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Tensile Properties of 3D Printed Recycled PLA Filament: A Detailed Study on Filament Fabrication Parameters

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ABSTRACT

Polylactic acid (PLA), a biodegradable and biocompatible thermoplastic commonly utilized in 3D Printing filaments, undergoes changes in properties upon recycling. The objective was to elucidate the role of extrusion temperature and screw speed in modulating the quality of recycled PLA filament, as well as in controlling its dimensional attributes. Recycled PLA pellets (3D850D) were extruded using a single filament extruder machine within an extrusion temperature range of 145°C to 165°C and a screw speed varying from 2 rpm to 6 rpm. The extruded filaments were subsequently 3D printed into specimens adopting a 0° raster angle, line infill pattern, and a 100 percent infill density, then tested as per ASTM D638 mechanical standards. The study revealed a profound influence of extrusion parameters on the filament's ultimate tensile strength, yield strength, and diameter. Optimal extrusion conditions - 155°C and 5 rpm - resulted in maximum mechanical strengths, while the parameters yielding filament diameters closest to commercial standards were identified as 5 rpm and 155°C. These results under-score the possibility of optimizing the recycled PLA filament's properties through adept control of extrusion parameters. Consequently, this investigation supports the potential use of recycled PLA filament in the 3D printing industry as a sustainable and performance-efficient material, offering a tangible step towards environmentally friendly additive manufacturing practices.

1. Introduction

The burgeoning field of 3D printing has, over recent years, revolutionized the traditional manufacturing industry, transcending its human-centric production paradigm to a highly efficient, high-value-added mechanism. Paramount to the allure of this technology is its ability to intricately design and optimize complex geometrical models, its remarkable design flexibility, recyclability, and

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minimal material wastage. The mounting global imperative for eco-friendly, sustainable technologies has instigated advancements in the development of 3D printing filament materials, particularly Poly-Lactic Acid (PLA) [1]. PLA distinguishes itself as an environmentally congenial choice due to its synthesis from renewable resources, biodegradability, low toxicity, and relative ease of processing [2, 3]. Hence, repurposing PLA filament waste into usable filament could potentially be highly desirable and economically efficient. Nevertheless, the mechanical characteristics of 3D-printed recycled PLA components can be influenced by a multitude of factors, ranging from the fabrication parameters of the filament to the intricacies of the recycling process. Consequently, a comprehensive study examining the tensile properties of 3D-printed recycled PLA filament is of critical importance. It not only enables the optimization of the material's performance but also broadens its applications, moving us one step closer to a sustainable and cost-effective 3D printing industry [4]. Previous work by Letcher and Waytashek [5] demonstrated the potential of recycling failed 3D-printed objects into reusable PLA filaments. Their study involved tensile, flexural, and fatigue testing, utilizing generic brand PLA material and an entry-level consumer-priced 3D printer.

Nevertheless, the quality of recycled materials is inherently dependent on the parameters of filament fabrication. Furthermore, employing recycled plastic waste for 3D printing could significantly alleviate environmental challenges associated with conventional 3D printing processes. A notable study by Lee *et al.,* [4] scrutinized the effects of successive recycling of PLA filaments on the mechanical properties of the recycled filaments and printed objects. They concluded that enhancing the mechanical strength of the bead, both in and out of a plane, and the bead adhesion strength was essential to improve the performance of recycled PLA. Interestingly, research has shown that recycled PLA-based filaments for 3D printing possess remarkably similar microstructural characteristics to those of virgin (new) PLA filaments. Antonella *et al.,* [6] recent study demonstrated that despite a slight decrease in the intensity of typical absorption bands of the PLA polymer, the thermal-mechanical properties of recycled and virgin filaments were analogous. Alexandre *et al.,* [7] investigated optimizing 3D printing parameters utilizing recycled PLA waste and determined that a print temperature of 150 °C to 160 °C, a layer height of 0.12 mm to 0.2 mm, and a maximum print speed of 50 mm/s can significantly enhance tensile strength. This discovery is further reinforced by the research conducted by Atakok *et al.,* [8], who determined that the layer thickness has the greatest impact on enhancing the mechanical properties of 3D printed objects made from recycled PLA. Their findings strongly support the notion that adjusting the layer thickness is the key parameter for maximizing the overall performance of these specimens.

