Preliminary Evaluation of Recycled-Virgin Polylactic Acid 3D Printing Waste from a University Makerspace: Processing and Tensile Response of Printed Specimens

Catherine Kirch, Samuel Estrada, Juan Pereira-Rojas, and Daniel Saloni *

*Corresponding author: desaloni@ncsu.edu

DOI: 10.15376/biores.22.1.205-219

GRAPHICAL ABSTRACT



Preliminary Evaluation of Recycled-Virgin Polylactic Acid 3D Printing Waste from a University Makerspace: Processing and Tensile Response of Printed Specimens

Catherine Kirch, Samuel Estrada, Juan Pereira-Rojas, and Daniel Saloni *

Fused filament fabrication (FFF) generates polylactic acid (PLA) waste that, in most cases, is sent to landfill. This study established a preliminary closed-loop recycling system and evaluated the tensile performance of filament produced from the recovered material. Waste PLA was ground in three passes using a benchtop shredder, blended with virgin PLA pellets at 20, 40, 60, and 80 wt.% recycled content, and extruded into 1.75 mm filament at 180 to 185 °C. Two specimens, based on Type I geometry described by ASTM D638, were printed and tested in tension alongside specimens made from commercial virgin filament and laboratory-extruded virgin filament. The extrusion step had an estimated material yield of approximately 91%. All recycled-content blends reached mean tensile strengths around 23.2 to 27.7 MPa compared to 23.5 MPa for commercial virgin PLA, with the 40 wt.% blend as the most promising, whereas laboratory-extruded virgin PLA had the lowest mean strength (18.1 MPa) and apparent tensile modulus (1.35 GPa). Recycled blends were also stiffer on average than either virgin control. Based on the evaluation, which involved two specimens per formulation, the proposed work establishes a first step for practical production of recycled–virgin PLA filaments from makerspace waste and identifies limitations relevant to reliable small-scale recycling.

DOI: 10.15376/biores.22.1.205-219

Keywords: Polylactic acid; 3D printing; Fused filament fabrication; Mechanical recycling; Circular economy; Tensile strength; Makerspace; Distributed recycling

*Contact information: Department of Forest Biomaterials, North Carolina State University, 431 Dan Allen Dr., Raleigh, NC 27695, United States; *Corresponding author: desaloni@ncsu.edu*

INTRODUCTION

Global plastics production has grown faster than almost any other manufactured material, and most of the plastic ever produced has not been recovered. Geyer *et al.* (2017) estimated that of the approximately 6300 Mt of plastic waste generated through 2015, only about 9% had been recycled and 12% incinerated, with the remaining 79% accumulated in landfills or the natural environment. Mechanical recycling is technically mature for several commodity polymers, but it is limited by contamination, mixed material streams, collection logistics, and the loss of properties that accompanies each reprocessing step (Hopewell *et al.* 2009). These limitations are especially acute for small, dispersed waste streams that fall outside municipal recycling programs.

The circular economy has emerged as a framework for addressing such problems by keeping materials in productive use for as long as possible, reducing dependence on virgin resources, and designing waste out of production systems (Ellen MacArthur Foundation 2013; Geissdoerfer *et al.* 2017). After analyzing 114 definitions of the concept,

Kirchherr *et al.* (2017) identified the reduce-reuse-recycle hierarchy and the pursuit of both environmental and economic value as common elements across the literature. To make the concept measurable, the Ellen MacArthur Foundation and Granta Design (2015) proposed the Material Circularity Indicator, which rewards products that use recycled feedstock and whose materials are recovered at end of use. In practical terms, a circular system benefits from short, well-defined loops in which the waste generator, the recycler, and the next user are located close together.

Polylactic acid (PLA) is an aliphatic thermoplastic polyester produced from lactic acid obtained by fermentation of renewable carbohydrate sources such as corn starch and sugarcane (Garlotta 2001; Auras *et al.* 2004). Its bio-based origin, compostability under industrial conditions, low processing temperature, and low warping tendency have made it the most widely used feedstock for desktop fused filament fabrication (FFF), also known as fused deposition modeling (Farah *et al.* 2016; Flynt 2017; Pereira-Rojas *et al.* 2026). PLA has a glass transition temperature of roughly 55 to 60 °C and a melting temperature of roughly 150 to 175 °C, depending on stereochemical purity and crystallinity, and injection-molded PLA typically exhibits tensile strengths on the order of 50 to 70 MPa (Garlotta 2001; Farah *et al.* 2016).

Because PLA is a thermoplastic, it can, in principle, be melted and reshaped repeatedly, making it a logical target for recycling. However, PLA is sensitive to hydrolysis and to thermo-mechanical degradation during melt processing. Residual moisture promotes chain scission at processing temperatures, reducing molecular weight and melt viscosity (Garlotta 2001; Auras *et al.* 2004). Valerga *et al.* (2018) showed that the storage and moisture condition of PLA filament measurably affects the dimensional and surface quality of FFF parts, underscoring the importance of drying for both virgin and recycled feedstocks.

The strength of an FFF part is governed not only by the polymer but also by the printing process. Printed parts are anisotropic and contain voids between deposited roads, so their strength depends strongly on layer height, raster orientation, number of perimeters, and infill density (Lanzotti *et al.* 2015). Consequently, printed PLA specimens generally exhibit lower tensile strength than molded specimens of the same material, and comparisons between feedstocks are meaningful only when printing parameters are held constant.

Although individual prints consume only small amounts of material, FFF produces a surprisingly large fraction of waste. Song and Telenko (2017) examined material use in a university FFF environment and found that a substantial share of the material consumed was lost to failed prints, prototypes, and support structures rather than retained in final parts. Common waste sources include failed or aborted prints, support structures and rafts, purge lines and excess material, and discarded iterations resulting from design errors. In a shared makerspace where printing is free to students, each user may generate only a modest amount of waste, but the aggregate stream accumulates rapidly across many users and printers. Because this waste is clean, polymer-specific, and generated at a known location, it is far better suited to recovery than mixed post-consumer plastic, provided that it is intercepted before it enters the general waste stream.

