Bachelor’s Thesis

The Influence of Recycling on the Tensile Properties of PLA Variants through Fused Granule Fabrication and Injection Molding Processes.

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Abstract:

This study looks at how the recycling sequence and processing method affect the mechanical characteristics of two commercially available PLA variants: injection moulding-grade PLA and CR-wood PLA. Recycled material was processed in various ways, including fused granule fabrication (FGF) and injection moulding. Six configurations were created and tensile tested to determine stiffness, yield strength, and strain at break. The CR-wood PLA was recycled twice, with shredding and reprinting between cycles, whereas the injection moulding-grade PLA was recycled only once. The results showed that moulded samples consistently had higher stiffness and yield strength than printed samples, and that performance declined when the final processing step was printing. The best strain at break was found in printed virgin material, while the worst was discovered in twice-processed printed CR-wood PLA. Secondary factors such as moisture retention, granule size, and infill percentage were found to have a significant impact on the results. The study confirms that processing order is critical in maintaining mechanical reliability in recycled PLA and emphasizes the difficulties of structural reuse with low-pressure printing methods.

Keywords:

PLA recycling, fused granule fabrication, injection moulding, mechanical properties, Young's modulus, yield strength, strain at break, wood-filled PLA, processing sequence, and strain-rate sensitivity

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1 Introduction

1.1 Background

Additive manufacturing (AM) allows you to create complex geometries while saving material, energy, and time. Among the various AM methods, fused filament fabrication (FFF) and fused granule fabrication (FGF) are among the most popular due to their low cost and material versatility. FFF uses thermoplastic filaments, whereas FGF allows use of granules, virgin or recycled, making it an ideal processing method for circular economy models (Mohammad et al., 2022; Mele et al., 2023).

Mechanical recycling of thermoplastics such as PLA through shredding, melting, and reprocessing is often the most practical option. Agbakoba et al. (2023) found significant reductions in tensile strength and ductility in 3D printed PLA after three recycling loops. Romani et al. (2024) discovered that repeated recycling resulted in increased molecular chain scission and a corresponding loss in crystallinity. Proper drying and processing are crucial for maintaining PLA's mechanical performance, particularly in open systems (Cruz-Sánchez et al., 2023; Stoclet et al., 2014).

Despite its potential, FGF has not been studied as thoroughly as FFF. Chien et al. (2024) investigated wood-PLA printed with FFF discovered mechanical decline of around 20% after one recycling step in wood-based PLA. Al Nabhani et al. (2023) compared virgin and FGF-recycled PLA, finding measurable stiffness loss even after one reprocessing. Few studies have been conducted to compare systems that combine FGF and injection moulding.

PLA performance is also influenced by material composition, processing method, infill percentage, and orientation (Anderson et al., 2023; Springer, 2024; Kundurthi et al., 2023). Due to filler-matrix interactions and uneven dispersion, wood-filled PLA fractures more inconsistently than standard PLA (Romani et al., 2024; Chien et al., 2024). Kundurthi et al. (2023) demonstrated that bead geometry in extruded parts introduces localized weaknesses. As a result, direct comparisons of material types and processing routes are required under consistent testing conditions. This study employs a controlled setup to examine six PLA configurations processed using FGF and/or injection moulding, as well as to measure their mechanical behaviour after recycling.

1.2 Research problem

Many studies concentrate on FFF or injection moulding separately, with only a few comparisons across various recycling processes. Although PLA is known to degrade after multiple cycles, current research focuses on filament-based setups with limited variation in process routes or material grades (Agbakoba et al., 2023; Cruz-Sánchez et al., 2023). Furthermore, comparative studies that combine FGF, injection moulding, and various types of PLA in a single experiment are extremely rare (Chien et al., 2024; Al Nabhani et al., 2023).

Another gap in the literature is the lack of comparative testing of wood-filled and moulding-grade PLA under identical mechanical conditions. Wood-filled PLA has been shown to be unpredictable during recycling due to void formation and poor filler dispersion (Romani et al., 2024; Chien et al., 2024), whereas moulding-grade PLA is expected to perform more consistently under controlled conditions (Anderson et al., 2023).

Some of these studies have investigated hybrid process paths such as FGF followed by moulding or vice versa. Studies typically isolate only one method, making it difficult to understand how the entire process chain influences mechanical reliability. This makes it difficult to define an optimal recycling route for real-world applications.

This thesis fills these gaps by comparing six PLA configurations involving wood-filled and moulding-grade variants processed using various recycling sequences. Each sample group is subjected to identical tensile testing procedures, allowing for direct comparisons of mechanical properties such as stiffness, strength, and ductility.

1.3 Objectives

The goal of this thesis is to examine how the recycling sequence, material type, and final processing method affect the mechanical performance of PLA. Six distinct configurations are tested with wood-filled and injection moulding-grade PLA, each routed through a unique combination of FGF and injection moulding. The emphasis is on evaluating tensile properties such as Young's modulus, yield strength, and strain at break under controlled testing conditions.

The goal is not only to compare FGF and moulding routes, but also to see how the order of processes (e.g., FGF then injection moulding versus moulding then FGF) affects performance. All samples are prepared with standardized geometries, drying protocols, and stress-strain testing setups.

1.4 Research Questions

This study is guided by the following research questions:

1. How do mechanical properties like Young's modulus, yield strength, and strain at break differ between different PLA types (wood-filled and moulding-grade) and recycling methods like FGF and injection moulding?

2. How do these mechanical properties change depending on the final processing method (FGF vs. injection moulding)?

3. Can variations in performance among the six tested configurations be linked to process-specific limitations such as void formation or interlayer bonding?

2 Literature Review

2.1 Recyclability and Material Degradation

PLA is recyclable through mechanical means such as shredding and reprocessing, but its mechanical properties deteriorate over time. According to several studies, if the material isn't adequately dried before reuse, the first one or two cycles already result in appreciable decreases in tensile strength and ductility (Agbakoba et al., 2023; Anderson et al., 2023; Cruz-Sánchez et al., 2023). Stiffness, on the other hand, appears to be relatively stable at first, though some results differ depending on the method. Romani et al. (2024) observed modulus loss after multiple pellet-based reprocessing steps, whereas Anderson et al. (2023) and Cruz-Sánchez et al. (2023) reported minimal modulus change after one or two filament cycles.

The type of PLA also plays an important role. Standard PLA behaves more predictably during recycling, with gradual elongation and strength losses, whereas wood-filled PLA appears to fail much faster, even after one loop. Chien et al. (2024) observed a 20% decrease in tensile strength with wood-filled PLA after one FFF cycle, and the fracture surfaces were rough and brittle. Their micrographs revealed internal voids, most likely caused by poor fibre-matrix adhesion. That pattern was also suggested by Romani et al. (2024), who observed unpredictable embrittlement in mixed formulations after several melt cycles.

There also appears to be some disagreement over the importance of crystallinity and chain scission. Romani et al. claimed that chain scission and reduced crystallinity were the primary causes of mechanical decline, particularly after 3-5 melt cycles. However, Agbakoba et al. (2023) and Anderson et al. (2023) focused more on interlayer bonding issues and surface quality, particularly in FFF-based recycling. They discovered that, even if the core material was acceptable, poor adhesion between printed layers made parts weaker in practice.

Taken together, PLA degrades during recycling, but the severity varies depending on how it is processed, how many times it is recycled, and the type of PLA used. Moisture, printing orientation, and filler content all influence whether modulus, strength, or ductility are affected most. This thesis tests both wood-filled and moulding-grade PLA under controlled conditions to compare their differences, particularly between FGF and injection moulding setups.

2.2 Processing Routes and their Effects

Mohammed et al. (2022) studied the performance of recycled polymers in FGF printing. They discovered that after several reprocessing cycles, the granule size became more inconsistent, resulting in uneven extrusion flow. Their tests revealed that these irregularities caused variations in bead thickness and reduced dimensional precision. This highlights a significant challenge in FGF setups: granule shape and flow behaviour have a direct impact on print quality, particularly when reprocessing recycled PLA.