The factors affecting tensile properties of 3D printed for virgin and recycled PLA filament are diverse and include print settings, temperature, layer height, print speed, blending of recycling material, and the type of filler utilized [9]. Through these experiments, it was discovered that the utilization of the Design of Experiment (DoE) approach to optimize 3D printing parameters could improve the mechanical strength of sustainable printing materials. Zurnaci *et al.,* [10] work has highlighted that infill density is the most potent parameter in bolstering mechanical strength. A plethora of methodologies have been adopted to optimize the 3D printing process of recycled PLA filaments. Breški *et al.,* [11] employed the design of an experimental approach to determine the suitability of applying recycled PLA filament in fused filament fabrication processes. Their findings indicated that continuous recycling could reduce the strain at the break by up to 10%. The quality of recycled PLA, however, is affected by repeated recycling, with studies revealing a decrease in tensile and flexural strength by up to 69% and 53%, respectively [12]. Nevertheless, a mixture of virgin and recycled materials can yield material properties that remain steady through repetitive recycling cycles [11]. Rahimizadeh *et al.,* [13] have successfully demonstrated the viability of a recycling and reusing process for end-of-life glass fiber-reinforced wind turbine blades. Scrapped turbine blades' short glass fibers were reclaimed and combined with PLA to produce a composite feedstock with recycled glass fibers for 3D printing.

The quality of recycled filaments heavily depends on the fabrication parameters utilized during their production. An exploration into the thermo-mechanical properties of composite filaments and the influence of non-uniform diameter on the quality of printed fabrics deduced that composite filaments are viable for 3D printing, albeit with a marginal reduction in print quality due to non-uniform diameter [14, 15]. Understanding the impact of recycling on the mechanical properties of 3D printed filament is crucial, as it directly affects the feasibility of recycling failed 3D print jobs back into reusable filament. Moreover, it is evident that the sustainability of the manufacturing process can be significantly enhanced by opting for recycled PLA filament over virgin PLA, particularly considering the minimal degradation in tensile strength or modulus. This underscores the potential for recycling and reusing end-of-life material in 3D printing, opening up a pathway to environmental sustainability through a circular economy. Therefore, this study strives to deepen the understanding of the mechanical behaviour of recycled PLA filament for 3D printing applications, to optimize filament fabrication parameters, thereby improving the material's mechanical performance.

2. Materials and Methods

2.1 Materials

Recycled PLA grade 3D850 pellets (see Figure 1) for 3D printing monofilament fabrication were used in this study.

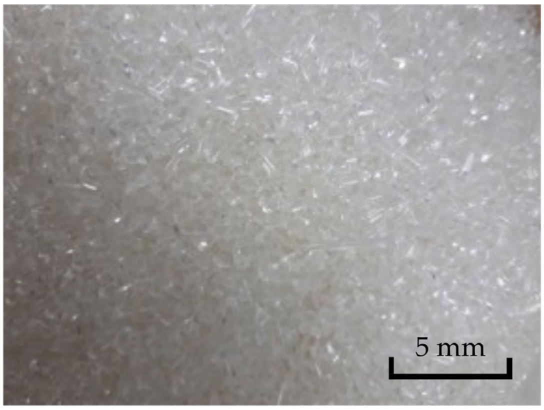


Fig. 1. Recycled PLA pellets (3D850)

2.2 Methods

The 3D850-grade PLA pellets, which had undergone recycling, were subjected to a drying process at 60°C for an eight-hour duration in an oven, a step imperative for the elimination of moisture content in the pellets. The process of extrusion, detailed in Figure 2, was subsequently set up, readying the system for the next phase. These dried, recycled pellets were then fed into a tabletop single-screw extrusion machine. This procedure was carried out at an interval of 25°C for the extrusion temperature and an interval extrusion speed of 1 rpm, aiming to fabricate these pellets into filaments. To ensure optimal performance, the single screw extruder was preheated to the specified temperatures, listed in the subsequent paragraph. Five distinct temperatures were used for the extrusion process, specifically 145°C, 150°C, 155°C, 160°C, and 165°C. Furthermore, the extrusion speeds implemented were diverse, ranging from 2 rpm to 6 rpm, at increments of 1 rpm.