The effect of repeated melt processing on PLA has been studied extensively. Pillin *et al.* (2008) subjected PLA to repeated injection-molding cycles and observed progressive reductions in molecular weight and viscosity, together with declining mechanical performance, most notably in ductility. Badia and Ribes-Greus (2016) reviewed the mechanical recycling of PLA and concluded that thermo-mechanical and hydrolytic

degradation are the main barriers to high-value reuse; they identified blending with virgin material, careful drying, and the use of chain extenders or other upgrading strategies as the principal means of recovering properties. Blending recycled material with virgin polymer is therefore a common, low-complexity strategy for balancing recycled content against performance.

A growing body of work has examined recycled PLA (rPLA) specifically as FFF feedstock, and several reviews have summarized the field (Fernandes 2019; Mikula *et al.* 2021). Anderson (2017) compared FFF specimens printed from virgin and recycled PLA filament and reported only a modest reduction in tensile strength for the recycled material, concluding that rPLA is a viable substitute for many applications. Cruz Sanchez *et al.* (2017) evaluated PLA through multiple recycling cycles in an open-source FFF context and found that tensile strength and molecular weight decreased with each cycle, which limits the number of loops the material can undergo without property restoration. Tanney *et al.* (2017) similarly tracked material degradation through repeated recycling of PLA in additively manufactured parts and observed declining mechanical properties with increasing recycling generations. Zhao *et al.* (2018) combined an experimental investigation of closed-loop PLA recycling for 3D printing with a life cycle assessment and reported that, although mechanical properties declined over successive cycles, recycling reduced environmental impacts compared with using virgin filament. More recently, Hidalgo-Carvajal *et al.* (2023) compared recycled PLA filaments derived from waste of different origins after repeated extrusion cycles, and Sibille *et al.* (2025) quantified the environmental impacts of rPLA across successive FFF cycles, showing that the sustainability benefit depends on how many cycles the material can sustain and on the energy used in reprocessing. Taken together, these studies indicate that one or two recycling generations generally yield printable filament with moderate property loss, whereas longer-term loops require monitoring brittleness and, potentially, adding virgin material.

Advances in benchtop grinding, extrusion, and spooling equipment have made it possible to produce filament close to where waste is generated, an approach termed distributed recycling. Baechler *et al.* (2013) demonstrated a low-cost, open-source extruder for converting waste polymer into RepRap feedstock, and (Kreiger *et al.* 2014) showed through life cycle analysis that distributed recycling of post-consumer HDPE into filament could reduce embodied energy compared with conventional centralized recycling, largely by avoiding collection and transportation. The basic operations of such systems (size reduction, drying, single-screw extrusion through a die, cooling, and winding) mirror those of industrial plastic extrusion at a smaller scale (Industrial Quick Search n.d.). For a university campus, local recycling offers several benefits: it diverts waste from landfill and reduces disposal costs, lowers reliance on purchased virgin filament, and provides students with an educational demonstration of circular material flows.

Despite the extensive literature on rPLA properties, few studies have documented the practical establishment of a collection-to-filament loop within a working university makerspace, including the logistical, processing, and quality challenges that arise at that scale. The present study addresses this gap through a case study at North Carolina State University (NC State). This was previously reported by Kirch and Saloni (2026). The work involved the collection and sorting of makerspace PLA waste, three successive grinding passes, and subsequent filament extrusion incorporating approximately 10 wt.% virgin PLA, with an estimated extrusion-stage material recovery efficiency of 91%. As part of ongoing screening tests to approach PLA waste from the university campus, this

preliminary work did not aim to establish statistical equivalence among PLA compositions or isolate molecular-weight changes, crystallinity, and printer-architecture effects. Based on this, the objectives were to (1) establish and describe a potential pilot closed-loop system for recovering PLA waste from the D. H. Hill Jr. Library Makerspace and converting it into filament at the Hodges Wood Products Laboratory; (2) estimate the material efficiency of the filament production process; and (3) conduct a preliminary evaluation of the tensile strength of filament containing 20 to 80 wt.% recycled PLA relative to commercial virgin filament and laboratory-extruded virgin filament.

EXPERIMENTAL

Materials

Recycled material consisted of PLA 3D printing waste (failed prints, support structures, excess material, and discarded iterations) collected from the D. H. Hill Jr. Library Makerspace at NC State University. Because this makerspace uses PLA exclusively for its FFF operations, cross-contamination with other polymers was not a significant concern. Virgin PLA pellets (Ingeo™ Biopolymer 4043D) supplied by NatureWorks LLC (Minnetonka, MN, USA) were used for blending and for the laboratory-extruded virgin control. The virgin pellets were processed using a benchtop single-screw extruder and an automated spooler (Felfil Srl, Turin, Italy), where the material was melted and extruded with a screw speed of 3 to 5 rpm at 180 to 185 °C to produce filament with a target diameter of 1.75 mm. Commercial black virgin PLA filament (1.75 mm; Anycubic, Shenzhen, China) served as the commercial reference.