Kundurthi et al. (2023) investigated how bead geometry in material extrusion systems can serve as stress concentration points. Their research demonstrated that the mechanical strength of printed parts could be considerably impacted by even small variations in the bead cross-section.

They concluded that weak inter-bead fusion zones are frequently the first to fail under tensile loading, particularly in recycled samples where extrusion is not as precise.

Anderson et al. (2023) studied FFF-processed PLA and discovered that after one or two recycling cycles, layer bonding deteriorated, even on visually smooth surfaces. This was particularly evident in strain at break values, which decreased faster than modulus. They discovered that the recycled filament had slight diameter inconsistencies, resulting in uneven extrusion pressure and reduced bonding strength across layers.

Mele et al. (2023) used Arburg Plastic Freeforming, a pellet-based system with a feed mechanism like the FGF, and discovered that blending virgin and recycled PLA reduced viscosity loss while improving mechanical performance. Their findings indicated that pure recycled PLA caused void formation and decreased fracture toughness, but these effects could be mitigated through processing control and material mixing.

Romani et al. (2024) discovered that even with uniform pellets, structural consistency was not guaranteed. Their large-format prints made from multi-cycle recycled PLA showed internal voids and inconsistent fusion, particularly when previous drying was skipped. Mechanical results varied significantly between prints, despite similar input material, indicating that processing history and temperature control are critical to reproducibility.

Chien et al. (2024) discovered that wood-filled PLA printed with FFF exhibited internal delamination and poor layer bonding even after only one cycle. They attributed this to the presence of large wood particles that interfere with bead fusion, and they hypothesized that this effect worsens after shredding and re-extrusion due to fibre misalignment and inconsistent feed.

In conclusion, the extrusion geometry, drying conditions, material purity, and processing technique all have a significant impact on the structural consistency of PLA recycling. FGF systems are especially sensitive to granule shape and thermal control, whereas injection moulding is more uniform but still prone to moisture-related defects. These issues are exacerbated by wood-filled PLA due to poor fibre dispersion and filler-related stress concentrations.

2.3 Influence of PLA Type on Mechanical Degradation due to Recycling

According to Agbakoba et al. (2023) and Cruz-Sánchez et al. (2023), standard 3D printing PLA typically exhibits a gradual loss of strain at break and a drop in strength, particularly after the second or third cycles. If it is dried and processed properly, modulus remains relatively stable early on, though surface quality and layer adhesion can degrade.

Wood-filled PLA is much more difficult to work with. Mechanical performance due to recycling is inconsistent, and even a single recycling loop can result in significant reductions in strength or fracture energy. When Chien et al. (2024) tested FFF-printed wood-PLA samples, they discovered uneven failure surfaces and noticeably more brittle parts. The presence of wood fibres causes poor bonding within the material, particularly after reprocessing, and filler clumping can cause internal voids (Romani et al., 2024).

Then there's injection moulding-grade PLA, which is more crystallized and designed for high-pressure applications. Al Nabhani et al. (2023) and Mele et al. (2023) demonstrated that this type of PLA performs better after one or two cycles, with higher modulus and lower strength losses than standard PLA. However, even this grade degrades when exposed to moisture or processed excessively, albeit more slowly. Romani et al. (2024) found that even in higher-grade materials, crystallinity decreases after a few melt cycles, and embrittlement occurs eventually.

Therefor, filler content and resin type are very important. Wood-filled PLA fails faster and less predictably, whereas injection moulding-grade PLA is more resistant to changes but not immune. This thesis directly compares both to determine whether the differences in performance are due to the material or the order of the processing steps.

2.4 Previous Studies' Incompatibility in Material and Processes

Although there has been a lot of research into recycled PLA, the results are difficult to compare between papers. One of the major issues is that different studies use different recycling methods, PLA grades, and sample geometries, making it difficult to compare what is causing changes in mechanical properties. Some studies use filament-based PLA, others use pellet extrusion, and a few combines injection and compression moulding (Romani et al., 2024; Chien et al., 2024; Mele et al., 2023). Even when the same procedure is followed, the strain rate during tensile testing is frequently not reported or varies from one research to another, rendering stiffness or yield strength comparisons nearly meaningless.

Romani et al. (2024) tested pellet-based PLA's tensile strength using rectangular dog bone samples, whereas Anderson et al. (2023) printed ASTM D638 samples from recycled filament. These differences may appear to be minor, but they have an impact on fracture behaviour and elongation results. Furthermore, some researchers test one or two cycles, whereas others test up to five. This alters the degradation trajectory completely. Cruz-Sánchez et al. (2023) found a small drop in performance after one cycle, whereas Agbakoba et al. (2023) found a much steeper decline after the second cycle. However, the materials, machines, and drying protocols were not identical.

Another inconsistency exists in drying and thermal history. Some studies dry the PLA at 50°C, while others skip it entirely, which drastically alters how brittle the reprocessed parts are. Kundurthi et al. (2023) demonstrated that even minor defects in bead geometry cause local failure points; however, their findings are based on uniform drying and low-moisture feedstock. This isn't always the case elsewhere.

All of this makes it difficult to draw valid conclusions or establish benchmarks. That is one of the reasons why this thesis employs consistent processing conditions, geometries, and testing setups across all material types and cycles. It enables a more accurate comparison of how different configurations behave, not just theoretically, but also in a repeatable manner.

3 Method

3.1 Materials

This study used two widely available PLA variants to investigate how material type influences mechanical performance across various recycling routes. The first material was Creality's CR-wood filament, which is a wood-filled PLA. The filament is a combination of PLA and a natural wood-based filler that is widely used in consumer-grade Fused Deposition Modelling (FDM) printing applications. While the manufacturer does not specify the exact filler percentage or wood species, studies have shown that similar materials exhibit increased brittleness and processing disparities after re-extrusion (Chien et al., 2024; Romani et al., 2024). Based on preliminary testing and shredding behaviour, this filament was found to break irregularly and form longer granules than standard PLA, potentially affecting feeding consistency in FGF applications.

Figure 1. Beads of Ingeo 4043D.

The second material used was NatureWorks' Ingeo 4043D, a pure PLA resin. This injection moulding-grade PLA is commonly used in pellet form and is engineered for consistent melt flow and dimensional control in the FGF. Mele et al. (2023) and Al Nabhani et al. (2023) investigated the performance of Ingeo-based PLA grades in reprocessing and discovered that they maintained mechanical properties better than filled or lower-grade substitutes when processed under controlled conditions.

The selection of both materials allowed for a clear comparison between a pure PLA with optimized properties (Ingeo 4043D) and a filler-loaded PLA with slightly more unpredictable behaviour (CR-wood). This distinction enables a controlled investigation of how material type influences mechanical degradation in various recycling and manufacturing workflows.

3.2 Experimental Workflow

This study examined six different processing configurations using two PLA materials: wood-filled PLA filament and injection moulding-grade PLA granules. Each configuration had a distinctive sequence that involved FGF printing, injection moulding, or both. The goal was to determine how material type and processing order affected mechanical performance after recycling.

Figures 4 and 5 show the processing routes for both materials. Each flowchart starts with the material and goes through the processing steps, with each colour representing a particular path.

The naming convention combines the material and processing type. "W" denotes wood-filled PLA, whereas "G" denotes injection moulding PLA. The following letters indicate the processing sequence: "P" for FGF printing and "M" for injection moulding. For example, WPM refers to wood-filled PLA that was first printed and then moulded, whereas GM refers to injection moulding-grade PLA that was moulded directly. This naming convention is used consistently throughout the analysis and results tables.

The wood-filled PLA filament was initially shredded five times with a Rapid GK1514 granulator. These repeated shredding cycles were carried out on the material to improve granule uniformity before printing or injection moulding. Early shredding cycles missed long, curled strands and irregular chunks. By the fifth pass, the shredder delivered more uniformly cut fragments with shorter lengths and less tangling, making them better suited for feeding into the FGF system through the printer hopper.

Figure 2. Photograph of the RapidGK1514 shredder.

