Penerbit Akademia Baru

Malaysian Journal on Composites Science and Manufacturing

Journal homepage:
https://www.akademiabaru.com/submit/index.php/mjcsm/
ISSN: 2716-6945

Effect of Sodium Chloride-Assisted Heat Treatment on Virgin and Recycled PLA Filaments in FDM 3D Printing

Open Access

Nurul Izzati Zaidi[1], Rahimah Abdul Hamid[1,*], Fawwaz Asyraf Muhammad Fakri[1], Amirul Anniq Mohd Yusof[1], Nurul Wirdah Mafazi[1], Shajahan Maidin[1], Teruaki Ito[2]

[1] Fakulti Teknologi dan Kejuruteraan Industri dan Pembuatan, Universiti Teknikal Malaysia Melaka, 76100 Durian Tunggal, Melaka, Malaysia
[2] Graduate School of Computer Science & Systems Engineering, Okayama Prefectural University, Soja-shi, Okayama 719-1197, Japan

ARTICLE INFO

Article history:
Received 15 February 2025
Received in revised form 25 March 2025
Accepted 26 March 2025
Available online 30 March 2025

ABSTRACT

Polylactic acid (PLA) is widely employed in Fused Deposition Modeling (FDM) owing to its biodegradability and ease of processing. Nonetheless, both virgin and recycled forms of PLA exhibit susceptibility to mechanical degradation, particularly under thermal stress. This study investigates the influence of sodium chloride-assisted post-processing heat treatment on the tensile properties of virgin PLA (vPLA), commercial recycled PLA (c-rPLA), and self-extruded recycled PLA (se-rPLA). Sodium chloride, used in the powder bed, helps regulate heat distribution during thermal treatment, improving tensile strength by reducing thermal degradation. Specimens were subjected to thermal treatment in a sodium chloride powder bed at 70°C, 85°C, and 100°C for 90 minutes. Tensile testing, conducted in accordance with ASTM D638, revealed strength improvements ranging from 3–6% for vPLA and 14–18% for c-rPLA. However, a tensile strength reduction of approximately 36% was observed in se-rPLA after heat treatment at 85°C, likely due to thermal sensitivity or material degradation. These findings suggest that while heat treatment can enhance the performance of commercial recycled and virgin PLA, its effectiveness for self-extruded PLA depends heavily on prior processing conditions. The study highlights the importance of carefully tailoring thermal post-processing protocols to the specific characteristics of recycled materials to support their use in sustainable 3D printing.

Keywords:
PLA, Recycled Filament, Heat Treatment, Mechanical Properties, FDM

1. Introduction

Fused Deposition Modeling (FDM), a widely adopted technique within additive manufacturing, enables the fabrication of three-dimensional objects directly from digital models using thermoplastic

* *Corresponding author.*
E-mail address: rahimah.hamid@utem.edu.my (Rahimah Abdul Hamid)
E-mail of co-authors: b052120031@student.utem.edu.my, m142420001@student.utem.edu.my, m142410008@student.utem.edu.my, nurulwirdah@utem.edu.my, shajahan@utem.edu.my, tito@ss.oka-pu.ac.jp

https://doi.org/10.37934/mjcsm.16.1.6984

filaments. Among the available materials, polylactic acid (PLA) is extensively utilized due to its biodegradability, biocompatibility, ease of processing, and cost-effectiveness [1-2]. Despite these advantages, PLA-printed parts often exhibit brittle failure, reduced mechanical strength, and poor interlayer adhesion—issues primarily stemming from the layer-by-layer deposition process. These factors contribute to internal porosity and anisotropic behavior, ultimately compromising the structural integrity of FDM components [3-4].

The increasing adoption of FDM has led to a growing volume of PLA waste generated from failed prints, expired spools, and moisture-induced degradation. Although PLA is often marketed as biodegradable, its decomposition under ambient conditions can take several decades, making natural degradation ineffective for short-term waste management solutions [5]. Consequently, recycling PLA has gained considerable attention. Recycled PLA is typically sourced via commercial reprocessing (c-rPLA) or single in-house extrusion methods (se-rPLA). However, studies have consistently shown that recycled PLA suffers mechanical degradation, including a 15–30% decrease in tensile strength and up to a 40% reduction in elongation at break, mainly due to thermal degradation during repeated processing cycles [6–8]. Additional issues such as fluctuating melt flow index (MFI) and inconsistent filament diameter further compromise print quality, posing challenges for precision-demanding applications like functional prototyping [9]. These limitations highlight the urgent need to enhance the quality and consistency of recycled PLA to enable its broader adoption in FDM-based manufacturing [10-11].

Improving the mechanical properties of both virgin and recycled PLA is therefore critical to expanding their usability in demanding applications. One promising approach to address these limitations is thermal post-processing, particularly heat treatment or annealing. Heat treatment, typically applied at temperatures between 70°C and 100°C, promotes polymer chain mobility, relieves internal stress, and increases crystallinity, ultimately improving interlayer bonding and mechanical performance [12-13]. However, conventional annealing methods, often performed in air, may result in uneven heating, oxidation, or dimensional warping. To overcome these drawbacks, sodium chloride (NaCl)-assisted heat treatment has emerged as a potentially more uniform and controllable alternative. Sodium chloride powder serves as a thermal medium that surrounds the specimen uniformly, promoting even heat distribution while minimizing deformation and oxidation. Despite its simplicity and low cost, this method remains underexplored in the context of FDM-printed PLA parts, particularly for recycled variants.

This study aims to bridge that gap by systematically evaluating the tensile performance of vPLA, c-rPLA, and se-rPLA fabricated via FDM and subjected to NaCl-assisted heat treatment at 70°C, 85°C, and 100°C for 90 minutes. The goal is to determine whether optimized thermal post-processing using NaCl can enhance the structural performance of recycled PLA to levels comparable with untreated virgin PLA, thereby contributing to more sustainable and circular material usage in additive manufacturing.

2. Methodology

2.1 Material preparation

This study investigates the mechanical behavior of virgin and recycled PLA filaments subjected to heat treatment in FDM applications. Three types of filaments analyzed were: virgin PLA (vPLA), commercial recycled PLA (c-rPLA), and self-extruded recycled PLA (se-rPLA). The vPLA filament used was PolyLite PLA with a 1.75 mm diameter, while c-rPLA was sourced from Kimya with a 2.85 mm diameter. The self-extruded filament was a mixture of various laboratory 3D printing waste, including PLA waste generated through multiple sources such as support structures, rafts removed from physical models, failed prints, defects in new PLA filaments, and partially used PLA filaments that had been exposed to humidity for extended periods, blended with vigin PLA pellets at varying ratios. To prepare the waste for extrusion, the PLA fragments were processed using a grinder machine, reducing them to small fragments within a size range of 2–3 mm. The fragments were then sieved using 2 mm and 3 mm mesh sizes to ensure uniformity and compatibility with the single-screw extruder's feed system. Reducing the size of the material was essential for optimizing extrusion flow, improving operational efficiency, and ensuring the production of continuous, high-quality filament [14].