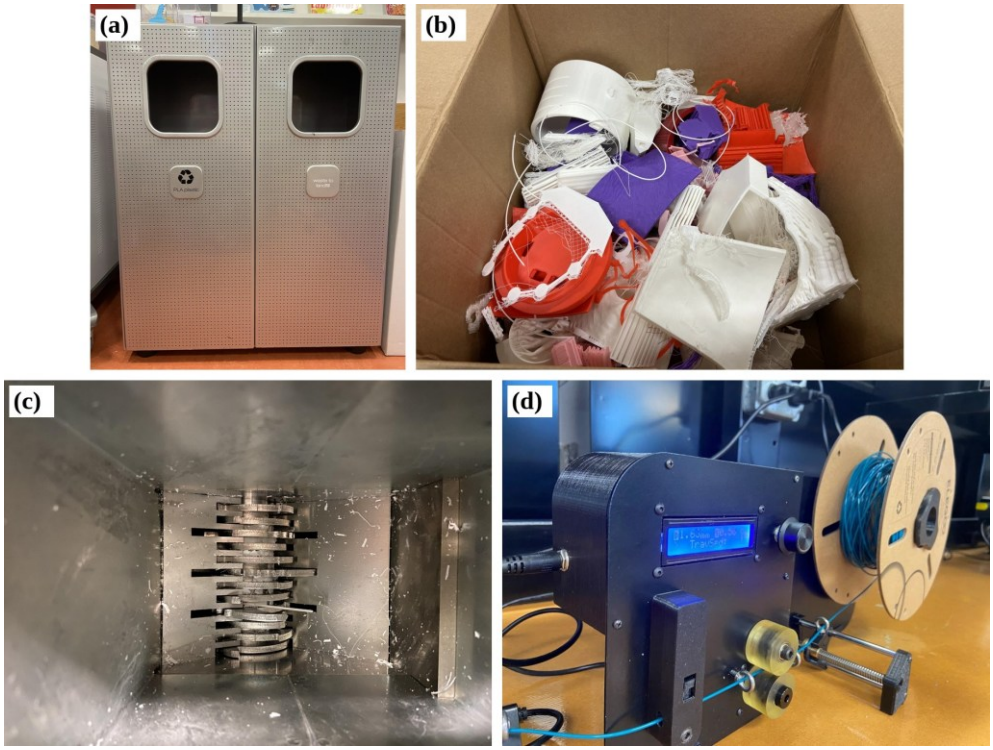


Fig. 1. Pilot closed-loop system: (a) PLA collection bin in the D. H. Hill Jr. Library Makerspace; (b) color-sorted PLA scraps delivered to the Hodges Wood Products Laboratory; (c) cutting chamber of the benchtop shredder; and (d) benchtop extruder and spooler producing recycled filament.

Collection and Sorting

A permanent collection bin for PLA scraps was installed in the D. H. Hill Jr. Library Makerspace (Fig. 1a). Makerspace staff roughly sorted the collected material into color families (*e.g.*, red, pink, purple, and white) before packing it into cardboard boxes, which were sent to the Hodges Wood Products Laboratory through the campus mail system (Fig. 1b). The boxes were stored in the laboratory until processing. Because the material arrived pre-sorted and uncontaminated, little additional processing was needed beyond the removal of any non-PLA items.

Size Reduction

The collected scraps were ground with a benchtop shredder (Felfil Shredder, model 750, Turin, Italy) (Fig. 1c). With the current equipment, the material had to pass through the shredder three times to reach a flake size suitable for extrusion (Fig. 2). Each pass reduced the particle size and increased uniformity, but the final flakes remained irregular in shape and generally larger than the virgin pellets.

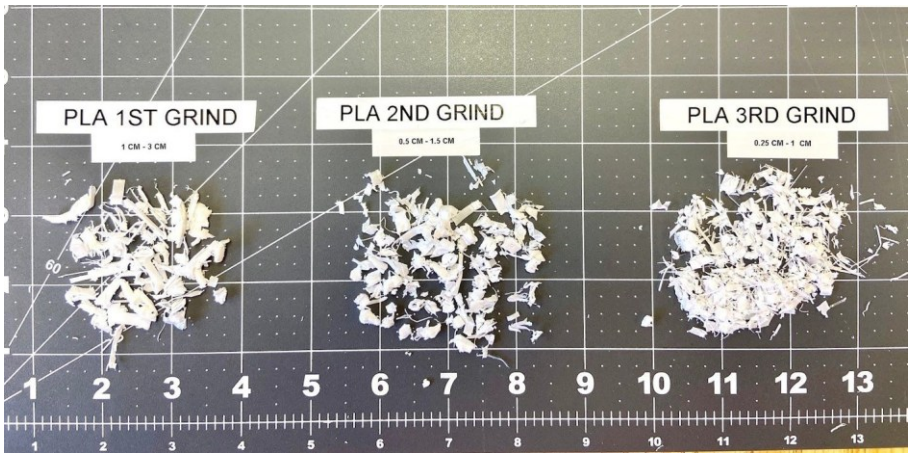


Fig. 2. Recycled PLA flakes after the first, second, and third passes through the shredder (scale in cm)

Blending and Drying

Shredded recycled PLA was blended by hand with virgin PLA pellets at predetermined mass ratios to produce batches of 150 g each. Four blends were prepared containing 20, 40, 60, and 80 wt.% recycled PLA (*i.e.*, 80, 60, 40, and 20 wt.% virgin PLA, respectively). A 0 wt.% recycled batch of virgin pellets was also extruded to serve as a laboratory-extruded virgin control, allowing the effects of recycled content to be separated from those of the in-house extrusion process. Because residual moisture can promote hydrolytic degradation of PLA during melt processing, all materials were dried in an oven at 50 °C for 24 h. The residual moisture content after drying was 0.363 ± 0.043%. During the initial pilot phase, recycled filament for general makerspace use was produced with approximately 10 wt.% virgin PLA added to improve strength and extrusion consistency.

Filament Extrusion and Spooling

Filament for all compositions was produced with a benchtop single-screw extruder and an automated spooler (Felfil Srl, Turin, Italy), following the parameters as described for the PLA pellets (Figs. 1d and 3). The processing parameters are summarized in Table 1.

Specimen Preparation

Tensile specimens conforming to the ASTM D638 Type I geometry (ASTM D638-14 2014) were printed on a Prusa MK4S printer (Prusa Research, Prague, Czech Republic) with a layer height of 0.2 mm and 20% infill density (Table 1).