The shredded material was then divided into two different batches. The first batch of granules were first printed with the FGF; which was either printed into ISO standard specimens and mechanically tested, or rectangular prisms with dimensions of 100 by 40 by 4 millimetres and then re-shredded and moulded. In the second batch, the material was injection moulded, and similarly, either directly tested or shredded and printed with the FGF. These four workflows were chosen to investigate whether completing the process with the FGF or moulding would better preserve mechanical properties. Prior research lacks clear comparisons between these two recycling orders under identical conditions, especially for wood-filled composites. This setup enabled direct evaluation of the final-stage impact while maintaining consistent material origins and intermediate steps.

The injection moulding-grade PLA (Ingeo 4043D) was delivered in uniform pellet form and therefor required no shredding. It was divided into only two groups: one was directly moulded, and the other was printed with FGF. Both groups were dried for three hours at 80°C before processing. In contrast, drying was applied inconsistently to the wood-filled samples, depending on the timing and route; WP, GP were dried before being printed and GM, WPM and WM were dried before the injection moulding, while WMP was dried before injection moulding, its first process, not its final. Moisture control is especially important for PLA, as even trace humidity can cause chain scission during melt processing, affecting tensile strength (Södergård & Stolt, 2002). The ISO 527-2:2025 standard emphasizes the importance of reporting any deviations from standard pre-conditioning, which is reflected in the way drying inconsistencies are documented in this study.

Cross-contamination between batches was reduced by manually cleaning the shredder and using visible colour differences to identify residue from previous cycles. However, due to similar tones in some batches, complete separation could not be guaranteed.

Figure 3. Photograph of the shredded wood-based, recycled PLA.

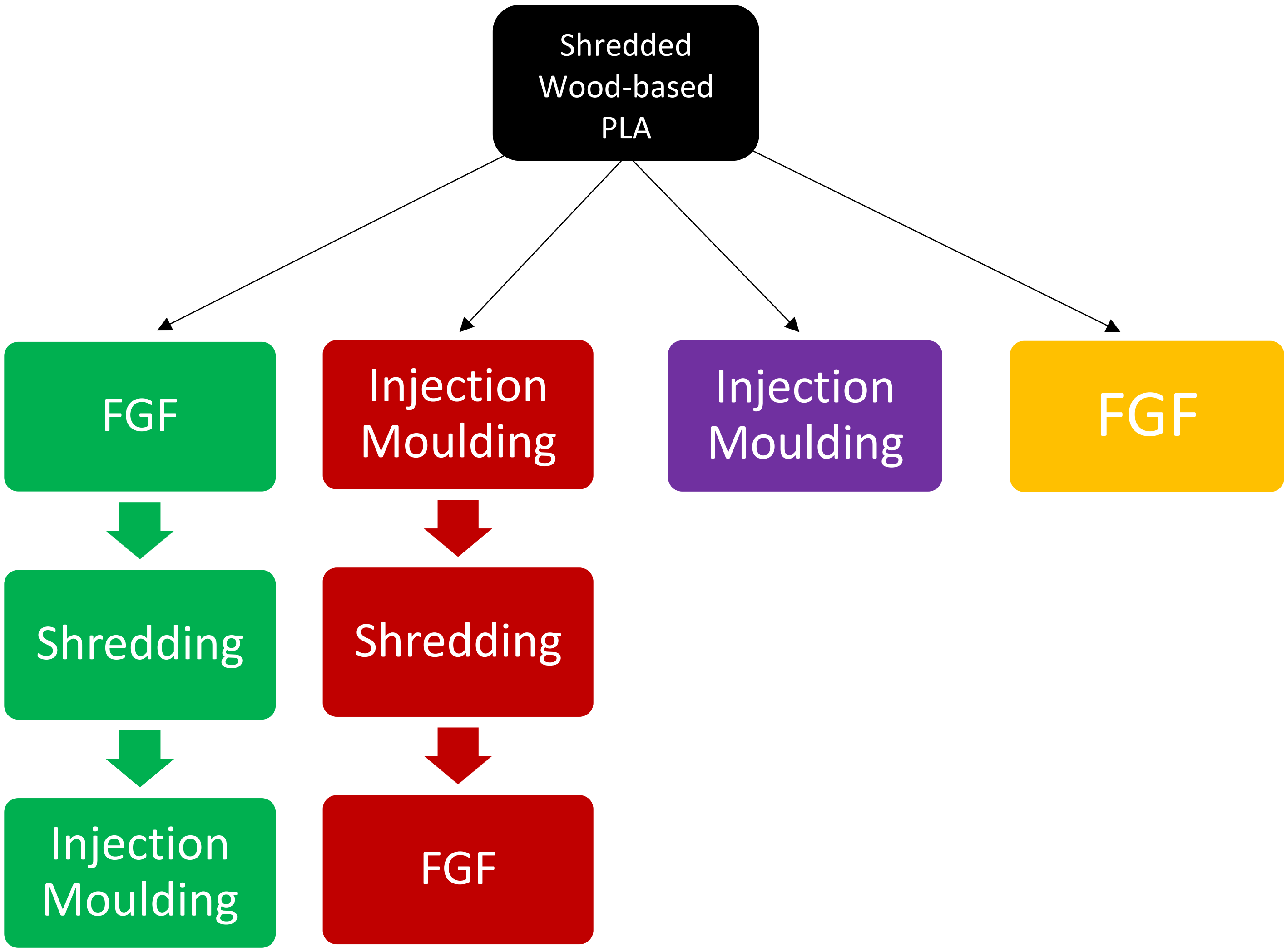

Figure 4. Flowchart of wood-based PLA.

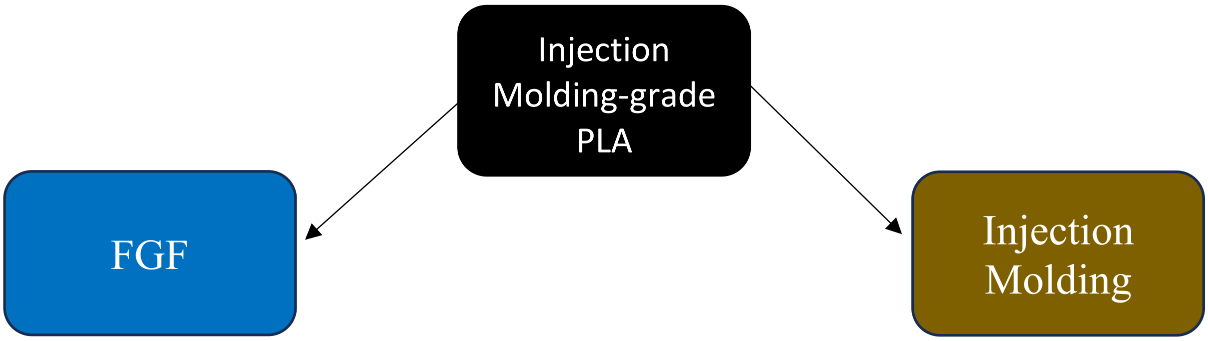

Figure 4. Flowchart of Ingeo 4043D PLA.

3.3 Sample Preparation

Following recycling and processing, all six material configurations were ready for tensile testing. The goal was to maintain consistent sample geometry while preserving differences resulting from each workflow. This section is based on ISO 527-2:2025 guidelines, which define thermoplastic testing conditions and specimen requirements.

A two-plate mould system was used to create dog bone-shaped samples for the injection moulded groups. All moulded specimens used the same nozzle temperature, injection pressure, and cooling time, as shown in Table 2. These values were chosen based on how the results formed and remained constant across all the batches. Table 1 is from the technical data sheet and was used as guidance. Samples were demolded and defect-checked before being stored in sealed and labelled containers.

The Piocreat G5 printer was used as the FGF. Groups such as GP and WMP, which were only processed through printing, or had a last processing step through the FGF, were printed in dog bone shape and tested without further modification. For groups such as WPM, which were printed before moulding, rectangular prints were first created, then shredded, and the resulting granules were processed in the injection moulding.