The next process after grinding was drying, performed to eliminate moisture in the recycled PLA before extrusion. PLA is hydrophilic due to its molecular structure and can absorb up to 0.5% moisture at 23 °C [15 -16]. Excess moisture during extrusion can lead to hydrolysis, chain scission, and ultimately reduced mechanical performance. In industrial settings, PLA is typically dried to below 250 ppm humidity to ensure optimal processability [17]. In this study, all recycled PLA materials were dried at 80 °C for 4 hours using an oven, consistent with the recommended standard for PLA drying [18]. The dried recycled PLA was then blended with virgin PLA pellets in specific ratios determined by a Taguchi L9 orthogonal array.

2.2 Filament extrusion using a single-screw extruder machine

The self-extrusion process was conducted using a single-screw extruder, with operational parameters optimized at three distinct levels: barrel temperature (182°C, 184°C, and 186°C), extrusion speed (700 rpm, 710 rpm, and 720 rpm), and virgin-to-recycled PLA ratios (20%, 30%, and 40%), as detailed in Table 1. Each parameter combination was systematically evaluated to assess its influence on filament dimensional consistency. Filament uniformity was measured along 1-meter segments, with an acceptable deviation set at ±0.05 mm from the target diameter of 1.75 mm. The overall extrusion workflow for the recycled PLA preparation is depicted in Figure 1.

Table 1
Factors and their levels

Factors	Barrel temperature (°C)	Extrusion speed (mm/min)	Virgin PLA ratio vPLA (%)
Level 1	182	700	20
Level 2	184	710	30
Level 3	186	720	40

2.3 FDM printing

FDM printing was conducted using two desktop 3D printers. The Creality Ender 3 V3 SE was used for printing vPLA and se-rPLA, both of 1.75 mm diameter, while the Ultimaker S3 handled c-rPLA of 2.85 mm diameter. Tensile specimens were designed in accordance with ASTM D638 Type IV. CAD modeling and slicing were performed using CATIA V5 and Ultimaker Cura software, respectively. Table 2 and 3 show the 3D printing parameters for the virgin and recycled PLA.

2.4 Heat Treatment

Post-processing heat treatment was applied to the printed tensile specimens to evaluate the effect of thermal annealing on mechanical properties. To minimize part warping and ensure uniform thermal distribution, all specimens were embedded in a powder bed of finely ground sodium chloride (NaCl) and placed inside stainless steel containers, as shown in Figure 2. The NaCl used in this experiment was sourced from Comax Scientific. It was selected due to its low cost, non-toxicity, fine grindability, and thermal stability, making it suitable for controlled heat transfer during treatment.

The NaCl was ground using a ball milling machine and sieved using a mesh 279 sieve, resulting in particles of ≤53 µm. Prior to use, the powder was dried at 200°C for 30 minutes to eliminate residual moisture and then cooled to room temperature. During treatment, printed specimens were placed in the sodium chloride (NaCl) bed and covered completely, with a 1.5 kg metal plate placed on top to apply light compression. This setup ensured minimal geometric deformation during heating.

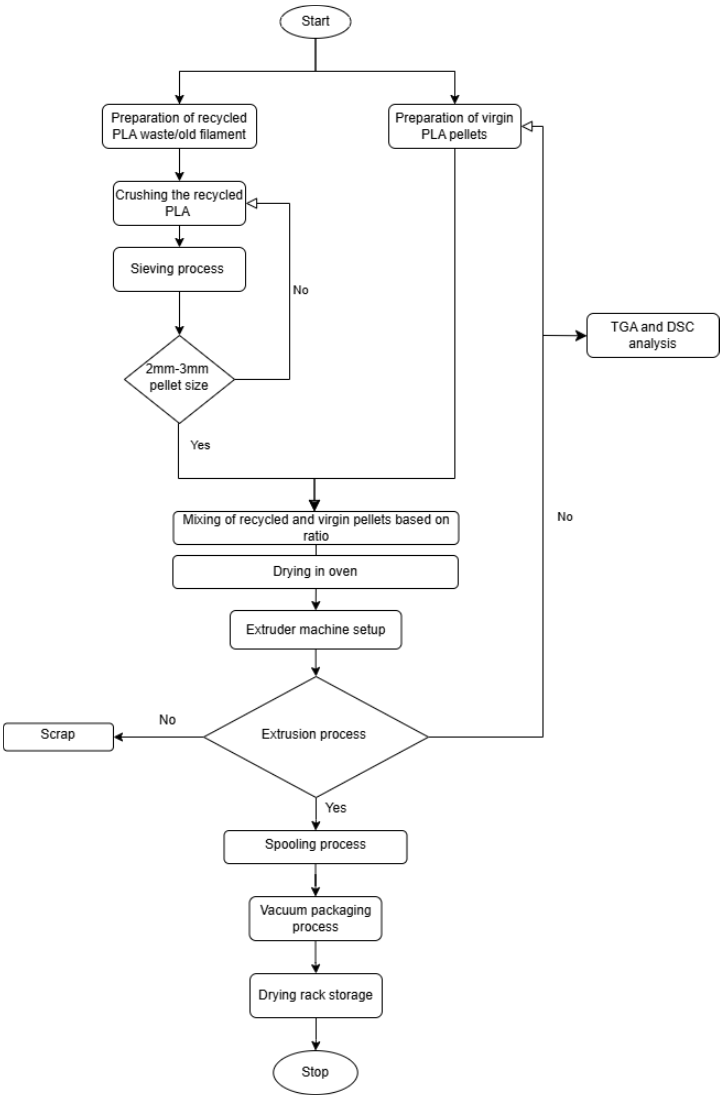


Fig. 1. Recycled filament extrusion process

Table 2
3D Printing parameters of the virgin PLA (vPLA)

Printing parameters	Setting
Infill percentage (%)	100%
Layer thickness (mm)	0.16
Printing temperature (°C)	210
Bed Temperature (°C)	60
Printing speed (mm/s)	50
Infill percentage (%)	100%

Table 3
3D printing parameters of c-rPLA and se-rPLA

Printing parameters	Setting	Reference
Infill percentage (%)	100%	
Layer thickness (mm)	0.2	[19]
Printing temperature (°C)	215	[20]
Bed Temperature (°C)	60	
Printing speed (mm/s)	60	[21]
Infill percentage (%)	100%	

Fig. 2. Heat treatment of the printed specimens

Heat treatment was conducted in a convection oven at three different temperatures: 70°C, 85°C, and 100°C, each maintained for 90 minutes. These temperatures were selected to remain above the glass transition temperature (Tg) of PLA (~60°C) but below its melting point (~150–160°C), allowing polymer chain relaxation without causing melting. For virgin PLA (vPLA) and commercial recycled PLA (c-rPLA), all three temperature conditions were tested using tensile specimens. For self-extruded PLA (se-rPLA), tensile specimens were treated only at 85°C for 90 minutes due to limitations in filament stability. This temperature was selected based on the recommendations of Kartal *et al.* [22], who identified 85°C as optimal for improving the mechanical performance of PLA without introducing defects. Following the heating cycle, the entire container was removed from the oven and allowed to cool gradually at room temperature (27°C) before specimens were unpacked. This gradual cooling process further reduced the risk of warping or thermal shock.

