series of eight distinct batches was prepared with varying process parameters. On the one hand, the fiber volume content and thus the initial fiber length were changed. For the test specimens, batch E4 from compounding with a fiber volume content of 19% and an initial fiber length of 260 µm (averaged by number) or 290 µm (averaged by weight) was used. On the other hand, charge E5 from the compounding with a fiber volume content of 9% and an initial fiber length of 455 µm (number average) or 502 µm (weight average) was used. Furthermore, the dynamic pressure was varied between 20 bar and 60 bar. As in compounding, the screw speed was also changed in the injection molding process. This was changed from 100 rpm to 200 rpm depending on the batch. All batches including the varied processing parameters are listed in Table 3. The injection speed was kept constant at a value of 20 cm^3/s. The processing temperature was 230 °C.

Table 3. Overview of the injection molding batches including processing parameters.

	Initial Fiber Length	Back Pressure	Screw Speed
Batch S1	260 µm	20 bar	100 rpm
Batch S2	260 µm	20 bar	200 rpm
Batch S3	260 µm	60 bar	100 rpm
Batch S4	260 µm	60 bar	200 rpm
Batch S5	455 µm	20 bar	100 rpm
Batch S6	455 µm	20 bar	200 rpm
Batch S7	455 µm	60 bar	100 rpm
Batch S8	455 µm	60 bar	200 rpm

4.2.4. Fiber Length Measurement

To evaluate the fiber lengths of the different batches, more than 2000 fibers per batch after extrusion and more than 1000 fibers after injection molding were digitally evaluated using an optical microscope from Carl Zeiss AG with the model designation Stemi 2000-C. The fiber-reinforced plastic was placed in a crucible, which was placed in a muffle furnace at 550 °C for 60 min to decompose the polymer matrix. The remaining fibers were then evaluated regarding the fiber length by first distributing them using a dispersing agent (decanol) to spread the fibers. Then, the whole mixture was finally covered with another cover glass. Digital images were taken with the mounted AxioCam ICc 1 camera and evaluated manually. When all analyzable fibers in a specific area were recorded, the fiber lengths were statistically evaluated. The arithmetic mean of all fiber lengths was calculated from each recording area. The mean values were collected for each batch. Within a batch, the mean value of the measured values including the deviation was then calculated. Not only was the arithmetic mean (averaged by number) calculated, but also the weight-averaged fiber length. In the calculation of the weight-average fiber length, the arithmetic mean is deliberately influenced in the direction of the longer fibers, so that the influence of longer fiber parts is made clearer.

4.2.5. Mechanical Properties

Since fiber length has an extremely crucial influence on the final product's properties, it is important to measure the mechanical properties. Thus, tensile tests were conducted based on DIN EN ISO 527-4 (test specimen geometry type 1b). Five samples of molded parts were used from each batch. All mechanical tests were performed in the warp direction using a universal testing machine (Shimadzu SFL-50KNAG, Shimadzu Corp., Kyoto, Japan), and were performed at room temperature at a constant testing speed of 1 mm/s.

5. Conclusions

The study's comprehensive analysis highlights the complex relationship among process parameters, fiber length, and mechanical properties in fiber-reinforced composites. Factors such as screw speed, temperature, and fiber volume impact the fiber length distribution. Higher screw speeds increase fiber damage and shorten lengths, while higher temperatures lead to longer lengths. Fiber volume intensifies fiber interactions, resulting in shorter lengths. The study emphasizes the need for careful parameter control to optimize distribution and mechanical properties. Longer fibers are more prone to breakage. The introduction of fibers enhances the modulus, with a clear correlation between fiber content and tensile modulus, emphasizing the importance of managing fiber content. Back pressure and screw speed significantly affect the modulus: increased back pressure leads to decreased modulus due to fiber shortening, while higher screw speed reduces modulus due to intensified fiber–screw interactions. Tensile strength improves notably with fiber incorporation, showing a positive correlation with fiber content. However, back pressure and screw speed have neutral effects on tensile strength. Elongation at break decreases with fiber introduction, demonstrating the negative correlation between fiber content and ductility. Back pressure and screw speed exhibit neutral effects on elongation at break.