The injection moulded samples had standard dog bone geometry, with inaccurately moulded specimens being discarded. The test region had final dimensions of 110 mm gauge length, 12.75 mm width, and 3 mm thickness, yielding a cross-sectional area of 38.25 mm^2. These values were used consistently throughout all data processing, as described in Section 3.4. While not exact ISO 527-2:2025 Type 1A specimens, which require 75 mm gauge length and 10 mm width, these dimensions are within the tolerances for general-purpose tensile testing. The modified geometry was chosen to match the mould dimensions available in the lab while also ensuring consistency across the recycled material groups.

All final specimens, whether printed or moulded, had a consistent target geometry. For printed rectangles during the intermediate stage, the dimensions were 100 mm long, 40 mm wide, and 4 mm thick.

Each sample was labelled with its processing route (e.g., WP, GM, or WPM) and stored in sealed containers to prevent moisture absorption prior to mechanical testing. Storage conditions were kept at room temperature with low humidity, and all groups' samples were tested within 24 hours of being prepared.

Table 1. Technical Data Sheet for PLA use in injection molding. (NatureWorks)

Processing Temperature Profile (In Degrees Celsius)	
Melt Temperature	210
Feed Throat	45
Feed Temperature	180
Compression Section	190
Nozzle	200

Table 2. Injection molding parameters used.

Processing Temperatures Used (in Degrees Celsius)	
Feed	45
Zone 1	180
Zone 2	190
Zone 3	200
Nozzle	200

3.4 Mechanical Testing

Tensile testing was performed using a Testometric X350-20 universal testing machine. Each sample was clamped and pulled under uniaxial tension until fractured. The goal was to determine three important mechanical properties: Young's modulus, yield strength, and strain at break.

The raw data from each test included force (N), extension (mm), and time (s). These were exported as CSV files and then manually processed in Excel. A fixed gauge length of 110 mm, based on crosshead extension, was used to calculate strain, and a cross-sectional area of 38.25 mm^2 (12.75 mm width × 3 mm thickness) was used to calculate stress.

To ensure consistency, all curves were manually cleaned prior to analysis. Values less than 20 N were removed to eliminate machine slack and initial seating effects. Each curve was then trimmed at the point of fracture, which is indicated by a visible vertical line in the stress-strain graph.

For each configuration, 7 to 8 samples were tested. From these, the five most consistent curves were chosen for further investigation. Young's modulus was calculated using the slope of the visible linear region near the beginning of each stress-strain curve. ISO 527-2:2025 recommends determining modulus between 0.0005 and 0.0025 strain for thermoplastics; this study used a manually selected range to match the linear, elastic portion of each curve (International Organization for Standardization, 2025). The slope was then calculated using Excel, and the resulting modulus values were saved in a separate column for comparison.

ISO 527-2:2025 (International Organization for Standardization, 2025) defines yield strength as the stress at the beginning of the yield plateau for materials with a distinct yield point.
There were no secondary peaks observed in the plastic region, so no distinction was made between yield strength and ultimate tensile strength. Strain at break was calculated as the final strain value just before the load dropped.

One sample from the GP group was tested at 5 mm/min, whereas all other tests were done at 10 mm/min. This outlier was removed from the group averages, but it is discussed in Section 5.3 to demonstrate PLA's sensitivity to strain rate.

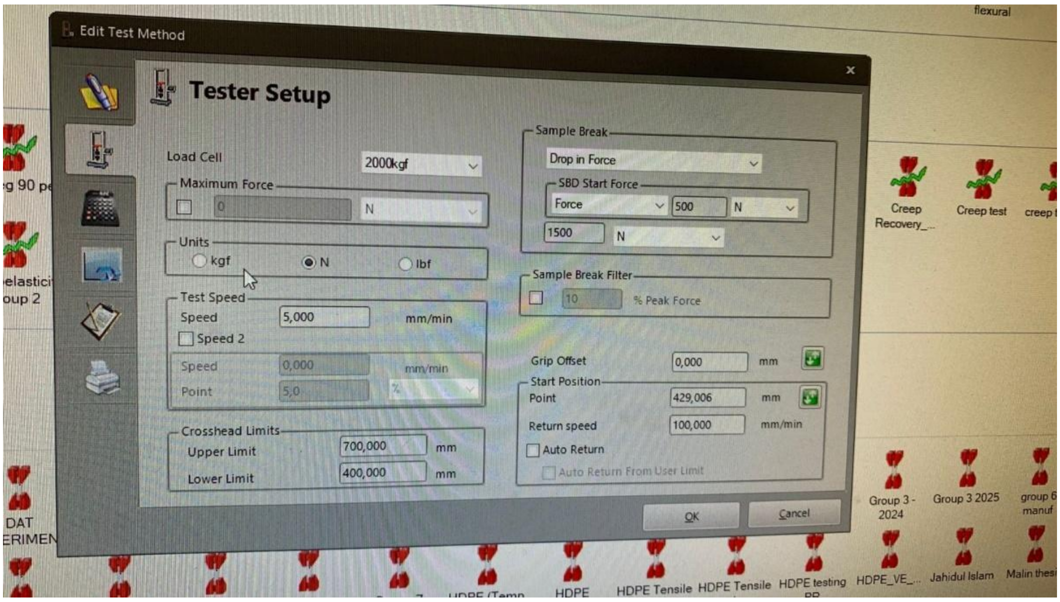

Figure 6. Testing parameters used for the first sample.

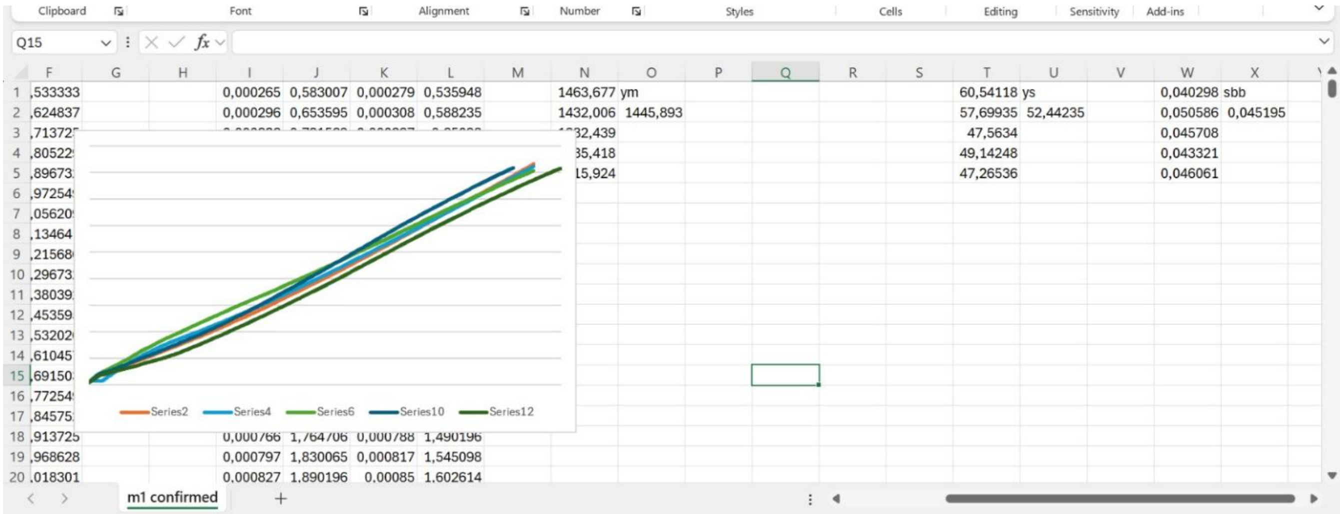

Figure 7. Processing of data via excel.

4 Results

This section presents the mechanical properties of the six tested PLA configurations. These include Young's modulus, yield strength, and strain at break, which are derived from each sample's cleaned stress-strain curve. The calculations were performed using five valid test samples per group. The results are presented in both table and visual form, with a brief description of the stress-strain curves to provide insight into the material's response under load.