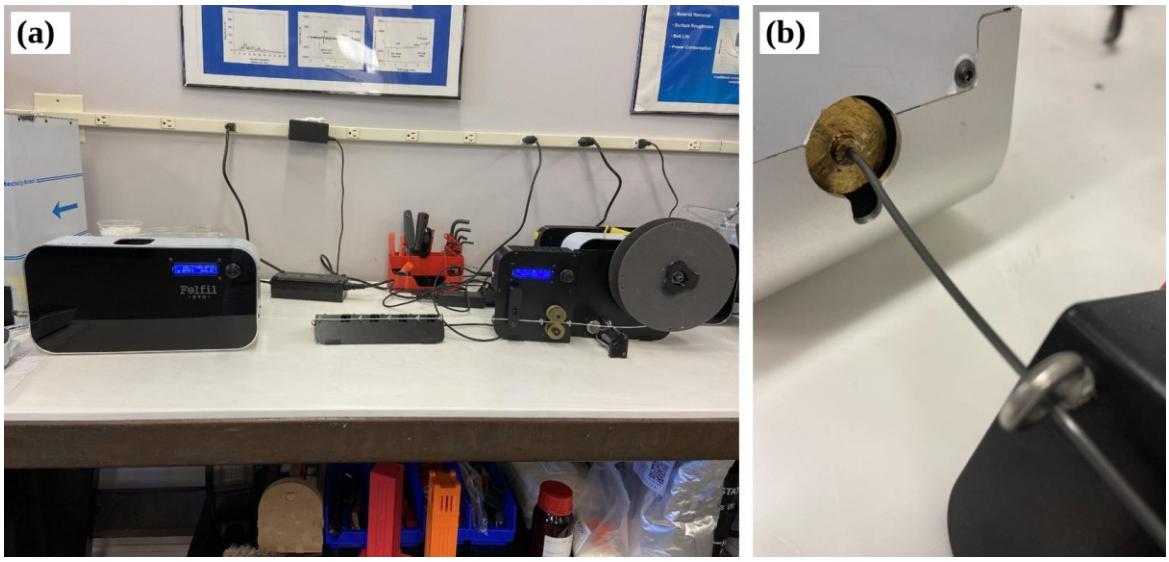


Fig. 3. (a) Benchtop extrusion and spooling station at the Hodges Wood Products Laboratory; (b) recycled PLA filament exiting the extruder die.

Table 1. Filament Production and Printing Parameters

Stage	Parameter	Value
Size reduction	Shredder passes	3
Blending	Batch mass	150 g
	Recycled content	0, 20, 40, 60, 80 wt.%
Extrusion	Screw speed	3 to 5 rpm
	Extrusion temperature	180 to 185 °C
	Target diameter	1.75 mm
	Measured diameter range	~1.6 to 1.9 mm
Printing	Printer	Prusa MK4S
	Layer height	0.2 mm
	Infill density	20%
	Printing orientation	Flat (XY plane)
	Infill pattern	Grid
	Normal fill angle	45°
	Number of perimeters	2
	Top solid layers	5
	Bottom solid layers	4
	Nozzle diameter/temperature	0.4 mm / 210°C
	Print speed	40-60 mm/s

Specimens were printed from six filaments: commercial virgin PLA, laboratory-extruded virgin PLA, and the four recycled blends (20, 40, 60, and 80 wt.% recycled PLA). Two specimens were produced for each composition (Fig. 4a). The width and thickness of the narrow section of each specimen were measured before testing; measured widths ranged from 12.76 to 13.38 mm and thicknesses from 3.08 to 3.45 mm, and the measured gauge length was approximately 50.8 mm (1.98 to 2.09 in).

Tensile Testing

Two tensile tests were performed in accordance with the Type I geometry described by ASTM D638 on an MTS Alliance RF/300 universal testing machine (MTS Systems, Eden Prairie, MN, USA) equipped with a 22.2 kN (5000 lbf) load cell (Fig. 4b) at a crosshead speed of 10 mm/min. Load at break was recorded, and the apparent tensile modulus was obtained from the testing software using crosshead displacement to estimate specimen deformation relative to the initial gauge length. Because strain was not directly measured using an extensometer, the reported modulus values were considered apparent estimates rather than intrinsic tensile modulus values. Data were recorded in US customary units (lbf, in., psi) and converted to SI units for reporting. One test of a 20 wt.% recycled specimen was repeated after the first attempt recorded an anomalous load of 7 N (1.6 lbf), which could be attributed to grip slip at one edge of the sample; only the valid repeat is reported. Tensile strength (σ, MPa) was calculated using Eq. 1,

$$\sigma = F_{max} / (w \times t) \quad (1)$$

where F_{max} is the maximum load (N), w is the width of the narrow section (mm), and t is the specimen thickness (mm). Tensile strength was calculated from the measured cross-section of each specimen, so it reflects the gross section including infill voids. Differences among compositions were evaluated by one-way analysis of variance (ANOVA) at a significance level of 0.05, and the association between strength and apparent modulus was examined with the Pearson correlation coefficient. The goal of this preliminary testing was to identify trends as a function of recycled content rather than to establish statistically definitive property values.

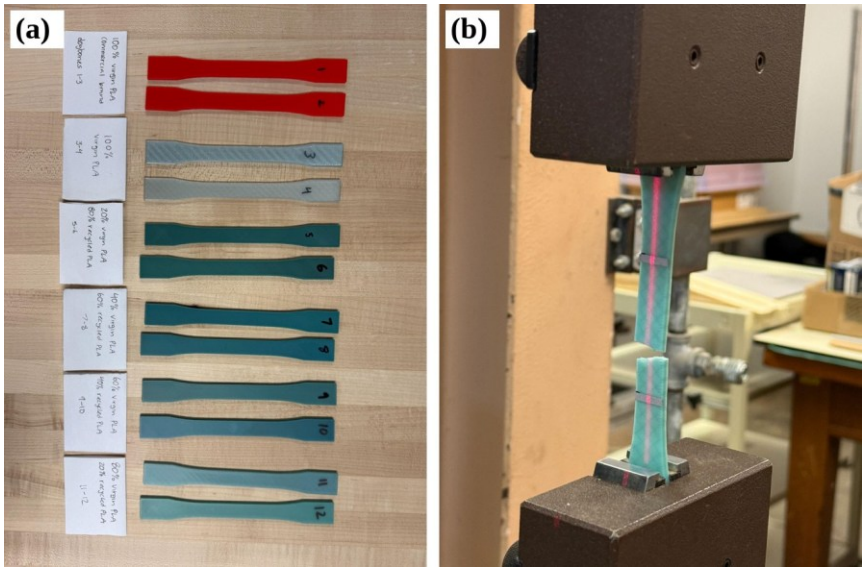


Fig. 4. (a) ASTM D638 Type I specimens printed from each filament composition; (b) specimen mounted in the MTS Alliance RF/300 universal testing machine

Material Efficiency

Material efficiency of the extrusion stage was estimated by comparing the mass of material fed to the extruder with the mass of usable filament recovered on the spool; material lost as purge, off-specification start-up filament, and residue retained in the extruder was counted as loss.