2.5 Tensile testing

Mechanical characterization was conducted using a Shimadzu Universal Testing Machine (UTM). Tensile testing adhered to ASTM D638 standards, employing a crosshead speed of 5 mm/min. For each material type and heat treatment condition, two specimens were tested to evaluate tensile performance. While the sample size is limited, the results offer valuable insights into the effects of material composition and thermal post-processing on the mechanical behavior of the printed PLA specimens. Figure 3 illustrates the tensile specimens for all set of parameters.

Fig. 3. Tensile specimens of all set of parameters

3. Results

This section discusses the results obtained from the mechanical properties study. The effects of heat treatment on the untreated and heat-treated sample of virgin PLA (vPLA), commercial recycled PLA (c-rPLA), and self-extruded recycled PLA (se-rPLA) are discussed in the next sub-section.

3.1 Tensile behaviour of untreated PLA specimens

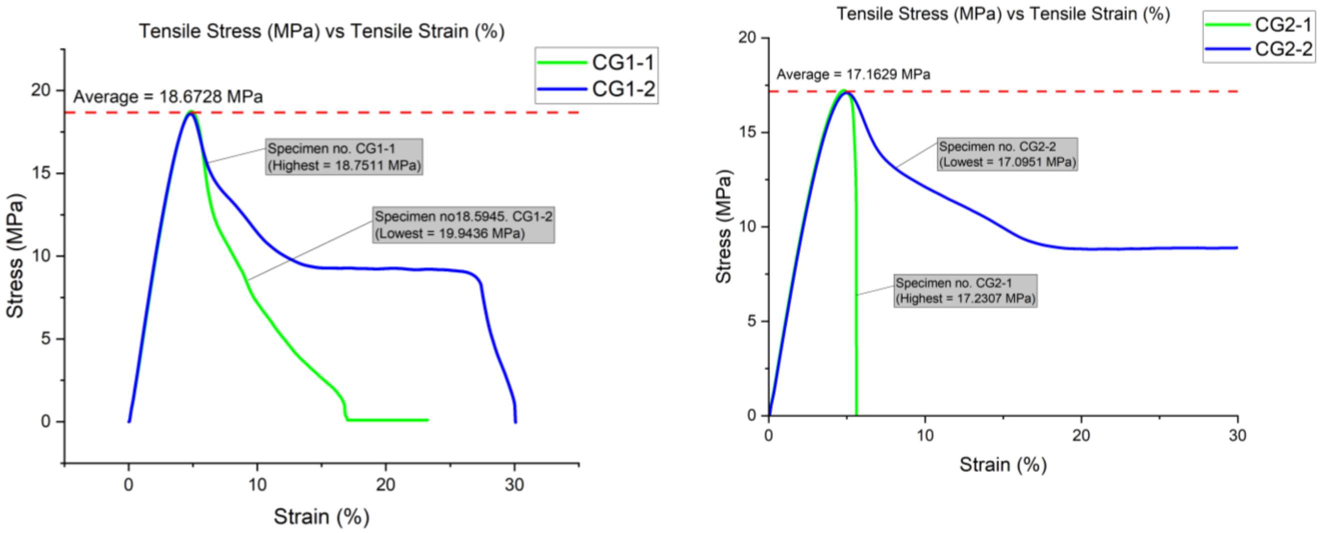
The tensile test results for untreated specimens of three PLA types—virgin PLA (vPLA), commercial recycled PLA (c-rPLA), and self-extruded recycled PLA (se-rPLA) reveal notable differences in mechanical strength, influenced by material history, extrusion technique, and recycled content. Serving as the benchmark, virgin PLA (CG1) recorded an average tensile strength of 18.673 MPa, while commercial recycled PLA (CG2) registered a slightly lower strength of 17.163 MPa, as shown in Table 4. This reflects an 8.1% reduction in tensile strength, primarily due to thermal degradation and molecular chain scission experienced during previous recycling cycles. The stress-strain curves in Figure 4 further illustrates that vPLA maintained a more stable elastic response and higher strength before failure, whereas c-rPLA showed an earlier onset of plastic deformation and reduced elongation capability.

In contrast, the self-extruded PLA (se-rPLA), fabricated using varying process parameters under a Taguchi L9 orthogonal array, yielded significantly lower tensile strength values. The lowest performance was observed in Set A (182°C, 700 rpm, 20% vPLA), with an average tensile strength of 7.332 MPa (Table 5, Figure 5a). This is attributed to the low virgin content and suboptimal extrusion temperature, which may have led to poor layer bonding and inconsistent filament quality.

A moderate increase in tensile strength was observed in Set B (182°C, 710 rpm, 30% vPLA), reaching 7.740 MPa (Figure 5b), suggesting that even slight increases in virgin content and screw speed can enhance melt flow and filament strength. Set C (182°C, 720 rpm, 40% vPLA) and Set D (184°C, 700 rpm, 40% vPLA) yielded higher tensile strengths of 8.804 MPa and 8.592 MPa, respectively (Figure 5c, 5d). These results indicate that increasing the recycled content beyond 30% can still produce usable filaments if compensated by higher screw speeds or optimized barrel temperatures. The improved performance in these sets can be linked to better plasticizing and mixing behavior during extrusion, which may have improved layer adhesion during printing.

Table 4
Tensile test data for the untreated vPLA and c-rPLA)

Type of PLA	Specimen No	Tensile force (N)	Tensile strength (MPa)
vPLA	CG 1-1	545.184	18.751
	CG 1-2	529.804	18.595
	Average	537.494	18.673
c-rPLA	CG2-1	1047.63	17.231
	CG2-2	1039.38	17.095
	Average	1043.505	17.163



(a) (b)

Fig. 4. Stress-strain curve for the untreated (a) vPLA, (b) c-rPLA specimens

Table 5
Tensile test data for the untreated self-extruded PLA specimens

Set	Parameter (rPLA)	Specimen No	Tensile force (N)	Tensile strength (MPa)
A	182°C, 700rpm, 20%	1-1	427.799	7.036
	vPLA	1-2	463.791	7.628
		Average	445.795	7.332
B	182°C, 710rpm, 30%	2-1	506.884	8.337
	vPLA	2-2	434.240	7.142
		Average	470.562	7.740
C	182°C, 720rpm, 40%	3-1	545.575	8.973
	vPLA	3-2	525.042	8.636
		Average	535.309	8.804
D	184°C, 700rpm, 40%	4-1	544.141	8.950
	vPLA	4-2	500.682	8.235
		Average	522.412	8.592

Despite improvements in the higher-performing se-rPLA sets, the untreated self-extruded filaments still fall significantly below the tensile performance of commercial PLA materials. This confirms that extrusion inconsistencies and thermal degradation of recycled PLA significantly affect the structural integrity of the printed parts. However, the outcomes also highlight that proper optimization of process parameters can meaningfully improve the baseline mechanical properties of recycled materials prior to any post-processing treatment. These untreated tensile results establish a crucial baseline for evaluating the impact of heat treatment in the next phase of analysis and demonstrate the importance of carefully balancing recycled content, extrusion conditions, and print settings to ensure acceptable filament performance in additive manufacturing.