Representative stress-strain curves revealed significant differences in material stiffness, plasticity, and fracture behaviour. The GM and WPM groups had steep initial slopes and relatively sharp failure points, indicating increased stiffness and brittle fracture. In contrast, GP and WM demonstrated more gradual slopes with extended strain before failure, particularly in the GP group, which exhibited the most ductile behaviour. WMP and WP showed early slope flattening and irregular fracture behaviour, as well as decreased elasticity and poor interlayer adhesion.

Table 3 presents the average mechanical properties for all material configurations. Young's modulus values were calculated from the visibly linear portion of the elastic region near the beginning of each curve, using slope extraction from manually cleaned data. Yield strength was recorded as the highest stress reached before failure. Strain at break was taken from the final strain value just before the force dropped, indicating fracture. The raw force-extension data was converted into stress–strain form using a cross-sectional area of 38.25 mm² and a gauge length of 110 mm.

Table 3. Results summarized.

	Young's Modulus (MPa)	Yield Strength (MPa)	Strain at Break (%)
WP	1058.62	23.11	3.27
WPM	1445.89	52.44	4.52
WM	1382.48	46.65	4.65
WMP	1024.95	23.17	2.90
GP	1181.94	64.75	5.69
GM	1795.03	71.34	4.97

Figures 14, 15, and 16 depicts a bar chart comparing the average Young's modulus, yield strength, and strain at break, respectively, for the six material configurations. Figures 8–13 show the stress-strain curves for each group individually, with five test curves per graph. These plots are not intended to be visually scaled against one another; rather, each graph represents only the internal variation within that specific material configuration.

Some curves have a distinct linear elastic region, whereas others exhibit early curvature or plateauing. Nonetheless, Young's modulus was calculated using the same linear approximation method across all samples. This was done to ensure methodological consistency and alignment with ISO-based tensile evaluation methods, even when the initial elastic region was less well defined.

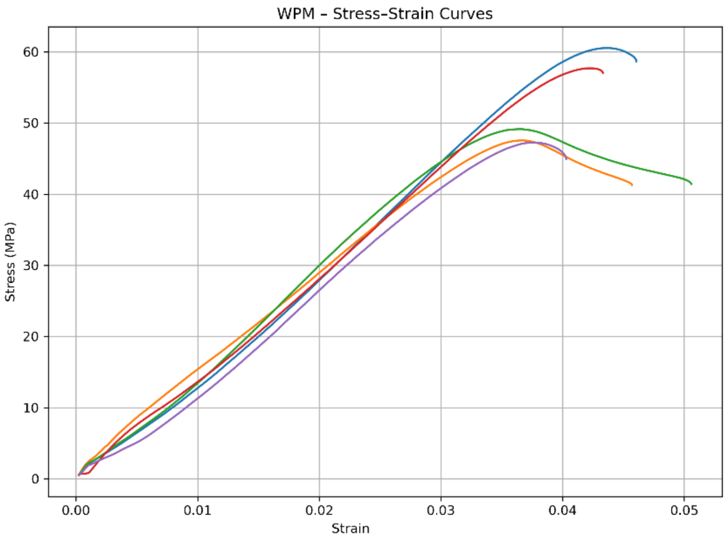

Figure 8. Graph for WPM.

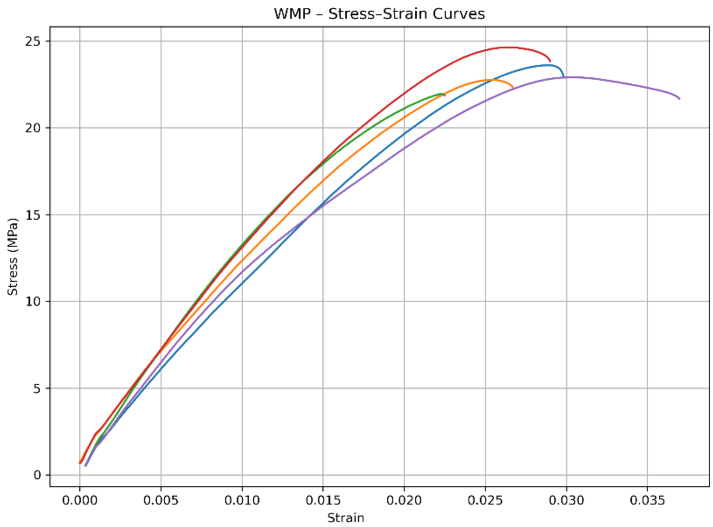

Figure 9. Graph for WMP.

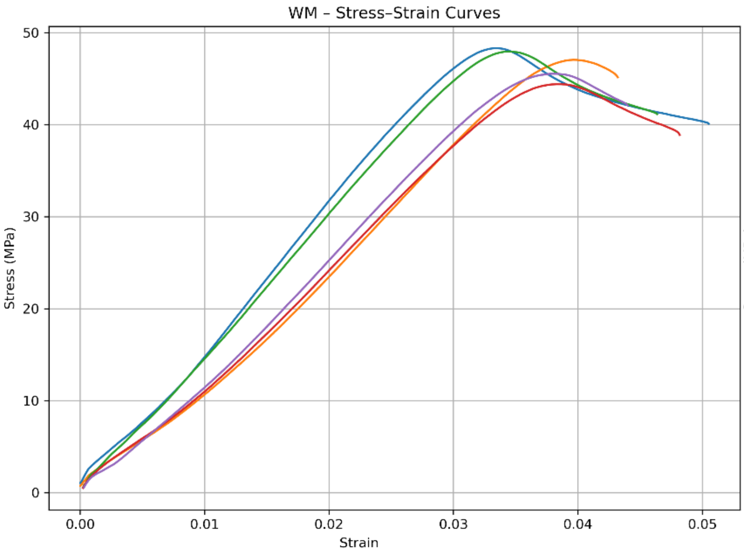

Figure 10. Graph for WM.

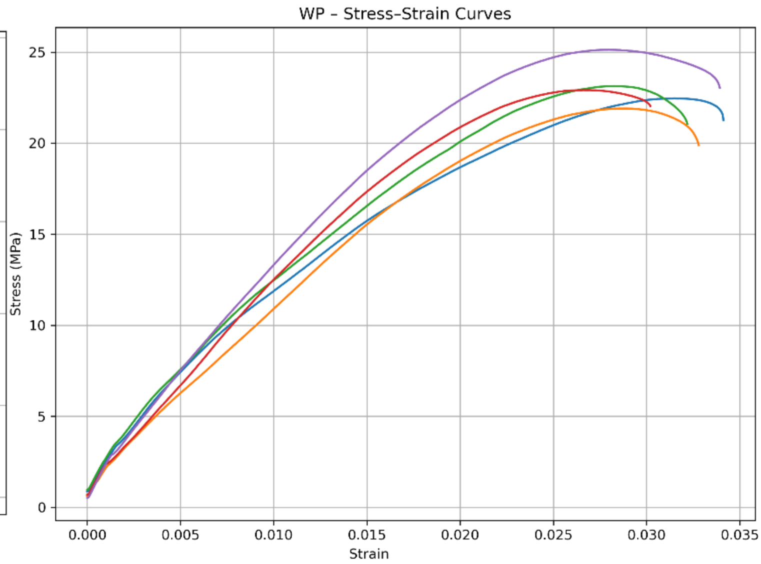

Figure 11. Graph for WP.

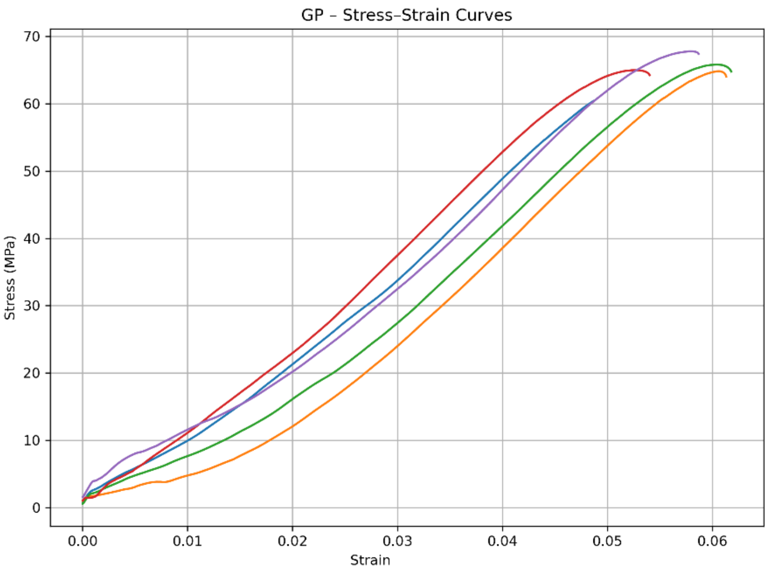

Figure 12. Graph for GP.