RESULTS AND DISCUSSION

Performance of the Pilot Collection and Processing System

The pilot program established the logistical feasibility of intercepting makerspace PLA waste and converting it into usable filament. The collection bin, staff sorting, and campus mail transport formed a low-cost supply chain that required no dedicated vehicles or additional personnel. Because the D. H. Hill Jr. Library Makerspace prints exclusively in PLA and staff pre-sorted the waste by color, the incoming stream was essentially free of polymer contamination, which is one of the principal barriers to mechanical recycling in general (Hopewell *et al.* 2009). Color sorting also allowed the production of recycled filament in reasonably consistent color families.

The main processing bottleneck was size reduction. Three passes through the benchtop shredder were required to reduce the scraps to an extrudable flake size, and even after three passes, the flakes were irregular in shape compared with the cylindrical virgin pellets (Fig. 2). Across the extrusion stage, approximately 91% of the input material was recovered as usable filament, with approximately 9% lost as purge, start-up material, and residue (Kirch and Saloni 2026). Material losses may occur during both the size reduction and extrusion stages, including fine particles generated during shredding, startup purging, off-specification filament production, and material retained within the processing equipment. Although some of this residual material could potentially be collected and reintroduced into subsequent processing cycles, its recoverability would depend on particle size, material condition, and potential processing-related degradation.

Recycled filament was successfully used to print functional objects, including demonstration keychains bearing the university logo (Fig. 5), which served as a visible outreach tool for communicating the recycling program to makerspace users.



Fig. 5. Demonstration keychains 3D printed from recycled PLA filament

Filament Quality

Filament diameter varied from approximately 1.6 to 1.9 mm around the 1.75 mm target. This variation is considerably larger than the tolerances typically specified for commercial filament and directly affects printing: because FFF slicers meter filament volumetrically on the assumption of a constant diameter, thinner sections cause under-

extrusion and voids, whereas thicker sections cause over-extrusion and, in extreme cases, jamming. Diameter variation was attributed to fluctuations in melt flow associated with the irregular flake geometry, the low and variable screw speed of the benchtop extruder, and the use of default spooler settings rather than closed-loop diameter control.

Tensile Properties

Individual specimen results are listed in Table 2, and the mean tensile strength and modulus of each composition are summarized in Table 3 and Fig. 6.

As an initial dataset, the laboratory-extruded virgin PLA had the lowest mean tensile strength (18.1 MPa), 23% below that of the commercial virgin filament (23.5 MPa). In contrast, every recycled-content blend reached a mean strength than that of the commercial filament. The 40 wt.% recycled blend had the highest mean strength (27.7 MPa, 18% above the commercial filament), followed by the 20 wt.% (26.8 MPa) and 60 wt.% (25.1 MPa) blends, while the 80 wt.% blend (23.2 MPa) was essentially equivalent to the commercial filament. The highest individual strength (29.3 MPa) was obtained from an 80 wt.% recycled specimen, and the lowest (17.1 MPa) from the other 80 wt.% specimen, giving that composition by far the largest scatter (coefficient of variation of 37%).

The tensile modulus followed a similar pattern. The in-house virgin PLA had the lowest apparent mean modulus (1.35 GPa), the commercial filament was intermediate (1.92 GPa), and all recycled blends were stiffer on average (1.99 to 2.39 GPa), the highest observed mean corresponding to the 20 wt.% recycled formulation. However, these values were estimated using crosshead displacement rather than direct measurements of strain. Across all twelve specimens, strength and modulus were positively correlated ($r = 0.72$, $p = 0.009$), indicating that specimens that were well consolidated tended to be both stronger and stiffer.

Table 2. Dimensions and Tensile Test Results of Individual Specimens

Filament	Spec.	Width (mm)	Thickness (mm)	Load at Break (N)	Tensile Strength (MPa)	Apparent Tensile Modulus (GPa)
Commercial virgin	1	13.38	3.45	1056	22.9	1.80
	2	12.80	3.33	1026	24.1	2.05
In-house virgin	3	12.81	3.17	752	18.5	1.28
	4	12.76	3.22	730	17.8	1.41
20 wt.% recycled	11	13.18	3.08	1008	24.8	2.54
	12	13.09	3.18	1198	28.8	2.24
40 wt.% recycled	9	13.09	3.40	1197	26.9	2.55
	10	13.07	3.21	1194	28.5	1.80
60 wt.% recycled	7	13.11	3.32	1015	23.3	1.76
	8	13.12	3.23	1138	26.9	2.22
80 wt.% recycled	5	13.09	3.30	739	17.1	1.79
	6	13.11	3.26	1253	29.3	2.28

Note: Loads, strengths, and moduli were measured in lbf and psi and converted to SI units (1 lbf = 4.448 N; 1 psi = 6.895 kPa).

Table 3. Mean Tensile Properties by Filament Composition (n = 2)

Filament	Tensile Strength (MPa)	CV (%)	Change vs. Commercial (%)	Apparent Tensile Modulus (GPa)
Commercial virgin	23.5 ± 0.8	4	–	1.92 ± 0.18
In-house virgin	18.1 ± 0.5	3	–23	1.35 ± 0.10
20 wt.% recycled	26.8 ± 2.8	10	+14	2.39 ± 0.21
40 wt.% recycled	27.7 ± 1.1	4	+18	2.17 ± 0.53
60 wt.% recycled	25.1 ± 2.5	10	+7	1.99 ± 0.32
80 wt.% recycled	23.2 ± 8.6	37	–1	2.04 ± 0.35

Note: Values are mean ± standard deviation; CV is the coefficient of variation of tensile strength.

One-way ANOVA did not detect statistically significant differences among compositions in either tensile strength ($F = 1.53$, $p = 0.31$) or modulus ($F = 2.48$, $p = 0.15$). This outcome reflects the small number of replicates and the large scatter in some blends rather than evidence that composition has no effect, and it means that the ranking among the recycled blends should be treated as provisional because it doesn't establish statistically reliable differences, equivalence, or superiority. No optimal recycled fraction can be identified from these observations. Additionally, the available experimental records did not allow reliable determination of elongation at break, limiting the assessment of potential changes in ductility associated with recycled PLA incorporation.