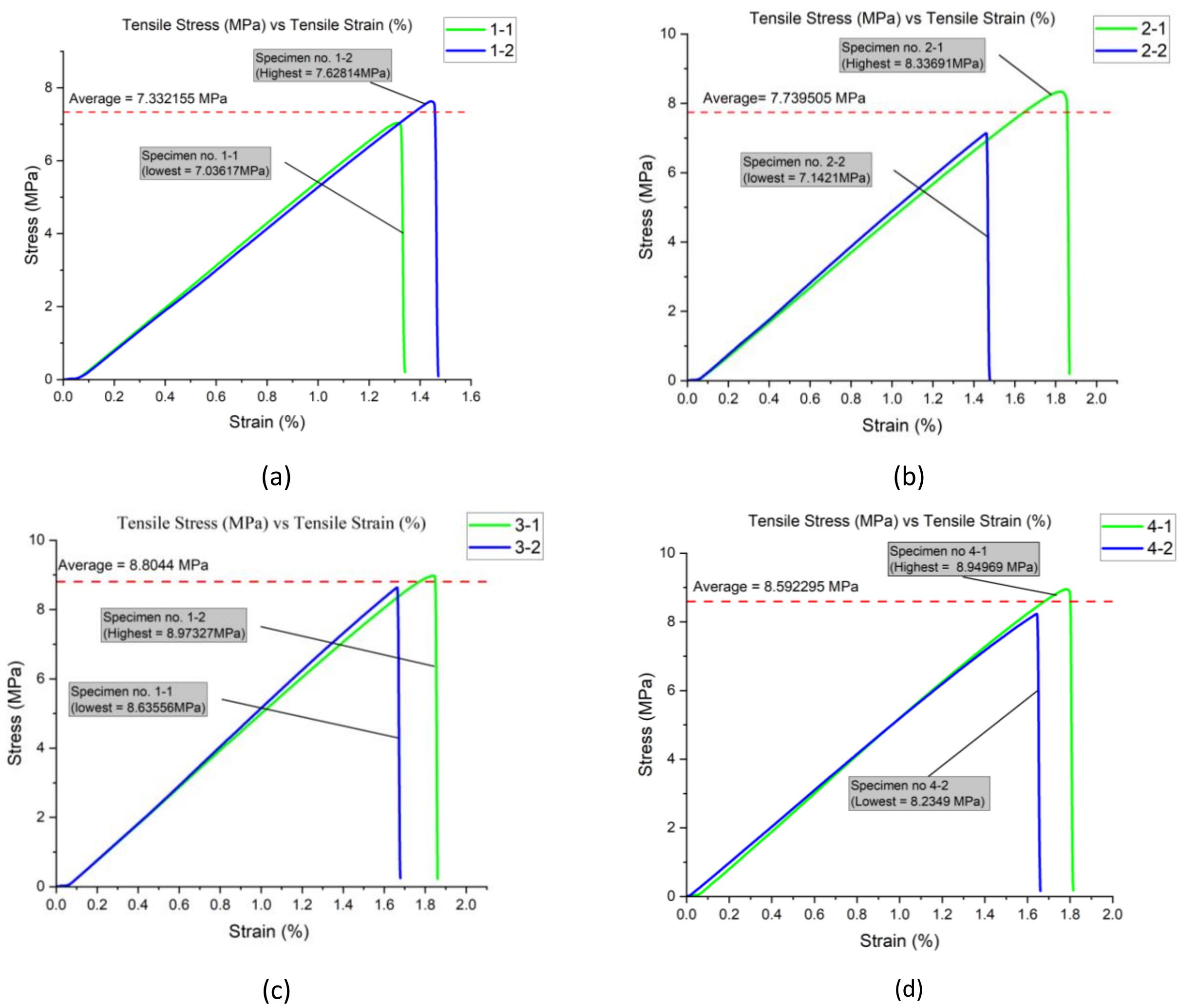


Fig. 5. Stress-strain curve for the heat-treated self-extruded (se-rPLA) specimens: (a) Set A, (b) Set B, (c) Set C, and (d) Set D

3.2 Effect of heat treatment on tensile strength

The tensile strength of PLA materials demonstrated notable improvements after undergoing heat treatment, with the extent of enhancement varying across PLA types and treatment temperatures. Heat treatment was applied at 70°C, 85°C, and 100°C for virgin PLA (vPLA) and commercial recycled PLA (c-rPLA), while self-extruded recycled PLA (se-rPLA) was treated only at 85°C due to process limitations. Each treatment condition was maintained for 90 minutes using a sodium chloride (NaCl) powder bed to ensure uniform thermal exposure and minimize warping.

3.2.1 Commercial virgin PLA (vPLA)

The tensile strength of virgin PLA (vPLA) specimens showed a modest improvement with increasing heat treatment temperatures. As presented in Table 6, the average tensile strength increased from 18.673 MPa (untreated, Table 4) to 19.289 MPa at 70°C, 19.423 MPa at 85°C, and 19.673 MPa at 100°C—representing relative increases of 3.32%, 4.02%, and 5.35%, respectively.

These enhancements are attributed to the annealing effect, which promotes polymer chain mobility, relieves residual stresses, and enhances crystallinity—particularly when the temperature exceeds the glass transition point of PLA. Although the highest strength was recorded at 100°C, the relatively small improvement compared to 85°C suggests that 85°C may be more favorable in energy-efficient applications. Figure 6 illustrates the corresponding improvements in tensile response across the temperature range.

This gradual improvement can be attributed to increased molecular mobility and recrystallization that occur when the material is annealed above its glass transition temperature (Tg ~60°C). The annealing process helps relieve internal stress, enhances interlayer bonding, and slightly improves ductility. Although 100°C yielded the highest tensile strength, the marginal difference between 85°C and 100°C suggests that 85°C may be a more energy-efficient yet effective post-treatment option.

3.2.2 Commercial Recycled PLA (c-rPLA)

Commercial recycled PLA (c-rPLA) also benefited from thermal post-treatment. As reported in Table 7, the average tensile strength improved from 17.163 MPa (untreated, Table 4) to:

- 20.337 MPa at 70°C (Set G),
- 20.098 MPa at 85°C (Set H), and
- 19.684 MPa at 100°C (Set I)

Table 6
Tensile test data for the heat-treated virgin PLA (vPLA)

Set	Parameter (rPLA)	Specimen No	Tensile force (N)	Tensile strength (MPa)
J	70°C, 90min	10-1	1194.97	19.654
		10-2	1150.62	18.925
		Average	1172.80	19.289
K	85°C, 90min	11-1	1209.61	19.895
		11-2	1153.55	18.973
		Average	1181.58	19.423
L	100°C, 90min	12-1	1203.55	19.795
		12-2	1188.66	19.550
		Average	1196.11	19.673

Although c-rPLA’s starting strength was lower than that of virgin PLA due to previous thermal degradation, the percentage increase from heat treatment was even more substantial—18.58%, 17.15%, and 14.68%, respectively. This suggests that the annealing process not only partially restored the polymer's mechanical integrity but also significantly enhanced its structural performance. The improved tensile behavior highlights the potential of recycled filaments to approach or even surpass untreated virgin PLA when subjected to appropriate thermal post-processing. The corresponding stress-strain profiles across all PLA types are illustrated in Figure 7, showing the consistent upward trend in tensile response after treatment.