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References

1. Zushi, H.; Odai, T.; Ohsawa, I.; Uzawa, K.; Takahashi, J. Mechanical Properties of CFRP and CFRTP after Recycling. In Proceedings of the 15th International Conference on Composite Materials (ICCM-15), Tokyo, Japan, 27 June–1 July 2005; Volume 6, pp. 1–10.
2. Shida, R.; Tsumuraya, K.; Nakatsuka, S.; Takahashi, J. Effect of automobile lightening by CFRP on the world energy saving. In Proceedings of the 9th Japan International SAMPE Symposium, Tokyo, Japan, 29 November–2 December 2005; Volume 11, pp. 8–13.
3. Shida, R. Structural Design and Energy Saving Effect of Ultra-Lightened Truck by CFRP. Bachelor's Thesis, University of Tokyo, Tokyo, Japan, 2006.
4. Fukui, R.; Odai, T.; Zushi, H.; Ohsawa, I.; Uzawa, K.; Takahashi, J. Recycle of carbon fiber reinforced plastics for automotive application. In Proceedings of the 9th Japan International SAMPE Symposium, Tokyo, Japan, 29 November–2 December 2005; Volume 11, pp. 44–49.
5. Composite Products, Inc. Available online: http://www.compositeproducts.com/application/agriculture.asp (accessed on 14 April 2011).

6. JEC Group. JEC Observer: Overview of the Global Composites Market. JEC Composite. 2020. Available online: http://www.jeccomposites.com/about-jec/press-releases/jec-observer-overview-global-composites-market (accessed on 26 November 2020).
7. Katsiropoulos, C.V.; Loukopoulos, A.; Pantelakis, S.G. Comparative environmental and cost analysis of alternative production scenarios associated with a helicopter's canopy. *Aerospace* **2019**, *6*, 3. [CrossRef]
8. Asmatulu, E.; Twomey, J. Recycling of fiber-reinforced composites and direct structural composite recycling concept. *J. Compos. Mater.* **2013**, *48*, 593–608. [CrossRef]
9. Takahashi, J.; Uzawa, K.; Ohsawa, I.; Matsutsuka, N.; Kitano, A.; Nagata, K. Mechanical properties of injection molded CFRTP by using recycled CFRP. In Proceedings of the 10th Japanese-European Symposium on Composite Materials, Ueda, Japan, 26–29 September 2006.
10. Tian, X.; Todoroki, A.; Liu, T.; Wu, L.; Hou, Z.; Ueda, M.; Hirano, Y.; Matsuzaki, R.; Mizukami, K.; Iizuka, K.; et al. 3D Printing of Continuous Fiber Reinforced Polymer Composites: Development, Application, and Prospective. *Chin. J. Mech. Eng. Addit. Manuf. Front.* **2022**, *1*, 100016. [CrossRef]
11. Parandoush, P.; Lin, D. A review on additive manufacturing of polymer-fiber composites. *J. Compos. Struct.* **2017**, *182*, 36–53. [CrossRef]
12. Wang, X.; Jiang, M.; Zhou, Z.; Gou, J.; Hui, D. 3D printing of polymer matrix composites: A review and prospective. *Compos. Part B Eng.* **2017**, *110*, 442–458. [CrossRef]
13. Ogi, K.; Nishikawa, T.; Okano, Y. Mechanical properties of ABS resin reinforced with recycled CFRP. *Adv. Compos. Mater.* **2007**, *16*, 181–194. [CrossRef]
14. Kouparitsas, C.E.; Kartalis, C.N.; Varelidis, P.C. Recycling of the fibrous fraction of reinforced thermoset composites. *Polym. Compos.* **2002**, *23*, 682–689. [CrossRef]
15. Palmer, J.A.T. Mechanical Recycling of Automotive Composites for Use as Reinforcement in Thermoset. Ph.D. Thesis, University of Exeter, Exeter, UK, May 2009.
16. Anandakumar, P.; Venkata Timmaraju, M.; Velmurugan, R. Development of efficient short/continuous fiber thermoplastic composite automobile suspension upper control arm. *Mater. Today Proc.* **2021**, *39*, 1187–1191. [CrossRef]
17. Hasan, M.M.B.; Abdkader, A.; Cherif, C.; Spennato, F. Fibre hybrid composites consisting of discontinuous waste carbon fibre and continuous glass filaments developed for load-bearing structures with improved impact strength. *Compos. Part A Appl. Sci. Manuf.* **2019**, *126*, 105610. [CrossRef]
18. Bernasconi, A.; Rossin, D.; Armanni, C. Analysis of the effect of mechanical recycling upon tensile strength of a short glass fibre reinforced polyamide 6, 6. *Eng. Fract. Mech.* **2007**, *74*, 627–641. [CrossRef]
19. Sam-Daliri, O.; Ghabezi, P.; Flanagan, T.; Finnegan, W.; Mitchell, S.; Harrison, N. Recovery of Particle Reinforced Composite 3D Printing Filament from Recycled Industrial Polypropylene and Glass Fibre Waste. In Proceedings of the 8th World Congress on Mechanical, Chemical, and Material Engineering, Prague, Czech Republic, 31 July–2 August 2022. [CrossRef]
20. Sam-Daliri, O.; Ghabezi, P.; Steinbach, Y.; Flanagan, T.; Finnegan, W.; Mitchell, S.; Harrison, N. Experimental study on mechanical properties of material extrusion additive manufactured parts from recycled glass fiber-reinforced polypropylene composite. *Compos. Sci. Technol.* **2023**, *241*, 110125. [CrossRef]
21. Birr, T. Processing of Long Fiber Reinforced Thermoplastics for Injection Molding Applications on the Planetary Roller Extruder. Ph.D. Thesis, Technical University of Berlin, Berlin, Germany, 2016.
22. *ISO 22314*; Plastics: Glass-Fibre-Reinforced Products: Determination of Fiber Length. British Standards Institution Group: London, UK, 2006.
23. Brast, K. Processing of Long Fiber Reinforced Thermoplastics in the Direct Plasticizing/Pressing Process. Ph.D. Thesis, Rheinisch-Westfälische Hochschule Aachen, Aachen, Germany, 2001.
24. Albrecht, K. Sustainable Fiber-Reinforced Plastics in Injection Molding: Fiber Orientation and Fiber Damage in Experiment and Simulation. Ph.D. Thesis, Bremen University of Applied Sciences, Bremen, Germany, 2019.
25. Yilmazer, U.; Cansever, M. Effects of processing conditions on the fiber length distribution and mechanical properties of glass fiber reinforced nylon-6. *Polym. Compos.* **2002**, *23*, 61–71. [CrossRef]
26. Evens, T.; Bex, G.J.; Yigit, M.; De Keyzer, J.; Desplentere, F.; Van Bael, A. The Influence of Mechanical Recycling on Properties in Injection Molding of Fiber Reinforced Polypropylene. *Int. Polym. Process.* **2019**, *34*, 398–407. [CrossRef]
27. Gupta, V.B.; Mittal, R.K.; Sharma, P.K. Some studies on glass fiber-reinforced polypropylene. Part I Reduction in fiber length during processing. *Polym. Compos.* **1989**, *10*, 8–15. [CrossRef]
28. Moritzer, E.; Heiderich, G.; Hirsch, A. Fiber length reduction during injection molding. In Proceedings of the AIP Conference, Paderborn, Germany, 14–15 October 2019; Volume 2055, p. 070001. [CrossRef]
29. Seong, D.G.; Kang, C.; Pak, S.Y.; Kim, C.H.; Song, Y.S. Influence of fiber length and its distribution in three-phase poly(propylene) composites. *Compos. Part B Eng.* **2019**, *168*, 218–225. [CrossRef]
30. Moldie. Interesting Facts about Counter-Pressure Injection Moulding. Available online: https://moldie.net/de/injection-molding-back-pressure/ (accessed on 26 June 2022).
31. Goris, S.; Back, T.; Yanev, A.; Brands, D.; Drummer, D.; Osswald, T. A novel fiber length measurement technique for discontinuous fiber reinforced composites: A comparative study with existing methods. *Polym. Compos.* **2017**, *39*, 4058–4070. [CrossRef]