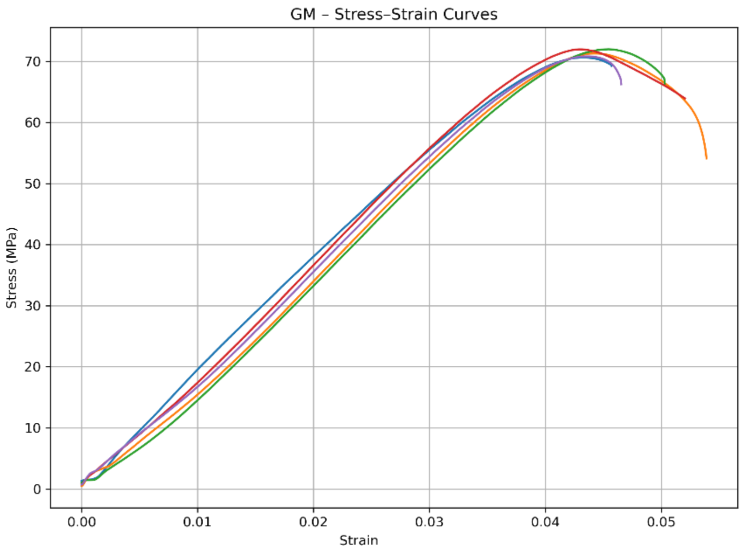

Figure 13. Graph for GM.

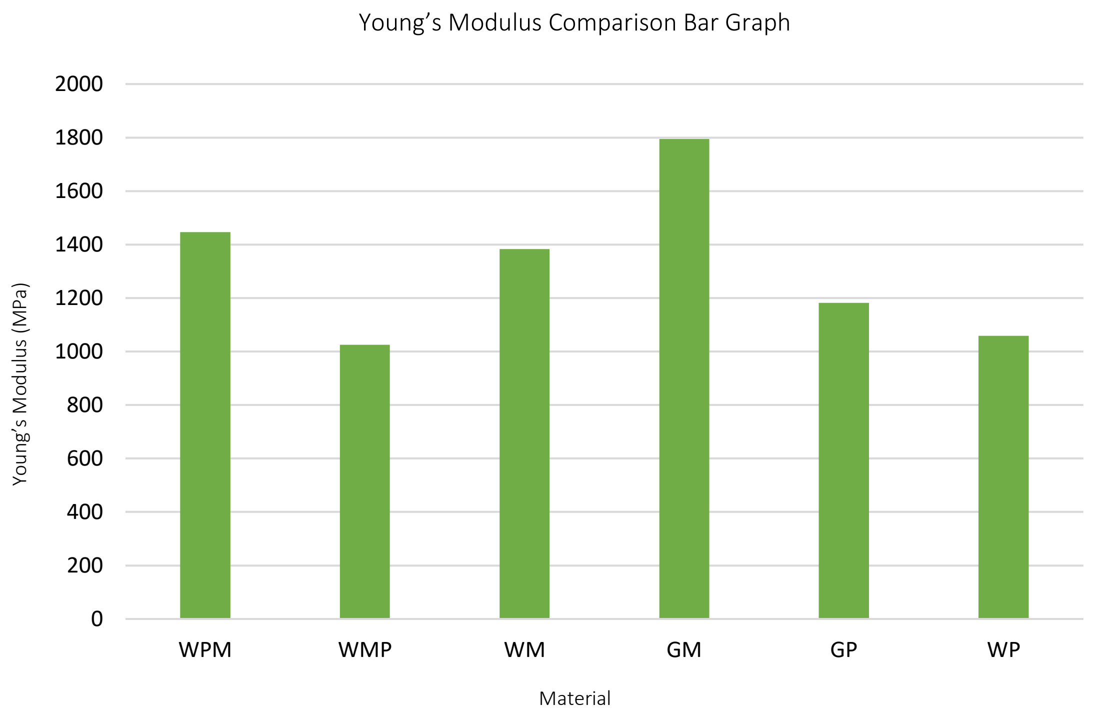

Figure 14. Young's Modulus.

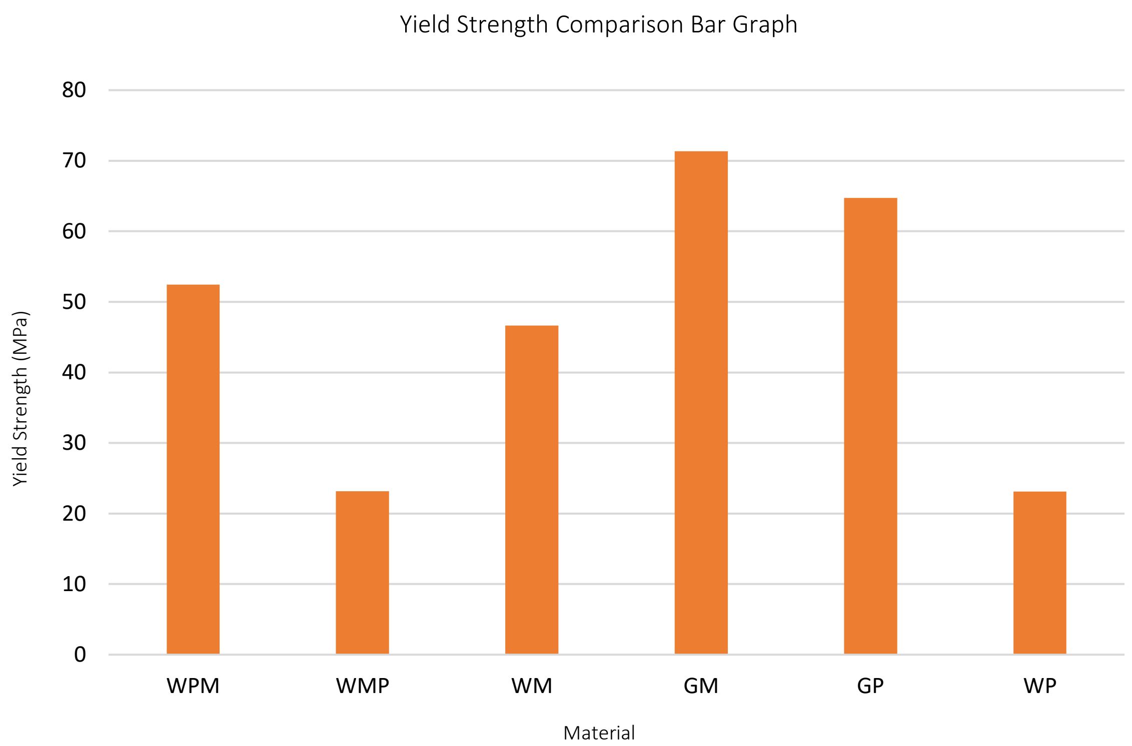

Figure 15. Yield Strength.