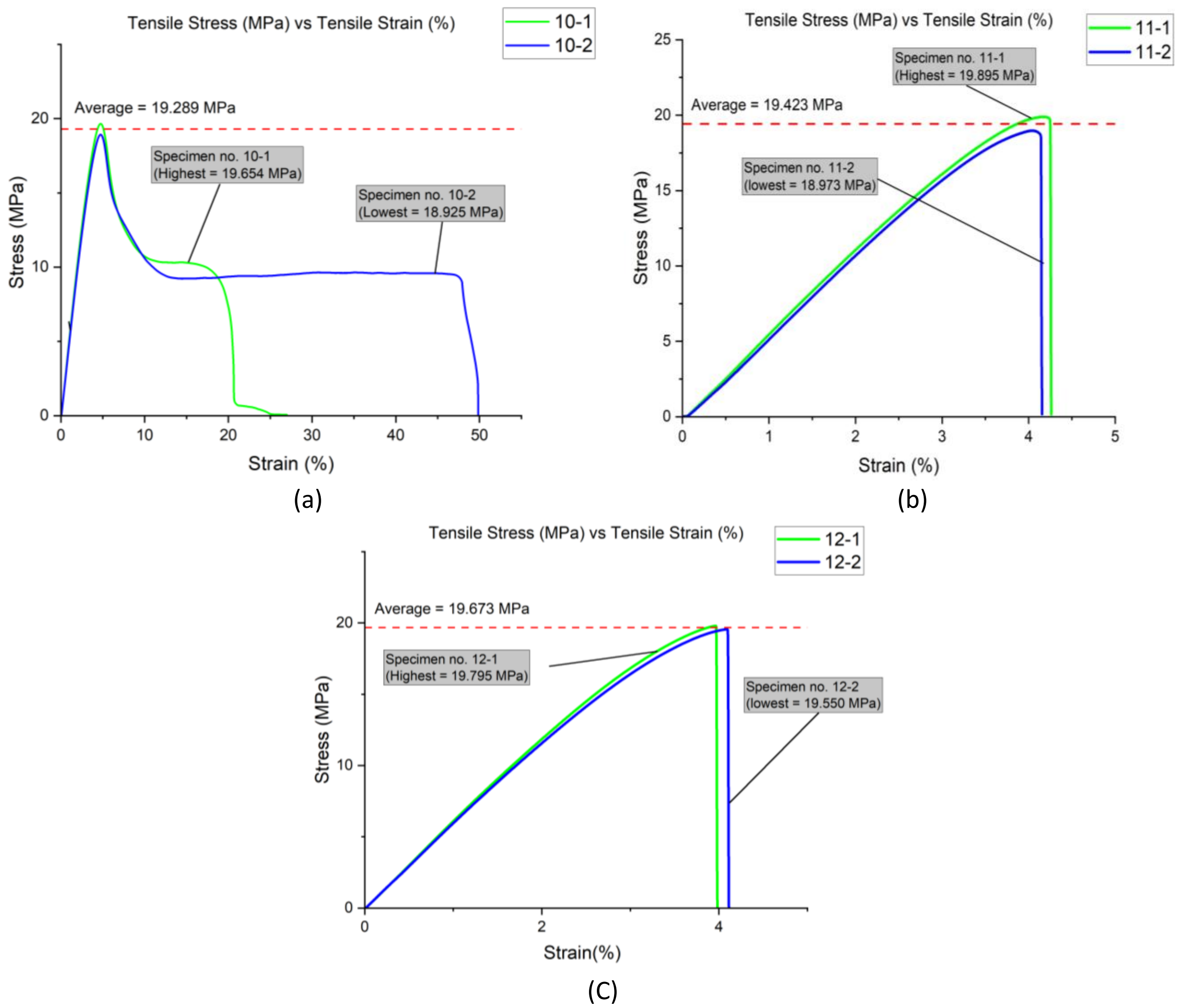


Fig. 6. Stress-strain curve for the heat-treated vPLA sample: (a) Set J, (b) Set K, and (c) Set L

Table 7
Tensile test data for the heat-treated commercial rPLA (C-rPLA)

Set	Parameter (rPLA)	Specimen No	Tensile force (N)	Tensile strength (MPa)
G	70°C, 90min	7-1	1244.09	20.462
		7-2	1228.91	20.212
		Average	1236.50	20.337
H	85°C, 90min	8-1	1224.53	20.140
		8-2	1219.33	20.055
		Average	1221.93	20.098
I	100°C, 90min	9-1	1180.97	19.424
		9-2	1212.57	19.944
		Average	1196.77	19.684