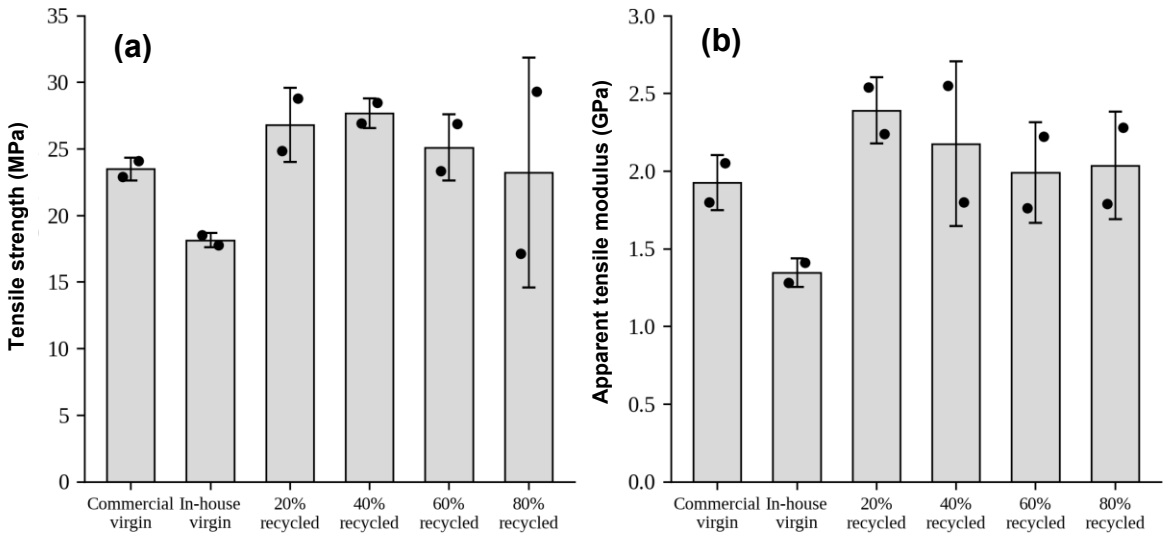


Fig. 6. Mean (a) tensile strength and (b) apparent tensile modulus of specimens printed from commercial virgin PLA, laboratory-extruded (in-house) virgin PLA, and blends containing 20 to 80 wt.% recycled PLA. Error bars are one standard deviation; points are individual specimens (*n* = 2).

The absolute strengths were well below the 50 to 70 MPa typical of molded PLA (Garlotta 2001; Farah *et al.* 2016). This difference is expected because the specimens were printed with only 20% infill, so a large fraction of the gauge cross-section was void, while strength was calculated on the gross measured cross-section; FFF parts are also limited by inter-road and interlayer bonding (Lanzotti *et al.* 2015). The tensile measurements

therefore characterize ASTM D638 Type I-shaped printed structures rather than the intrinsic properties of dense bulk PLA. Internal voids, raster and perimeter architecture, interlayer bonding, and the observed filament diameter range (approximately 1.6 to 1.9 mm) may influence the measured gross-section stress. Although nominal printing parameters were maintained across formulations, the resulting internal structures were not independently quantified.

The finding that recycled blends did not underperform commercial virgin PLA contrasts with the property losses commonly reported after multiple recycling cycles (Pillin *et al.* 2008; Cruz Sanchez *et al.* 2017; Tanney *et al.* 2017; Zhao *et al.* 2018), but it is consistent with studies showing only modest losses after a single recycling generation (Anderson 2017). The makerspace waste used here had experienced only one prior filament extrusion and one printing cycle, but its exposure to different environments could promote slight degradation due to PLA's hygroscopic nature (Banjo *et al.* 2022). The more informative comparison is between the recycled blends and the in-house virgin control, which share the same extrusion equipment and handling: all four blends were 28 to 53% stronger and 47 to 77% stiffer on average than the in-house virgin filament. Two explanations are plausible. First, the recycled flakes originate from commercial filaments, which may be formulated with processing aids, nucleating agents, or colorants and may differ in molecular weight from the virgin pellets used here; blending would then introduce these characteristics into the in-house filament. Second, PLA that has been reprocessed can become stiffer and more brittle, for example through increased crystallinity following chain scission (Pillin *et al.* 2008; Badia and Ribes-Greus 2016), which is consistent with the higher modulus of the blends. At this stage, therefore, the quality and formulation of the in-house virgin feedstock and extrusion process, rather than recycled content, appear to be the dominant factors controlling strength. Thermal and molecular weight characterization would be needed to distinguish between these mechanisms.

The large scatter in some recycled groups, most notably the 80 wt.% blend, is attributed to several interacting sources. The irregular, larger flakes and the smaller, uniform pellets tend to segregate during hand blending and feeding, so the local recycled fraction entering the extruder likely varied along the filament length. This compositional variation, combined with the diameter fluctuation discussed above, would produce specimens of varying internal density and bond quality; a section of undersized filament during printing of one specimen could readily explain the 42% difference between the two 80 wt.% specimens. Moisture uptake by the high-surface-area flakes, if not fully removed, would further promote hydrolytic degradation during extrusion (Garlotta 2001; Valerga *et al.* 2018). The virgin controls, which contained no flakes, were far more repeatable, supporting the view that feedstock heterogeneity is the main source of scatter.

Challenges and Limitations

The pilot highlighted four principal challenges. (1) Mixing: differences in size and shape between recycled flakes and virgin pellets can cause uneven blending. (2) Degradation over multiple cycles: PLA can become stiffer and more brittle as recycling generations accumulate (Pillin *et al.* 2008; Cruz Sanchez *et al.* 2017), which must be monitored in a long-term closed loop where printed recycled parts may themselves return as waste. Also, incorporating a chain extender can help limit deterioration of melt-flow properties during successive extrusion cycles due to its effect on mitigating molecular weight reduction (Li *et al.* 2023; Velghe *et al.* 2023). (3) Extrusion consistency: variable filament diameter translated into variable print quality. In addition, the small sample size

(which prevented statistically significant differences from being detected), the low infill density, and the absence of elongation-at-break data limit the conclusions that can be drawn from the tensile data.