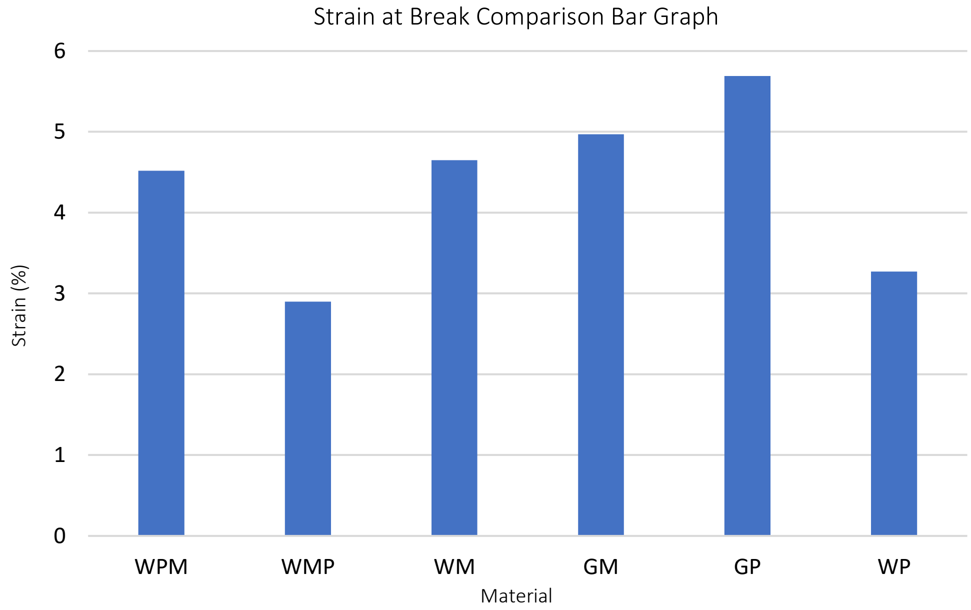

Figure 16. Strain at Break.

The GM configuration outperformed all others in stiffness and strength, confirming the benefits of using virgin-grade granules and controlled molding. GP, although lower in stiffness, had the highest ductility, showing that printing reduces rigidity but allows for greater elongation. Among wood-filled PLA groups, WPM showed stronger performance than WP or WMP, suggesting that finishing with molding is more effective for structural recovery. WMP, which was printed after being molded, showed the lowest values across all metrics, likely due to compounded degradation and void formation.

Fracture behaviour varied depending on configuration. Injection moulded samples typically fracture along smooth, continuous lines. Samples that were printed showed stepped break surfaces and sporadic indications of delamination between print layers, especially WP and WMP.

These findings are consistent with previous research, particularly Anderson et al. (2023) and Romani et al. (2024), who found similar trends in mechanical decline across reprocessing cycles. The findings highlight how processing order and filler content influence the mechanical reliability of recycled PLA.

5 Discussion

5.1 Comparison of Mechanical Behaviours

5.1.1 Young’s Modulus

The stiffness of the tested materials, as measured by Young's modulus, varied significantly depending on both the material type and the final processing method. Moulded samples were consistently stiffer than their printed counterparts, with GM having the highest value across all configurations. This outcome is in line with research by Romani et al. (2024), who found that compression-based processing, like injection moulding, increases stiffness by enhancing molecular packing and decreasing internal voids. The higher modulus in WPM compared to WMP and WP suggests that finishing the recycling loop with injection moulding consolidates the material more effectively than printing. These findings are supported by Agbakoba et al. (2023), who discovered that early-stage recycling did not significantly reduce stiffness when moulding was used as the final processing step.

In contrast, printed configurations, such as WMP and WP, had significantly lower modulus values, which can be attributed to poor interlayer bonding and inconsistent extrusion. Kundurthi et al. (2023) showed how bead geometry variation and surface roughness during FGF can result in stress concentration points that reduce overall stiffness. The use of shredded CR-wood filament in WP and WMP resulted in granules with longer average lengths (~6.65 mm), potentially disrupting flow and uniformity during printing. According to Mohammed et al. (2022), irregular particle shapes in recycled feedstock can reduce print consistency and mechanical response, especially in stiffness-dominant regimes.

5.1.2 Yield Strength

Yield strength results followed similar trends, with the moulded groups outperforming their printed counterparts. The GM configuration demonstrated the greatest strength, followed by WPM and WM. These findings reflect the superior cohesion and low internal flaw content that are typical of moulded parts. Anderson et al. (2023) found similar differences between virgin PLA processed via moulding and printing, attributing strength retention to more complete fusion and a narrower thermal history. In this study, WPM maintained much of its yield performance even after one FGF cycle, most likely due to consolidation during the final moulding stage.

The lowest yield strength values were found in WMP and WP. These configurations went through two stages of thermal processing before being printed, which most likely resulted in thermal degradation and poor interlayer adhesion. Chien et al. (2024) found similar results when recycling wood-PLA composites, noting that thermal cycling, combined with uneven filler dispersion, caused premature failure and brittle fracture. In the current study, WMP had low strength despite having been moulded, implying that re-extruding moulded material into printed form negated any previous structural benefit. This effect is consistent with Hasan et al. (2024), who demonstrated that repeated heating and filler buildup significantly reduce tensile strength by creating weak interfaces and disrupting polymer continuity.

5.1.3 Strain at break

The GP and WM groups had the highest strain at break, a measure of ductility, whereas the WMP and WP groups had the lowest elongation prior to failure. The ductile behavior of GP suggests that printing with virgin granules can result in relatively compliant structures when drying is adequate and extrusion is consistent. This group's reduced stiffness but enhanced elongation supports Stoclet et al. (2014)'s finding that slower deformation or a more uniform thermal history promotes strain-induced crystallization and chain alignment in PLA, increasing ductility.

In contrast, the low strain at break observed in WMP and WP suggests brittle failure and low energy absorption capacity. These configurations most likely suffered from moisture retention, weak interlayer bonding, and infill discontinuities, all of which have been shown to reduce ductility. Banks-Sills et al. (2016) demonstrated how poor interface quality in particle-filled polymers frequently results in reduced strain tolerance, particularly under tensile loading. Springer (2024) confirmed that using 80% diagonal infill in WMP and GP reduced internal continuity by linking infill density and pattern to PLA prints' ability to distribute tensile stress. The poor elongation performance observed in printed wood-PLA configurations is most likely due to a combination of degraded polymer chains, reduced infill, and inconsistent bonding.

5.2 Factors Influencing Mechanical Outcomes

The quality of fusion, thermal history, material degradation, and geometry all had a significant impact on the differences observed between configurations. Fused Granule Fabrication introduced inconsistencies such as irregular bead shapes and poor fusion between adjacent lines. These defects most likely included trapped air, edge gaps, and thin inter-bead contact areas, all of which reduced mechanical strength and stiffness. This finding is consistent with the analysis of bead-induced stress concentrations presented by Kundurthi et al. (2023). Moulding, on the other hand, exposed the material to higher pressure and consistent heating, resulting in improved interfacial adhesion and a more uniform internal structure (Romani et al., 2024).

Moisture played an important role in the mechanical outcomes. Not all configurations dried evenly, and some FGF prints were created without any pre-drying. PLA is known to degrade in the presence of moisture, particularly during thermal processing, because hydrolysis shortens molecular chains and reduces structural strength (Hasan et al., 2024). This is likely responsible for the lower strain at break in undried prints like WMP. Even among dried batches, timing and temperature control did not match, introducing additional variation between configurations (Mohammed et al., 2022).

The print infill percentage had an impact on the results as well. Intermediate prints were created using 100% infill, resulting in a dense internal structure. In contrast, final stage prints like WMP and GP used 80% infill in a diagonal pattern. While this method saves print time and material, it also results in internal voids and stress concentration sites. Springer (2024) showed that lower infill density weakens the internal load path and reduces the effective strength of PLA structures, particularly in tension. These discontinuities weaken structural continuity across the print, reducing stiffness and increasing the likelihood of delamination under tensile load.

Shredding consistency was another important consideration. The wood-filled PLA was manually shredded five times to improve granule uniformity. While early cycles produced long, curled strands, the fifth pass produced fragments at largest around 6.65 mm long, nearly double the 3.35 mm average length of commercial PLA granules. These larger, irregular granules may have created uneven flow during FGF printing, resulting in local variations in bead thickness. According to Al Nabhani et al. (2023), recycled PLA processed through FGF exhibits irregular flow paths and weak fusion zones due to granule size inconsistency, reducing mechanical performance in stiffness and strength.