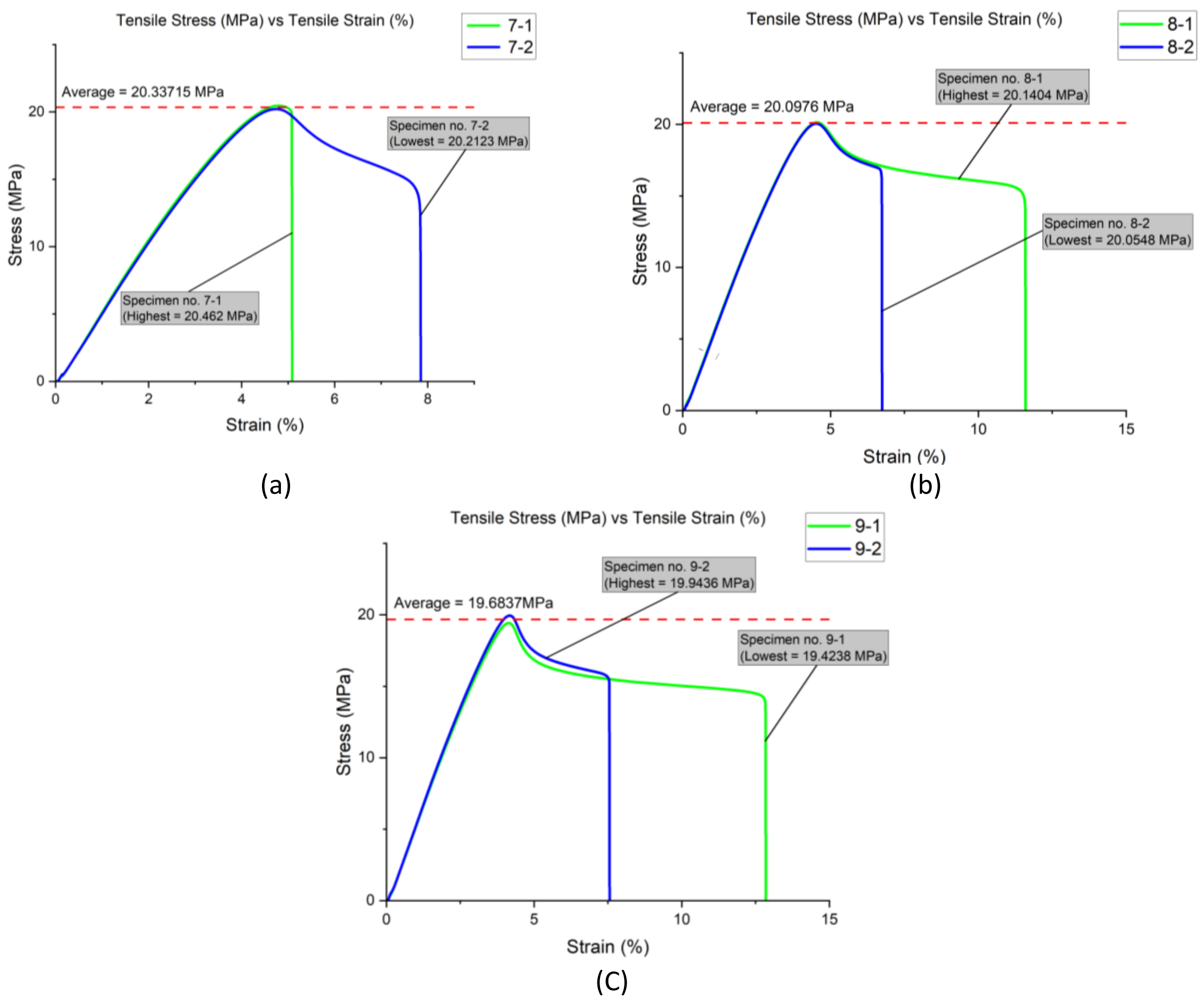


Fig. 7. Stress-strain curve for the heat-treated c-rPLA sample: (a) Set G, (b) Set H, and (c) Set I

3.2.3 Self-Extruded Recycled PLA (se-rPLA)

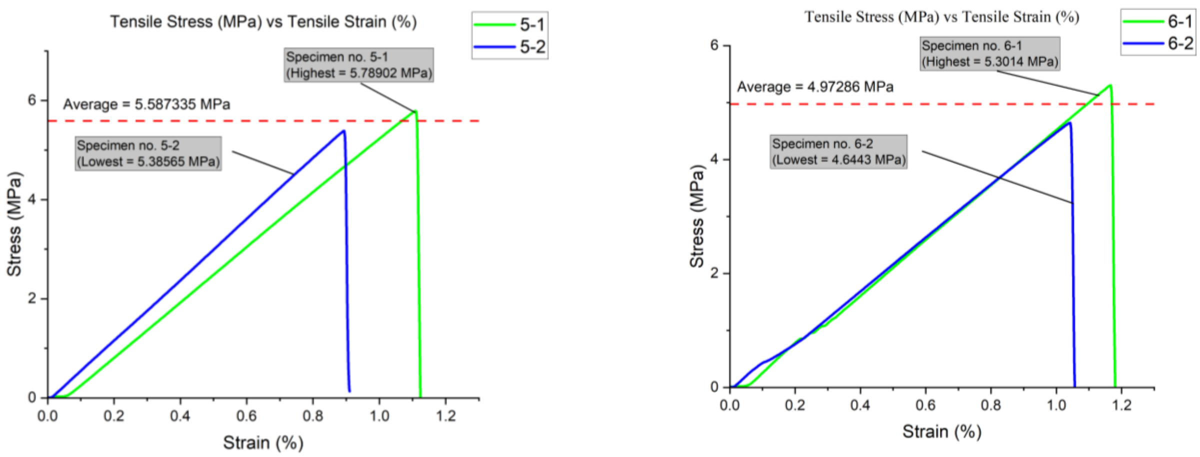
Due to the thermal sensitivity of self-extruded PLA (se-rPLA), heat treatment was only applied at 85°C for 90 minutes, based on prior recommendations by Kartal *et al.* [22]. As shown in Table 8, the tensile strength of Set E specimens (extruded at 182°C, 720 rpm, 40% vPLA) decreased from 8.804 MPa (untreated, Set C in Table 5) to 5.587 MPa (Figure 8a) after heat treatment. This represents a 36.48% reduction in tensile strength. The decrease suggests that the chosen thermal post-processing condition, while beneficial for virgin and commercial PLA, may not be suitable for self-extruded PLA with this composition. It is possible that further degradation, increased brittleness, or unfavorable crystallization occurred due to repeated thermal exposure. These results indicate that heat treatment parameters must be carefully tailored to the extrusion history and material condition of recycled PLA.

The significant reduction in tensile strength observed for heat-treated se-rPLA may be attributed to several interrelated factors inherent to recycled PLA and its thermal history. Unlike virgin or commercially recycled PLA, se-rPLA in this study underwent multiple thermal cycles—including the initial 3D printing failure, grinding, re-extrusion, and finally heat treatment. Each cycle exposes the PLA to elevated temperatures, which can induce chain scission and reduction in molecular weight, thereby compromising mechanical strength. Furthermore, self-extruded PLA typically contains a more heterogeneous mix of degraded and partially oxidized polymer chains due to inconsistent feedstock quality. This increases its susceptibility to thermal oxidative degradation during heat treatment. While heat treatment is intended to promote polymer chain relaxation and crystallization, the crystallization behavior of heavily recycled PLA is often erratic. Instead of forming well-ordered spherulites that improve strength, recycled PLA may form brittle or imperfect crystalline regions, which can act as stress concentrators and reduce ductility.

Residual moisture, even after standard drying procedures, may also contribute to the observed degradation. Trapped moisture within the polymer matrix can promote hydrolytic degradation during heat treatment, leading to polymer chain scission and a consequent decline in mechanical integrity. Additionally, the combination of high recycled content, limited chain entanglement, and the presence of pigment or filler residues from previous print cycles may have exacerbated the thermal sensitivity of se-rPLA, resulting in embrittlement rather than mechanical enhancement following annealing. These findings underscore the necessity of carefully optimized post-processing protocols, particularly when working with self-extruded PLA derived from heterogeneous or thermally degraded waste streams.

Table 8
Tensile test data for the heat-treated self-extruded rPLA (se-rPLA)

Set	Parameter (rPLA)	Specimen No	Tensile force (N)	Tensile strength (MPa)
E	182°C, 720rpm,	5-1	351.973	5.789
	40% vPLA	5-2	327.447	5.386
		Average	339.710	5.587
F	184°C, 700rpm,	6-1	322.326	5.301
	40% vPLA	6-2	282.373	4.644
		Average	302.350	4.973



(a) (b)

Fig. 8. Stress-strain curve for the heat-treated se-rPLA sample: (a) Set E, and (b) Set F

3.3 Comparative analysis and process optimization

The tensile performance of PLA specimens across different material types and treatment conditions highlights the effectiveness of heat treatment and process optimization [23] in enhancing mechanical properties, particularly for recycled materials. This section consolidates key observations and identifies optimal settings based on tensile strength results and process parameters. Among the three PLA types tested, virgin PLA (vPLA) consistently recorded the highest tensile strength in both untreated and heat-treated conditions. However, the strength differences between vPLA and the other groups narrowed significantly after heat treatment. The optimal treatment temperature for vPLA was found to be 100°C, with an average tensile strength of 19.673 MPa, compared to 18.673 MPa in its untreated form. While this was the highest observed value, the improvement between 85°C (19.423 MPa) and 100°C was marginal, indicating that 85°C may offer a more energy-efficient alternative without significantly compromising mechanical performance.