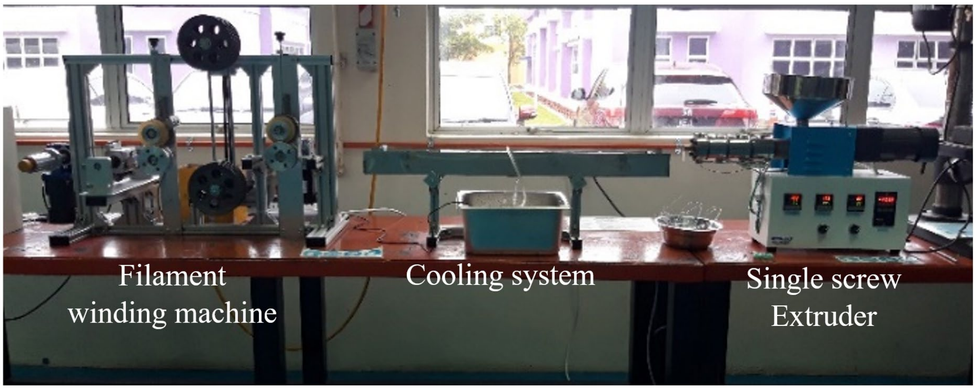


Fig. 2. 3D Printing filament fabrication process

The research undertaken aimed to explore the impact of different filament extrusion parameters, such as the speed of extrusion and the extrusion temperature, on the diameter and tensile properties of the reprocessed PLA filament. During the process, the filament's diameter was consistently monitored using an inline measurement gauge. This measurement was taken at every one-meter interval throughout the extrusion process, providing continuous and accurate data regarding the filament's dimensionality during extrusion.

Table 1
Qidi X-Max 3D Printer parameters

Parameters	Value
Extruder temperature (°C)	175
Bed temperature (°C)	55
Printing speed (mm/s)	35
Nozzle diameter (mm)	0.4
Layer height (mm)	0.15
Raster angle (°)	0
Infill pattern	Line
Infill density (%)	100

In the context of this study, five unique specimens were crafted utilizing CATIA software, then subsequently brought to life using a Qidi X-Max 3D printer. Each specimen was generated from a different combination of extrusion parameters (see Table 1), all in accordance with the ASTM D638 standard [16]. To optimize each specimen's strength, a linear infill pattern with a 0° raster angle was chosen. The infill density was kept at 100%, a decision made with the intention of achieving maximal robustness within the specimens. Post-fabrication, each specimen was subjected to rigorous tensile testing on a Universal Testing Machine (UTM). The test involved a pulling force of 10kN, exerted at a speed of 1mm/min, until the point of fracture. Upon completion of the testing, the tensile stress of the recycled PLA FDM specimens was calculated following the method delineated in Eq. (1).

$$\sigma = \frac{F}{A} \tag{1}$$

In the given context, σ signifies the tensile strength of the FDM specimen and is measured in Pascal (*Pa*). The variable *F* stands for the maximum force exerted at the point of break, expressed in Newtons (*N*), while *A* represents the cross-sectional area, quantified in square meters (m^2). The influential factors in filament fabrication, considering the designated level, are presented in Table 2. The investigative approach adopted in this study took into account only two factors at five different levels for each parameter. Consequently, the Taguchi method was employed for its versatility in dealing with multi-level factors. The equation $N = 5^2$ was used to calculate the total number of experimental runs. Therefore, an orthogonal array of $L_{25}(5^2)$ was implemented, indicating that a total of 25 experimental runs were required for comprehensive testing.

Table 2
Qidi X-Max 3D Printer parameters

Extrusion factors	Levels					Unit
	1	2	3	4	5	
Extrusion temperatures	145	150	155	160	165	°C
Extrusion speeds	2	3	4	5	6	rpm

