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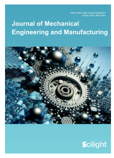

Article

Viability Analysis of Reusing Polymers in Additive Manufacturing

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Abstract: Additive manufacturing (AM) has grown into a widely accessible technology. This shift has been driven largely by advances in low-cost, user-friendly equipment, particularly in fused deposition modelling (FDM) systems. However, material use remains a major cost and sustainability challenge in FDM printing. Polylactic acid (PLA) is the most common and affordable filament, although routine operations such as purging when changing filament color, printing support structures, and discarding failed prints generate significant waste. These drawbacks motivate efforts to recycle waste PLA into new filament, reducing environmental impact and material expense. This study investigates the mechanical performance of recycled PLA, aiming to understand optimal processing parameters. Test specimens were printed for tensile, flexural, and Charpy impact testing. One set of specimens printed from virgin PLA served as the control, while three recycled-PLA sets were printed at different nozzle temperatures: 220 °C (virgin PLA baseline), 237 °C, and 255 °C. All other printing parameters remained constant. Charpy tests, carried out in a manual pendulum system, were also replicated at low temperatures (−30.9 °C). It was concluded that, while recycled PLA demonstrated higher strength and stiffness compared to virgin PLA in both tensile and flexural tests, it showed a substantially lower strain at break. The absorbed energy measurements showed significant reductions for recycled PLA at room temperature over virgin PLA, and major reductions with the testing temperature. Overall, recycled PLA shows promise for specific applications requiring stiffness, but further optimization is needed to improve toughness and ensure consistent manufacturing reliability.

Keywords: additive manufacturing; fused deposition modelling; polymer recycling; polylactic acid; printing temperature

1. Introduction

Developments by AM equipment manufacturers have lowered the cost of purchasing these machines and made them simple enough to use [1]. Determining the mechanical properties of the material used in AM is a fundamental aspect, as these properties vary with the printing temperature [2]. In this context, the ISO 527-1 standard qualifies polymers by estimating their mechanical tensile properties, including for rigid and semi-rigid thermoplastic materials for extrusion [3]. Alternatively, the ASTM D638-14 standard can be followed [4]. The testing equipment must comply with ISO 7500-1 and ISO 9513 standards. The relevant mechanical properties include the Young's modulus (E), yield stress (if applicable to the polymer under analysis), tensile strength, yield strain (if applicable), elongation at break, and Poisson's ratio (if an extensometer is used). For bending characterization, the ISO 178 standard can be used [5]. Two procedures exist to estimate the flexural modulus (E_f) and the stress-strain (σ-ε) curve, one using a constant strain rate of 1%/minute throughout the test, and another applying this strain rate until calculating E_f, at which point the rate is changed to 5%/minute or 50%/minute [6]. Impact resistance is another important characteristic of polymers. There are different standards, namely ISO 179-1 and ISO 179-2 for Charpy-type tests and ISO 180 for Izod-type tests [7]. According to ISO 179-1, the Charpy method is more appropriate for materials that exhibit interlaminar shear fracture, or materials that exhibit surface effects due to environmental factors. It is also important to determine the melting temperature (for semi-crystalline polymers) and the glass transition temperature [8]. To this end, differential scanning calorimetry (DSC) can be performed, following the ISO 11357-1:2016 standard [9].

There are several different processes within the field of AM. According to ISO/ASTM 52900: 2015, AM processes can be divided into seven categories: Binder Jetting, Directed Energy Deposition, Vat Photopolymerisation, Powder Bed Fusion, Material Extrusion, Sheet Lamination, and Material Jetting [10]. The FDM process, framed as a Material Extrusion process, is also known as Fused Filament Fabrication (FFF). The first step in using FDM technology is to create a computer-aided design (CAD) model of the part, which must then be exported as a stereolithography file (STL). This file is then fed into specific AM software, whose main purpose is to divide the model into layers (slicing), during which the G code is created [11]. Some plastics are more suitable for processing by the FDM process than others, due to a variety of factors, including the cost/quality of the material and its mechanical properties and the processability by extrusion [12]. It should also be noted that small amounts of fibers or metal powders are sometimes added to the base plastic to improve certain properties of the final product [13]. One of the main process variables is layer thickness, which can affect the mechanical properties of the product, especially E [14]. According to a study conducted for acrylonitrile butadiene styrene (ABS) and PLA [15], the variation in layer height for values of 0.2 mm, 0.3 mm, and 0.4 mm showed minimal differences in the yield stress of the test pieces produced with ABS. However, for the PLA test pieces, there was a 24.5% difference in yield stress between using 0.2 mm and 0.3 mm layers. The diameter of the extrusion nozzle is inversely proportional to the part geometrical accuracy and surface quality [16]. Czyżewski et al. [17] points to a correlation between an increase in nozzle diameter and a slight increase in the density of the components produced. The fill ratio is a variable linked to the area of voids inside the component. A lower fill ratio reduces costs and mass, while decreasing processing times. However, lower fill ratios lead to less material to resist mechanical stresses. A study [18] comparing the yield stress of 100% and 20% fill rates for ABS and PLA showed that, for ABS, twice the yield stress would be obtained. For PLA, the yield stress was 2.5 times higher than that of the test pieces with a lower fill rate. The fill angle reflects the orientation of the extruded material inside the printed components. This parameter can be varied between each layer of deposited material [15]. Studies on ABS show that a fill angle of 0°, in which the direction of mechanical stress is aligned, provides the highest tensile strength [19]. In another study [20], for PLA, it was found that a 45° angle results in 10% higher tensile strength than that obtained for a 0° angle. The extrusion temperature refers to the temperature at which the material is expelled from the extrusion head and deposited on the build base or another layer of material. Wittbrodt and Pearce [21] indicated that, for PLA, within its processing temperature range, the highest yield stress is obtained for values closer to the upper recommended limit (215 °C). Natayu et al. [22] analyzed the influence of annealing on the mechanical properties of PLA specimens fabricated by FDM. It was recommended that annealing was executed at 95 °C for 30 min, leading to the highest stiffness and strength.