Implications for a Campus Circular Economy

Despite these limitations, the results support the technical feasibility of a makerspace-scale closed loop. Makerspace PLA waste is clean, single-polymer, and generated at a known location; it can be collected with minimal infrastructure; the extrusion yield of approximately 91% indicates little material loss; and filament containing up to 80 wt.% recycled PLA produced printed specimens with mean strength and apparent tensile modulus that potentially could be compared with commercial virgin filament. Local processing avoids the transportation associated with centralized recycling, which has been identified as a major source of energy savings in distributed recycling systems (Kreiger *et al.* 2014), and life cycle studies suggest that recycled PLA filament can reduce environmental impacts relative to virgin feedstock (Zhao *et al.* 2018; Sibille *et al.* 2025). Beyond material savings, such a system reduces landfill disposal, lowers purchases of virgin filament, and gives students a tangible demonstration of circular design. Scaling the system across campus will require higher-capacity equipment, standardized procedures, quantification of waste generation across all makerspaces, and outreach that encourages users to design parts that minimize supports and failed prints.

Future Work

Planned work includes additional tensile tests with more specimens per composition to allow statistical analysis; reporting of elongation at break and toughness; three-point bending tests; standardized drying protocols with moisture measurement; printing of specimens at 100% infill to isolate material effects; refinement of extrusion parameters and diameter control; and evaluation of a dedicated pelletizer to convert shredded flakes into uniform pellets that blend evenly with virgin material. Characterization of molecular weight and thermal properties (*e.g.*, by gel permeation chromatography, thermogravimetric analysis, and differential scanning calorimetry) across recycling generations would help predict how many loops the material can sustain. At the program level, next steps include seeking funding for high-capacity recycling equipment, quantifying waste-stream sizes across campus makerspaces, and developing educational materials on sustainable design for 3D printing.

CONCLUSIONS

1. A pilot closed-loop recycling system linking the D. H. Hill Jr. Library Makerspace with the Hodges Wood Products Laboratory was established using a dedicated collection bin, staff color sorting, and campus mail transport. The single-polymer makerspace stream required minimal sorting and was essentially free of contamination.
2. Three passes through a benchtop shredder produced extrudable flakes, and the extrusion stage recovered approximately 91% of the input material as usable 1.75 mm filament.
3. In preliminary tensile tests, specimens printed at 20% infill, blends containing 20 to 80 wt.% recycled PLA achieved mean tensile strengths of 23.2 to 27.7 MPa, compared to

commercial virgin PLA (23.5 MPa), and mean moduli of 1.99 to 2.39 GPa, compared with 1.92 GPa for commercial PLA. The 40 wt.% blend had the highest mean strength. Laboratory-extruded virgin PLA had the lowest mean strength (18.1 MPa) and apparent tensile modulus (1.35 GPa). This suggests that, at this stage, in-house extrusion quality may influence strength more than recycled content.

4. Differences among compositions were not statistically significant with two specimens per group. High variability within some blends (up to 37% coefficient of variation for the 80 wt.% blend) was attributed to filament diameter variation (approximately 1.6 to 1.9 mm), uneven mixing of flakes and pellets, and non-standardized drying. Before scaling the system campus-wide, larger sample sizes, pelletization, standardized drying, improved diameter control, and more replicates are needed.

ACKNOWLEDGMENTS

The authors thank the staff of the D. H. Hill Jr. Library Makerspace at North Carolina State University for establishing the collection program and sorting material, and the Hodges Wood Products Laboratory in the Department of Forest Biomaterials for providing equipment and facilities.

Conflict of interest

The authors declare no conflict of interest.

REFERENCES CITED

Anderson, I. (2017). "Mechanical properties of specimens 3D printed with virgin and recycled polylactic acid," *3D Printing and Additive Manufacturing* 4(2), 110-115. https://doi.org/10.1089/3dp.2016.0054

ASTM D638-14 (2014). "Standard test method for tensile properties of plastics," ASTM International, West Conshohocken, PA, USA.

Auras, R., Harte, B., and Selke, S. (2004). "An overview of polylactides as packaging materials," *Macromolecular Bioscience* 4(9), 835-864. https://doi.org/10.1002/mabi.200400043

Badia, J. D., and Ribes-Greus, A. (2016). "Mechanical recycling of polylactide, upgrading trends and combination of valorization techniques," *European Polymer Journal* 84, 22-39. https://doi.org/10.1016/j.eurpolymj.2016.09.005

Banjo, A. D., Agrawal, V., Auad, M. L., and Celestine, A.-D. N. (2022). "Moisture-induced changes in the mechanical behavior of 3D printed polymers," *Composites Part C: Open Access* 7, article 100243. https://doi.org/10.1016/j.jcomc.2022.100243

Baechler, C., Devuono, M., and Pearce, J. M. (2013). "Distributed recycling of waste polymer into RepRap feedstock," *Rapid Prototyping Journal* 19(2), 118-125. https://doi.org/10.1108/13552541311302978

Cruz Sanchez, F. A., Boudaoud, H., Hoppe, S., and Camargo, M. (2017). "Polymer recycling in an open-source additive manufacturing context: Mechanical issues," *Additive Manufacturing* 17, 87-105. https://doi.org/10.1016/j.addma.2017.05.013

Ellen MacArthur Foundation (2013). *Towards the Circular Economy, Vol. 1: Economic*

and Business Rationale for an Accelerated Transition, Ellen MacArthur Foundation, Cowes, UK.

Ellen MacArthur Foundation and Granta Design (2015). *Circularity Indicators: An Approach to Measuring Circularity – Project Overview*, Ellen MacArthur Foundation, Cowes, UK.

Farah, S., Anderson, D. G., and Langer, R. (2016). "Physical and mechanical properties of PLA, and their functions in widespread applications — A comprehensive review," *Advanced Drug Delivery Reviews* 107, 367-392. https://doi.org/10.1016/j.addr.2016.06.012

Fernandes, C. P. (2019). "Use of recycled poly lactic acid (PLA) polymer in 3D printing: A review," *International Research Journal of Engineering and Technology* 6(9), (https://www.irjet.net/archives/V6/i9/IRJET-V6I9286.pdf)

Flynt, J. (2017). "Polylactic acid (PLA): The environment-friendly plastic," 3D Insider (https://3dinsider.com/what-is-pla/), Accessed on 25 May 2026.