3. Results and Discussions

3.1 Effect of Extrusion Temperature and Screw Speed on Ultimate Tensile Strength of Recycled PLA Filament

Table 3 and Figure 3 provided data reflecting the ultimate tensile strength (UTS) of recycled PLA filament under various conditions of extrusion temperature and screw speed, revealing a complex interplay between these parameters. The maximum recorded UTS was 32.3 MPa at an extrusion temperature of 155°C and a screw speed of 5 rpm, while the minimum was 13.2 MPa at 165°C and 2 rpm. Clearly, the manipulation of extrusion temperature and screw speed is pivotal in achieving the desired tensile strength of the recycled PLA filament. Understanding the effect of extrusion temperature on UTS requires consideration of the thermal behaviour of PLA. As previous studies have indicated [17], increased temperature enhances the mobility of polymer chains and improves the UTS up to a certain limit. Beyond this limit, thermal degradation sets in, reducing the UTS, as seen in the reduction in UTS at temperatures beyond 155°C in our dataset. The impact of screw speed is seen in terms of frictional heat generated during the extrusion process. While a moderate screw speed can lead to adequate mixing and uniform temperature distribution, enhancing the UTS [18], higher screw speeds can induce shear degradation and consequently decrease the UTS, as indicated by the drop in UTS at 6 rpm. In the context of recycled PLA, these effects are even more significant. The recycling process often leads to a reduction in the molecular weight of the polymer due to chain scission reactions [7, 8]. This can decrease the material's inherent strength. However, careful control of the extrusion parameters, as seen in this study, can partly mitigate these adverse effects. Optimal extrusion conditions may help to realign the polymer chains and promote entanglement, resulting in improved mechanical properties.

Table 3
Ultimate tensile stress, (MPa) under different extrusion temperatures and extrusion speed

Extrusion speeds	Extrusion temperatures				
	145°C	150°C	155°C	160°C	165°C
2 rpm	16.5	16.8	26.3	18.3	13.2
3 rpm	17.2	23.2	28.7	23.8	14.3
4 rpm	20.3	26.2	30.5	27.6	15.2
5 rpm	22.4	27.3	32.3	29.5	15.9
6 rpm	18.6	24.5	31.1	28.3	14.2

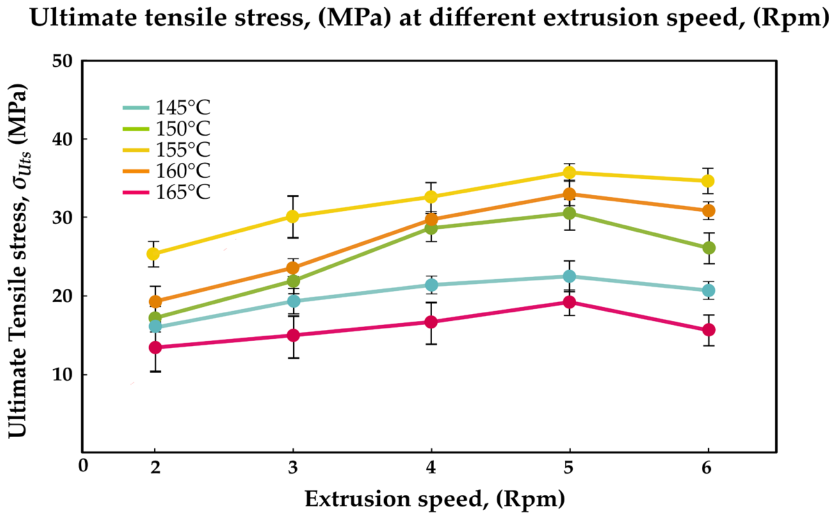


Fig. 3. Ultimate tensile stress vs. extrusion speed

Table 4 and Figure 4 show tabulated data that offer insightful observations on how the tensile properties of recycled PLA filament - yield strength, Young's modulus, and elongation at break - are influenced by extrusion speed under a constant extrusion temperature of 155°C.