Commercial recycled PLA (c-rPLA) also benefited notably from heat treatment, with tensile strength increasing from 17.163 MPa in its untreated form to 19.684 MPa after treatment at 100°C. Comparable gains were observed at 85°C, where the strength reached 20.098 MPa, highlighting this temperature as a practical and energy-efficient post-processing option. Although c-rPLA initially exhibited lower mechanical performance than virgin PLA due to prior thermal degradation, the post-treatment results demonstrate that it can match or even slightly exceed the tensile strength of virgin PLA under optimized conditions. This finding underscores the potential of commercial recycled PLA for non-critical structural applications, especially when combined with appropriate thermal post-processing.

For self-extruded recycled PLA (se-rPLA), the combination of extrusion parameters and post-processing conditions played a critical role in determining mechanical performance. Among the untreated sets, the highest tensile strength was observed in Set C (182°C, 720 rpm, 40% vPLA), reaching 8.804 MPa. However, after heat treatment at 85°C, the tensile strength decreased to 5.587 MPa, representing a 36.48% reduction. This unexpected decline suggests that, unlike virgin or commercially recycled PLA, se-rPLA may be more susceptible to thermal degradation [24] due to its complex thermal history, repeated processing cycles, and heterogeneous composition. The results highlight that while in-house recycling offers sustainability and cost-saving benefits, it also demands precise control over extrusion and post-treatment protocols to preserve mechanical integrity and ensure the viability of recycled filament in functional applications.

The extrusion optimization results, presented in Figure 9, confirm that extrusion temperature and speed have the most significant influence on the tensile performance of se-rPLA. As shown in the main effect plot, extrusion speed exhibits a clear positive correlation with tensile strength, with higher speeds improving filament properties up to an optimal point. This improvement is likely due to faster material throughput, which enhances plasticization and promotes more uniform material flow during extrusion. On the other hand, moderate extrusion temperatures are found to be the optimal range for effective plasticization of the recycled feedstock. At these temperatures, the polymer chains gain sufficient mobility to bond effectively, contributing to stronger layer adhesion during printing. However, excessively high or low temperatures can disrupt the plasticization process, leading to reduced filament quality, as shown by the plot’s trends. These findings emphasize the importance of processing consistency in filament quality, especially when working with recycled feedstock. The data underline that controlling both extrusion speed and temperature is essential for producing reliable, high-quality filaments, ensuring that mechanical properties, particularly tensile strength, are not compromised.

In summary, heat treatment at 85°C for 90 minutes emerged as the most effective and consistent condition across all material types, offering significant improvements in tensile performance with minimal risk of warping or deformation. When combined with process optimization, particularly in self-extruded PLA, heat treatment can bring recycled materials closer in performance to virgin PLA, making them more viable candidates for sustainable 3D printing applications.

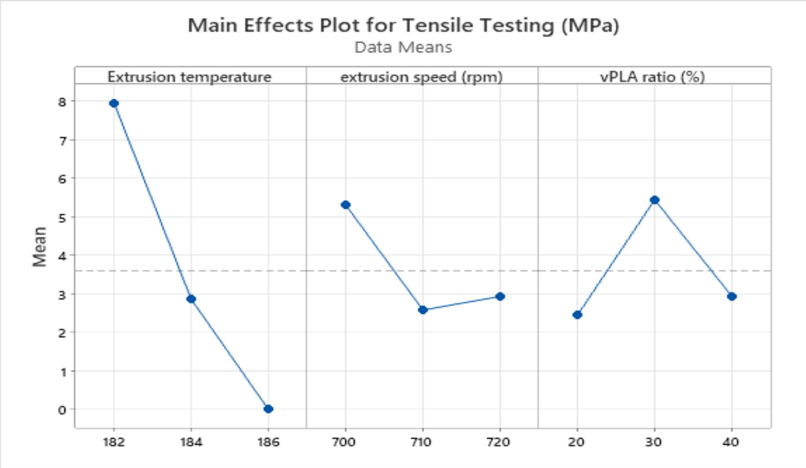


Fig. 9. Main effects plot graph relationship between 3 parameters and tensile testing (MPa)

4. Conclusions

This study explored the effect of heat treatment on the tensile strength of three types of PLA filaments: virgin PLA (vPLA), commercial recycled PLA (c-rPLA), and self-extruded recycled PLA (se-rPLA) used in Fused Deposition Modeling (FDM). The study aimed to optimize the material ratio for self-extruded PLA, compare tensile strength across different PLA types, and evaluate the impact of heat treatment on improving mechanical properties. The optimal extrusion settings for se-rPLA were determined using a Taguchi L9 orthogonal array, with a 30% virgin-to-70% recycled PLA ratio, 184°C barrel temperature, and 710 rpm extrusion speed, which produced consistent filaments suitable for FDM printing. The results showed that untreated se-rPLA had the lowest tensile strength among the three types, and unlike vPLA and c-rPLA, its performance did not improve after heat treatment. In fact, a slight reduction in tensile strength was observed, possibly due to additional thermal degradation during the annealing process. In contrast, both c-rPLA and vPLA showed measurable improvements in tensile strength after heat treatment at 85 degrees Celsius for 90 minutes, with c-rPLA demonstrating the most notable gains. Overall, while heat treatment enhanced the tensile strength of commercial recycled and virgin PLA, it was less effective for self-extruded recycled PLA. These findings highlight the importance of careful thermal management when processing recycled materials and suggest that additional refinement steps may be needed to improve the quality of self-extruded filaments for structural 3D printing applications.

Acknowledgment
This research was funded by a grant from Universiti Teknikal Malaysia Melaka: Short-Term Research Grant (PJP Perintis) - Project Number:PJP/2024/FTKIP/PERINTIS/SA0024.