Garlotta, D. (2001). "A literature review of poly(lactic acid)," *Journal of Polymers and the Environment* 9(2), 63-84. https://doi.org/10.1023/A:1020200822435

Geissdoerfer, M., Savaget, P., Bocken, N. M. P., and Hultink, E. J. (2017). "The circular economy – A new sustainability paradigm?," *Journal of Cleaner Production* 143, 757-768. https://doi.org/10.1016/j.jclepro.2016.12.048

Geyer, R., Jambeck, J. R., and Law, K. L. (2017). "Production, use, and fate of all plastics ever made," *Science Advances* 3(7), article e1700782. https://doi.org/10.1126/sciadv.1700782

Hidalgo-Carvajal, D., Muñoz, Á. H., Garrido-González, J. J., Carrasco-Gallego, R., and Alcázar Montero, V. (2023). "Recycled PLA for 3D printing: A comparison of recycled PLA filaments from waste of different origins after repeated cycles of extrusion," *Polymers* 15(17), article 3651. https://doi.org/10.3390/polym15173651

Hopewell, J., Dvorak, R., and Kosior, E. (2009). "Plastics recycling: Challenges and opportunities," *Philosophical Transactions of the Royal Society B: Biological Sciences* 364(1526), 2115-2126. https://doi.org/10.1098/rstb.2008.0311

Industrial Quick Search. "Plastic extrusion," (https://www.iqsdirectory.com/articles/plastic-extrusion.html), Accessed on 25 May 2026.

Kirch, C., and Saloni, D. (2026). "Closing the loop: Recycling PLA waste from 3D printing into value-added filament at NC State University," *BioResources* 21(1), 13-15. https://doi.org/10.15376/biores.21.1.13-15

Kirchherr, J., Reike, D., and Hekkert, M. (2017). "Conceptualizing the circular economy: An analysis of 114 definitions," *Resources, Conservation and Recycling* 127, 221-232. https://doi.org/10.1016/j.resconrec.2017.09.005

Kreiger, M. A., Mulder, M. L., Glover, A. G., and Pearce, J. M. (2014). "Life cycle analysis of distributed recycling of post-consumer high density polyethylene for 3-D printing filament," *Journal of Cleaner Production* 70, 90-96. https://doi.org/10.1016/j.jclepro.2014.02.009

Lanzotti, A., Grasso, M., Staiano, G., and Martorelli, M. (2015). "The impact of process parameters on mechanical properties of parts fabricated in PLA with an open-source 3-D printer," *Rapid Prototyping Journal* 21(5), 604-617. https://doi.org/10.1108/RPJ-09-2014-0135

Mikula, K., Skrzypczak, D., Izydorczyk, G., Warchoł, J., Moustakas, K., Chojnacka, K., and Witek-Krowiak, A. (2021). "3D printing filament as a second life of waste

plastics – A review," *Environmental Science and Pollution Research* 28, 12321-12333. https://doi.org/10.1007/s11356-020-10657-8

Pereira-Rojas, J., Barrios, N., Patiño-Agudelo, Á. J., Rojas, O. J., Peresin, M. S., and Saloni, D. (2026). "Cellulose modifications for fused deposition modeling: Functionalization strategies, performance enhancement, and future perspectives," *Carbohydrate Polymers* 381, article 125115. https://doi.org/10.1016/j.carbpol.2026.125115

Pillin, I., Montrelay, N., Bourmaud, A., and Grohens, Y. (2008). "Effect of thermo-mechanical cycles on the physico-chemical properties of poly(lactic acid)," *Polymer Degradation and Stability*, 93(2), 321-328. https://doi.org/10.1016/j.polymdegradstab.2007.12.005

Ramos-Hernández, T., Robledo-Ortíz, J. R., González-López, M. E., Martín del Campo, A. S., González-Núñez, R., Rodrigue, D., and Pérez-Fonseca, A. A. (2023). "Mechanical recycling of PLA: Effect of weathering, extrusion cycles, and chain extender," *Journal of Applied Polymer Science* 140(16), article e53759. https://doi.org/10.1002/app.53759

Sibille, A., Ashkbous, M., Doublet, L. H. C., Farahani, R. D., Binet, F., Bodkhe, S., Therriault, D., and Keivanpour, S. (2025). "The sustainability of recycled polylactic acid via fused filament fabrication: Environmental impacts across cycles," *The International Journal of Advanced Manufacturing Technology* 137, 1915-1928. https://doi.org/10.1007/s00170-025-15281-9

Song, R., and Telenko, C. (2017). "Material and energy loss due to human and machine error in commercial FDM printers," *Journal of Cleaner Production* 148, 895-904. https://doi.org/10.1016/j.jclepro.2017.01.171

Tanney, D., Meisel, N. A., and Moore, J. (2017). "Investigating material degradation through the recycling of PLA in additively manufactured parts," in: *Proceedings of the 28th Annual International Solid Freeform Fabrication Symposium*, Austin, TX, USA, pp. 519-531.

Valerga, A. P., Batista, M., Salguero, J., and Girot, F. (2018). "Influence of PLA filament conditions on characteristics of FDM parts," *Materials* 11(8), article 1322. https://doi.org/10.3390/ma11081322

Velghe, I., Buffel, B., Vandeginste, V., Thielemans, W., and Desplentere, F. (2023). "Review on the degradation of poly(lactic acid) during melt processing," *Polymers* 15(9), article 2047. https://doi.org/10.3390/polym15092047

Zhao, P., Rao, C., Gu, F., Sharmin, N., and Fu, J. (2018). "Close-looped recycling of polylactic acid used in 3D printing: An experimental investigation and life cycle assessment," *Journal of Cleaner Production* 197, 1046-1055. https://doi.org/10.1016/j.jclepro.2018.06.275

Article submitted: September 30, 2026; Peer review completed: October 31, 2026; Revised version received and accepted: November 5, 2026; Published: November 11, 2026.
DOI: 10.15376/biores.22.1.205-219