32. Huang, P.-W.; Peng, H.-S.; Hwang, S.-J.; Huang, C.-T. The Low Breaking Fiber Mechanism and Its Effect on the Behavior of the Melt Flow of Injection Molded Ultra-Long Glass Fiber Reinforced Polypropylene Composites. *Polymers* **2021**, *13*, 2492. [CrossRef] [PubMed]
33. Ramesh, M.; Rajeshkumar, L.; Srinivasan, N.; Kumar, D.; Balaji, D. Influence of filler material on properties of fiber-reinforced polymer composites: A review. *e-Polymers* **2022**, *22*, 898–916. [CrossRef]
34. Maiti, S.; Islam, M.R.; Uddin, M.A.; Afroj, S.; Eichhorn, S.J.; Karim, N. Sustainable Fiber-Reinforced Composites: A Review. *Adv. Sustain. Syst.* **2022**, *6*, 2200258. [CrossRef]
35. Capela, C.; Oliveira, S.E.; Pestana, J.; Ferreira, J.A.M. Effect of fiber length on the mechanical properties of high dosage carbon reinforced. *Procedia Struct. Integr.* **2017**, *5*, 539–546. [CrossRef]
36. Djafari Petroudy, S.R. Physical and mechanical properties of natural fibers. In *Advanced High Strength Fibre Composites in Construction*; Fan, M., Fu, F., Eds.; Elsevier: Tehran, Iran, 2017; pp. 59–83. [CrossRef]
37. Wolf, H. On the Influence of Screw Plasticization on the Fiber Structure of Discontinuously Long-Fiber-Filled Thermoplastics. Ph.D. Thesis, Technical University of Darmstadt, Darmstadt, Germany, 1996.
38. Brenner, J. Practical Implementation to Increase Added Value. In *Lean Production*, 3rd ed.; Kleppmann, W., Ed.; Hanser: Munich, Germany, 2020. [CrossRef]