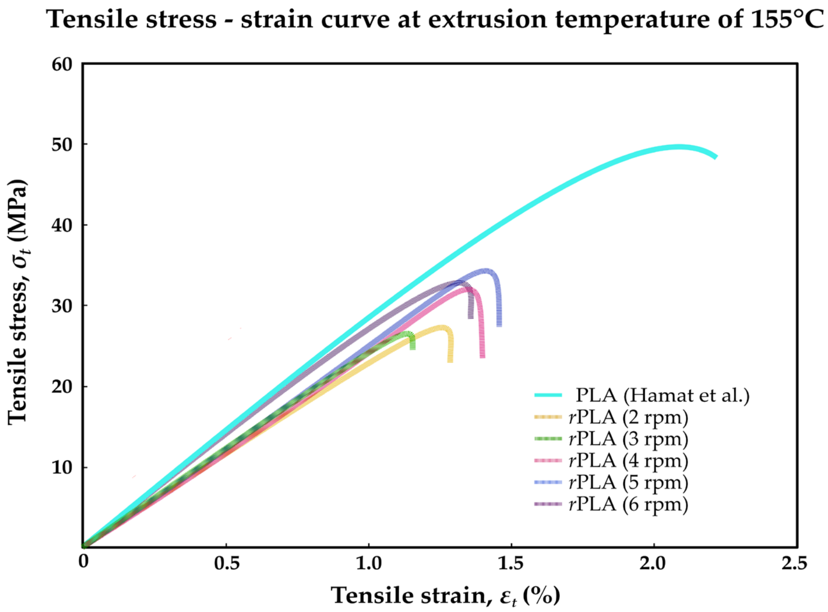
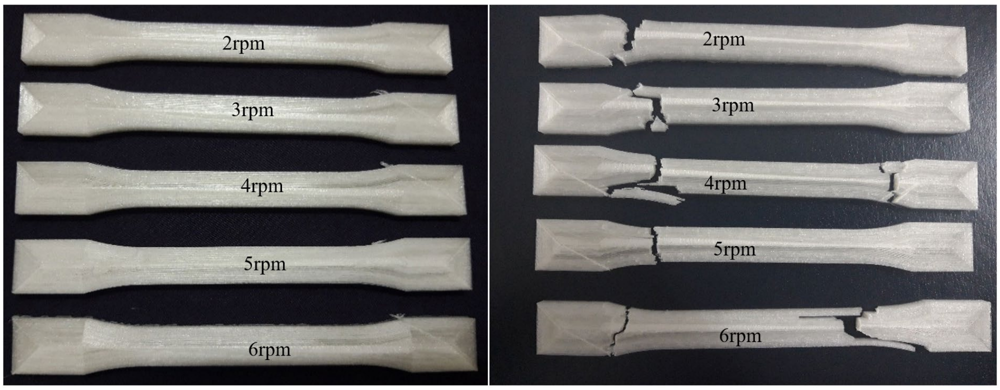


Fig. 4. Stress-strain graph at an extrusion temperature of 155 °C

The highest yield strength recorded is 33.6 MPa at 5 rpm, a stark contrast to virgin PLA's yield strength of 46.5 MPa [15]. This represents a drop of about 28% in yield strength after recycling. As the extrusion speed increases, the yield strength tends to increase, peaking at 5 rpm before slightly decreasing at 6 rpm. Young's modulus demonstrates a similar trend. The highest recorded modulus was 1.98 GPa at 5 rpm, which is approximately 28% lower than the virgin PLA's modulus of 2.77 GPa. This variation could be associated with the increased alignment of polymer chains at higher screw speeds, which reinforces the material's rigidity. The elongation at break reveals a less noticeable but still important increase from 1.21% (3 rpm) to 1.48% (5 rpm). However, these values are substantially lower than the 2.18% seen with virgin PLA, indicating that the material becomes less ductile after recycling - nearly a 32% decrease in ductility, as can see in Figure 5 the tensile specimen experienced more fracture damages. Previous research into polymer processing has correlated these observations with the microstructural transformations induced during the extrusion process. Increased screw speeds introduce enhanced shear forces, which can lead to the alignment of the polymer chains in the direction of flow, thus augmenting the material's tensile properties [8, 10]. Conversely, excessively high speeds could induce shear degradation, which may reduce these properties, as potentially observed at 6 rpm. The pronounced effects on recycled polymers are a result of chain scission reactions during the recycling process, which lead to a reduction in the polymer's molecular weight and an inherent decrease in the material's strength [7, 8]. Furthermore, the brittleness of the recycled polymers often escalates due to thermal and mechanical degradation during reprocessing. However, by adeptly controlling the extrusion parameters, it's feasible to mitigate these adverse effects to some extent and enhance the mechanical properties of the recycled PLA.