References
[1] W. Ahmed, S. Siraj, and A. H. Al-Marzouqi, "3D Printing PLA Waste to Produce Ceramic Based Particulate Reinforced Composite Using Abundant Silica-Sand: Mechanical Properties Characterization," Polymers (Basel) 12, no. 11 (2020): 1–19.
https://doi.org/10.3390/polym12112579
[2] A. Aimar, A. Palermo, and B. Innocenti, "The Role of 3D Printing in Medical Applications: A State of the Art," International Journal of Biomaterials (2019):1-10.
https://doi.org/10.1155/2019/5340616

[3] M. N. Sudin, S. A. Shamsuddin, F. R. Ramli, and N. Md Daud, "A Brief Review of Factors Affecting the Mechanical Properties of Fused Deposition Modelling Part," Journal of Advanced Mechanical Engineering Applications 3, no. 2 (2022):1-13.
https://doi.org/10.30880/jamea.2022.03.02.001
[4] A. Al Rashid and M. Koç, "Additive Manufacturing for Sustainability and Circular Economy: Needs, Challenges, and Opportunities for 3D Printing of Recycled Polymeric Waste," Materials Today Sustainability (2023):1-13. https://doi.org/10.1016/j.mtsust.2023.100529
[5] M. R. Hasan, I. J. Davies, A. Pramanik, M. John, and W. K. Biswas, "Impact of Process Parameters on Improving the Performance of 3D Printed Recycled Polylactic Acid (rPLA) Components," International Journal of Advanced Manufacturing Technology 131, no. 7–8 (2024): 3751–3779.
https://doi.org/10.1007/s00170-024-13140-7
[6] C. C. Kuo, J. Y. Chen, and Y. H. Chang, "Optimization of Process Parameters for Fabricating Polylactic Acid Filaments Using Design of Experiments Approach," Polymers (Basel) 13, no. 8 (2021):1-19.
https://doi.org/10.3390/polym13081222
[7] J. Sasse, L. Pelzer, M. Schön, T. Ghaddar, and C. Hopmann, "Investigation of Recycled and Coextruded PLA Filament for Additive Manufacturing," Polymers (Basel) 14, no. 12 (2022): 1-16.
https://doi.org/10.3390/polym14122407
[8] Oumaima Boughanmi, Lamis Allegue, H. Marouani, Ahmed Koubaa and Yasser Fouad, "Repetitive Recycling Effects on Mechanical Characteristics of Poly-Lactic Acid and PLA/Spent Coffee Grounds Composite Used for 3D Printing Filament," Polymer Engineering & Science (2024).
https://doi.org/10.1002/pen.26938
[9] Naiara C. Farias, Ludivine Coudert, Declan Devine, Golnoosh Abdeali and Romina Pezzoli, "Repeated Mechanical Recycling of Biodegradable Polymers: PLA Exhibits Less Deterioration than PBAT/PLA Blend," Current Research in Green and Sustainable Chemistry (2024): 1-11.
https://doi.org/10.1016/j.crgsc.2024.100430
[10] Yu-Chen Chien, J.Y.H. Wu, Chiao-Hsuan Shu, Jung-Tien Lo and Teng-Chun Yang, "Closed-Loop Recycling of 3D-Printed Wood–PLA Composite Parts: Effects on Mechanical and Structural Properties via Fused Filament Fabrication," Polymers (2024).:1-14.
https://doi.org/10.3390/polym16213002
[11] Shady Farah, David G. Anderson and Robert Langer, "Physical and Mechanical Properties of PLA, and Their Functions in Widespread Applications—A Comprehensive Review," *Advanced Drug Delivery Reviews* 107 (2016): 367–392. https://doi.org/10.1016/j.addr.2016.03.008
[12] Z. Pan, Q. Zhao, Q. Wei, Z. Wu, and N. Li, "Heat Treatment on the Multiple-Impact Mechanical Responses and Damage Behaviors of 3D and 2D Woven GF/PP/Epoxy Composites," Thin-Walled Structures 183 (2023):1-17.
https://doi.org/10.1016/j.tws.2022.110415
[13] C. G. Amza, A. Zapciu, G. Constantin, F. Baciu, and M. I. Vasile, "Enhancing Mechanical Properties of Polymer 3D Printed Parts," Polymers 13, no. 4 (2021): 1-18.
https://doi.org/10.3390/polym13040562
[14] M. R. Hasan, I. J. Davies, A. Pramanik, M. John, and W. K. Biswas, "Fabrication and Characterisation of Sustainable 3D-Printed Parts Using Post-Consumer PLA Plastic and Virgin PLA Blends," Processes 12, no. 4 (2024):1-30.
https://doi.org/10.3390/pr12040760
[15] L. T. Sin and B. S. Tueen, "Injection Molding and Three-Dimensional Printing of Poly(Lactic Acid)," In Polylactic Acid, 325–345. Elsevier, (2019):325-345.
https://doi.org/10.1016/B978-0-12-814472-5.00010-8
[16] G. Wypych, "PLA Poly(lactic acid)," In Handbook of Polymers, ChemTec Publishing, (2016): 450–454. https://doi.org/10.1016/B978-1-895198-92-8.50139-7
[17] E. Castro-Aguirre, F. Iñiguez-Franco, H. Samsudin, X. Fang, and R. Auras, "Poly(lactic acid)—Mass Production, Processing, Industrial Applications, and End of Life," Advanced Drug Delivery Reviews 107 (2016): 333–366. https://doi.org/10.1016/j.addr.2016.03.010
[18] E. K. Cuff, C. G. Seben, F. De, B. Gluck, and A. Luís Gasparin, "A Review about Polylactic Acid Filament Recycling to 3D Printing Process / Uma Revisão Sobre a Reciclagem de Filamentos de Ácido Poliláctico ao Processo de Impressão 3D," Brazilian Journal of Development 8, no. 3 (2022): 16624–16634.
https://doi.org/10.34117/BJDV8N3-074
[19] M. Christiliana, Y. Oktriadi, J. Teknik Mesin, and P. Manufaktur Negeri Bangka Belitung, "Optimasi Parameter Proses pada 3D Printing FDM terhadap Akurasi Dimensi Filament PLA Food Grade," Manutech: Jurnal Teknologi Manufaktur 13, no. 1 (2021): 1–8.
https://doi.org/10.33504/MANUTECH.V13I01.163

[20] S. Gebrehiwot, A. S. Z. Gebrehiwot, L. Espinosa-Leal, P. Linderbäck, and H. Remes, "Optimising the Mechanical Properties of Additive-Manufactured Recycled Polylactic Acid (rPLA) Using Single and Multi-Response Analyses Methods," International Journal of Advanced Manufacturing Technology (2023). https://doi.org/10.21203/rs.3.rs-3115087/v1

[21] S. Raja, M. K. Kandan, V. Vijayan, K. Arul, R. Rameshkumar, and R. S. Prabu, "Optimization of 3D Printing Process Parameters of Polylactic Acid Filament Based on the Mechanical Test," International Journal of Chemical Engineering 2022 (2022): 1-7. https://doi.org/10.1155/2022/5830869

[22] F. Kartal, A. Kaptan, and F. Kartal, "Effects of Annealing Temperature and Duration on Mechanical Properties of PLA Plastics Produced by 3D Printing," Engineering and Manufacturing Sciences 7, no 3 (2023): 152-159. https://doi.org/10.26701/ems.1290961

[23] Rahimah Abdul Hamid, Siti Nur Hidayah Husni, and Teruaki Ito, "Effect of Printing Orientation and Layer Thickness on Microstructure and Mechanical Properties of PLA Parts," Malaysian Journal on Composites Science and Manufacturing 8, no. 1 (2022): 11–23. https://doi.org/10.37934/mjcsm.8.1.1123

[24] Zaman, Haydar, "Physico-Mechanical Behaviors of Chemically Treated Natural Fibers Reinforced Hybrid Polypropylene Composites," Malaysian Journal on Composites Science and Manufacturing 15, no 1 (2024): 25–40. https://doi.org/10.37934/mjcsm.15.1.2540