5.3 Sources of Error

Contamination between batches was not completely avoided, despite cleaning the shredder between each material group. While colour differences between batches were used to visually track residue, full separation was not reliable because some groups, which have the same material, had the same colours. These undetected fragments could have served as stress concentrators or contributed to inconsistent specimens. This reflects the concerns expressed by Staplevan et al. (2024), who discovered that even minor contamination in bioplastics can reduce structural reliability due to interface instability. WPM may have been less contaminated because it was processed in a different order, allowing for re-shredding to reduce residual debris.

Drying conditions also differed due to limited equipment and time constraints. While some batches were dried at 80°C for three hours, others, particularly those printed before moulding, were not dried at all. This inconsistency most likely influenced the mechanical results, particularly moisture-sensitive properties such as yield strength and strain at break. It is well known that PLA is sensitive to residual moisture and that this sensitivity affects chain scission during thermal processing (Agbakoba et al., 2023; Hasan et al., 2024). Although exact moisture levels were not measured in this study, the brittle fractures observed in several undried prints support the hypothesis that drying differences had a significant impact.

Minor bias was introduced during testing by manually selecting only five of the most consistent curves for final analysis. While this method adheres to common small-sample practice in materials testing, it may have excluded valid but slightly irregular samples, skewing the reported average values. Anderson et al. (2023) noted that manual selection can underestimate mechanical variability in recycled polymers, especially when structural heterogeneity is high.

Figure 17. Cold drawing sample.

5.4 Impacts of Plan Adjustments

The original plan planned for testing three types of PLA: CR-wood filament, Hyper PLA, and injection moulding-grade PLA. Each was to go through several reprocessing cycles with both FGF and moulding methods. The study was narrowed to only CR-wood PLA and injection moulding-grade PLA, with two processing loops for each material. This change reduced the number of configurations while improving control and comparability between groups.

Focusing on fewer materials allowed for a more thorough examination of how the processing sequence affects mechanical outcomes. For example, comparing WMP and WPM showed that finishing with printing versus moulding has a significant impact on mechanical performance, even when the same base material is used. When evaluating recycled PLA in FGF systems, Al Nabhani et al. (2023) discovered similar results, observing that the final processing step had a strong influence on stiffness and yield strength regardless of prior history. In this study, limiting the comparison to only two material families resulted in more consistent recycling processes, thermal histories, and test geometries across groups.

The incorporation of CR-wood PLA offered important insight into the practical constraints of reprocessing filled materials, even though Hyper PLA was not included in the final testing phase. This revised scope ensured greater depth and technical reliability in the results. Romani et al. (2024) proposed reducing the number of experimental variables in studies involving recycled polymers in order to improve reproducibility and isolate the role of specific process factors. This logic guided the decision to simplify the plan, which helped to ensure the dataset's consistency.

5.5 Extension Rate Consistency and Cold Drawing

During tensile testing, one of the GP samples was unintentionally tested at a crosshead speed of 5 mm/min rather than 10 mm/min. This sample demonstrated significantly greater elongation and a more gradual decline in force after yielding than others in the same group. Despite being a single data point, its behaviour was noticeably different and closely resembled the effects reported in the literature on strain rate sensitivity in PLA.

This observation is consistent with the findings of Stoclet et al. (2014), who investigated the cold-drawing behaviour of PLA and discovered that lower strain rates promote chain alignment and strain-induced crystallization. These structural changes increase ductility while maintaining initial stiffness. The slow-tested sample's unique response in this study supports their findings and adds to the evidence that deformation speed has a significant influence on post-yield behaviour in PLA materials.

The anomalous nature of this result emphasizes the importance of using consistent test speeds when evaluating recycled polymers. In this case, the deviation provided an unexpected but valuable confirmation of PLA's known rate dependence. Future research should include controlled strain rate comparisons in the test matrix, particularly when characterizing recycled feedstocks that have already undergone molecular degradation.

5.6 Comparison With Recent Studies

The mechanical trends observed in this study are consistent with a large body of published research on recycled PLA. Multiple studies have shown a progressive decline in stiffness, strength, and ductility after mechanical recycling, especially when extrusion-based processes like FGF or FFF are used. Agbakoba et al. (2023) found significant reductions in tensile strength and strain at break after three recycling loops of filament-based PLA, which is consistent with the losses observed in WMP and WP. Similarly, Romani et al. (2024) emphasized the importance of chain scission and crystallinity loss during pellet-based reprocessing, which is consistent with the decreased stiffness and yield strength observed in both CR-wood and moulding-grade groups following extrusion.

Anderson et al. (2023) discovered a noticeable degradation in ductility and yield strength even after a single recycling cycle, highlighting the fragility of PLA's mechanical performance as thermal history accumulates. Their findings also support the notion that moulding-grade PLA retains superior strength when not reprinted. Chien et al. (2024) investigated recycled wood-PLA composites and discovered delamination, void formation, and inconsistent fracture surfaces, which are identical to the brittle fracture and poor strain-at-break results seen in WP and WMP.

Hasan et al. (2024) presented a broader review of the limitations of recycled PLA, confirming that both material composition and process order have a significant impact on structural properties, especially when fillers are added. Kundurthi et al. (2023) found that inconsistent bead geometry causes local stress concentrations and reduced load-bearing capacity in printed PLA parts. This explains some of the mechanical scatter observed in the WMP group, which featured irregular granules and poor print uniformity. Mohammed et al. (2022) also demonstrated how extrusion-based processes suffer from poor repeatability, especially when granule quality varies, which is confirmed here in the discussion of shredded vs. commercial granule consistency.

Staplevan et al. (2024) cautioned that even small amounts of bioplastic cross-contamination during recycling can jeopardize mechanical reliability. Although the current study did not include mixed polymers, the contamination risks between PLA batches, particularly WP and WMP, raise similar concerns. Finally, the rate-dependent behaviour observed in the single 5 mm/min sample from GP is consistent with the cold drawing and strain-induced crystallization mechanisms described by Stoclet et al. (2014), who linked slower deformation to increased ductility and energy absorption.

Overall, the results show that reprocessing PLA through multiple thermal and mechanical steps weakens its structural properties, especially when low-pressure extrusion routes such as FGF are used. However, they also demonstrate that careful drying, optimized infill, and moulding at the end of the recycling loop can help maintain mechanical reliability. The high level of agreement between this study and at least ten recent publications strengthen the findings' relevance and validity in the context of sustainable PLA reuse.

6 Conclusion

This study investigated the mechanical properties of recycled PLA variants processed using FGF and injection moulding. Six different processing configurations were used to test two different material types: wood-filled PLA and injection-moulded PLA. The goal was to determine how the processing route, recycling sequence, and material composition influence tensile properties like Young's modulus, yield strength, and strain at break.

The results clearly showed that the processing method is the most important factor in determining final mechanical performance. In terms of stiffness and strength, injection moulded configurations consistently outperformed FGF configurations. Among the wood-based samples, WPM (printed then moulded) had better mechanical properties than WMP (moulded then printed), indicating that finishing with moulding helps recover or preserve mechanical integrity more effectively. In all measured properties, GM obtained the highest values for the injection-moulded-grade PLA, confirming the benefits of using virgin-grade granules and carefully regulated moulding conditions.

The findings also highlight the importance of secondary factors like drying infill settings, contamination, and strain rate. Undried or inconsistently processed samples, particularly those containing wood-based PLA, demonstrated lower ductility and more brittle fracture behaviour. The 5 mm/min strain test confirmed PLA's strain-rate sensitivity, demonstrating that ductility increases significantly at slower deformation speeds.

Finally, the study shows that FGF is a good way to reprocess PLA, but its problems with layer adhesion and thermal uniformity need to be fixed to make the mechanical quality of moulded samples the same. Moisture, granule quality, and recycling sequence must be carefully controlled in any application that requires structural reliability.

Future research should focus on larger sample sizes, different material grades, and controlled environmental aging. Comparative testing using post-processing techniques might uncover new ways to stabilize performance in recycled PLA systems.

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Appendices