Table 4
Mechanical tensile properties of filament (recycled and virgin PLA) under extrusion temperature of 155°C

Extrusion speeds	Tensile properties		
	Yield strength (MPa)	Young modulus (GPa)	Elongation at break (%)
2 rpm	25.6	1.51	1.32
3 rpm	24.3	1.43	1.21
4 rpm	30.4	1.79	1.44
5 rpm	33.6	1.98	1.48
6 rpm	31.2	1.84	1.38
Virgin PLA	46.4	2.86	2.23

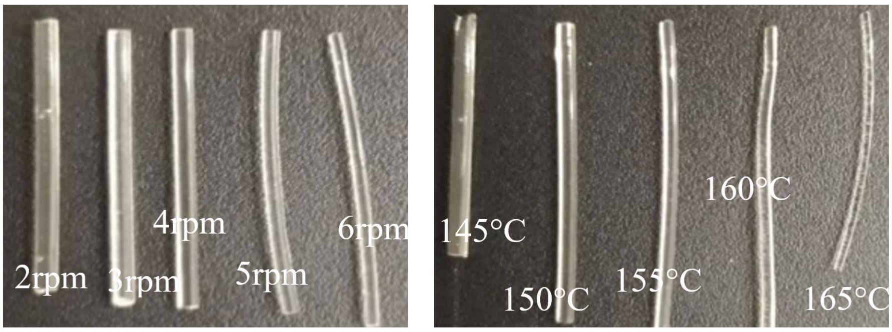


(a) (b)

Fig. 5. Tensile specimen of tensile testing under 155°C (a) before testing (b) after testing

3.2 Effect of Extrusion Temperature and Screw Speed on Diameter of PLA Filament

A careful examination of Table 5 provides a nuanced understanding of how the extrusion parameters influence the diameter of recycled PLA filament. The filament diameter varies from 1.88 mm (2 rpm at 145°C) to 1.48 mm (6 rpm at 165°C), denoting a decrease of approximately 21.3% in filament diameter. Notably, this variation highlights the pivotal role of extrusion conditions in determining filament dimensions and shape. As the extrusion temperature escalates, the filament diameter seems to diminish (see Figure 6). This pattern could be attributed to the increased viscosity and melting rate of the PLA at higher temperatures. In other words, the increased heat at higher temperatures can decrease the PLA's viscosity, which allows it to flow more smoothly through the die, resulting in a smaller filament diameter [12], [18]. Similarly, an increase in screw speed tends to decrease the filament diameter. The amplified shear forces at higher screw speeds lead to better mixing and optimal heat distribution in the polymer melt, which when combined with thermal effects, results in a more significant reduction in diameter [11]. Recycled PLA, subjected to thermal and mechanical degradation during the recycling process, shows heightened responses to these effects. The degradation process generally results in reduced molecular weight and an increased melt flow rate [12] leading to a more significant diameter decrease at higher temperatures and screw speeds. Comparing these results with the commercial filament diameter of 1.75 mm, the extrusion parameters at 5 rpm and 155°C deliver filament diameters closest to the commercial standard.



(a) (b)

Fig. 6. Fabricated filament under (a) at an extrusion temperature of 155°C (b) at 5rpm

Table 5
Diameter, (mm) of filament under different extrusion temperatures and extrusion speeds

Extrusion Speeds	Extrusion temperatures				
	145°C	150°C	155°C	160°C	165°C
2 rpm	1.88	1.85	1.79	1.76	1.61
3 rpm	1.86	1.84	1.77	1.76	1.59
4 rpm	1.85	1.83	1.75	1.74	1.60
5 rpm	1.82	1.78	1.75	1.75	1.58
6 rpm	1.83	1.77	1.76	1.74	1.48

4. Conclusions

This research has provided valuable insights into the effects of extrusion temperature and screw speed on the mechanical properties and diameter of recycled PLA filament. The interplay between extrusion temperature and screw speed has a significant impact on the ultimate tensile strength (UTS) and yield strength of the filament. The optimal conditions for maximum UTS and yield strength were found at an extrusion temperature of 155°C and a screw speed of 5 rpm, demonstrating the potential for mitigating the adverse effects of the recycling process on the material's inherent strength. It was also observed that the extrusion parameters affect the filament's diameter, with a higher temperature and screw speed resulting in a smaller filament diameter due to the polymer's increased viscosity and melting rate. The extrusion parameters at 5 rpm and 155°C were found to deliver filament diameters closest to commercial standards. These findings hold significant implications for the processing of recycled PLA, suggesting that careful control of extrusion parameters can enhance the material's mechanical properties and control its dimensions, thereby contributing to the development of sustainable and efficient recycling practices for PLA-based products.

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