Nowadays, it becomes important to consider sustainability in polymeric AM processes. Concerns about the impact of accumulating unrecycled plastics and the potential threats they pose to natural ecosystems are not new. In this context, FDM printers require purging of the equipment before a new print can be started and, often, between different steps of the same print. These purges represent inefficiencies, material losses, and costs [23]. Moreover, many prints require support structures to be produced with the best quality. These structures are removed at the end and discarded as waste. Thus, the recycling of plastic waste created by AM equipment plays an important role, as it represents an opportunity for reuse in the production of new filament and cost reduction. Al Rashid and Koç [24] listed the main needs, challenges, and opportunities for the use of recycled polymers in AM. There are essentially three different ways to recycle plastics: mechanically, chemically, or using heat. Each method has its advantages and disadvantages, but chemical recycling is referred to as the most difficult to implement, yet with the greatest long-term benefits. The challenges of recycling polymers are linked to their chemical compositions, the need for separation, especially in mechanical recycling, the removal of additives and coatings, contamination, and the recycling of thermosetting plastics. Dohan et al. [25] presented a comparison between the mechanical properties of new and recycled polyethylene terephthalate glycol (PETG) components obtained by AM using FDM technology. Although only a small stiffness difference was found, the recycled material had higher stiffness. Nonetheless, it was shown that recycled material could occasionally have better properties, but there is also greater variation in its performance in mechanical tests. Olawumi et al. [26] explored the sustainability of polymer recycling (reinforced PLA, ABS, PETG, and others) using FDM technology. A study was also conducted on the variation in mechanical properties with recycling cycles, according to which the yield stress falls to 90% of the original value after the first cycle and 80% after the third. It is also noted that recycling requires 30% less energy than processing new material, and that the carbon footprint of the recycling process is 25% lower than that of processing new material. With regard to PLA recycling, some authors point out that after one recycling cycle there is a slight decrease in the molecular mass of this material [27]. Others also indicated that PLA degradation increases by up to 30% after three cycles and 60% after seven cycles [28]. Lanzotti et al. [29] reported that, in flexural tests performed in accordance with ASTM D2344, PLA with one recycling cycle had a flexural yield stress of 106.8 ± 9.0 MPa, and PLA with two recycling cycles had values of 108.5 ± 9.9 MPa. According to the authors, these values are close to those of the virgin material, which was also tested, leading to a flexural yield stress of 119.1 ± 6.6 MPa. However, after a third recycling cycle, the flexural yield stress of PLA dropped considerably to 75.0 ± 16.2 MPa. Romani et al. [30] examined the thermal, rheological, and mechanical behavior of PLA feedstocks used in large-format additive manufacturing after up to six recycling cycles. Compared with desktop extrusion systems, reduced thermomechanical degradation was observed, largely due to fewer reprocessing steps, indicating that recycled PLA granulates can serve as a viable alternative to virgin materials in practical applications. Selvaraj et al. [31] proposed a recycling route for rigid polyurethane (PU) waste through its incorporation into PLA to produce composite filaments for FDM printing. Composites containing 3 wt.% rigid PU showed optimal mechanical behavior, with tensile and flexural strengths exceeding those of neat PLA, while higher loadings resulted in performance losses due to particle agglomeration and weaker interfacial bonding. Simon et al. [32] incorporated copper microparticles recovered from electronic waste into recycled PLA. To simulate recycling, extruded filaments were pelletized and re-extruded, with commercial 60 wt.% copper-filled filament used as a reference. All experimental filaments showed superior fracture toughness compared with the commercial material, although re-extrusion led to toughness reductions of 34% and 9% for quarter- and half-loaded composites.

This study investigates the mechanical performance of recycled PLA, aiming to understand optimal processing parameters. Test specimens were printed for tensile, flexural, and Charpy impact testing. One set of specimens printed from virgin PLA served as the control, while three recycled-PLA sets were printed at different nozzle temperatures: 220 °C (virgin PLA baseline), 237 °C, and 255 °C. All other printing parameters remained constant. Charpy tests, carried out in a manual pendulum system, were also replicated at low temperature (−30.9 °C). This work aims to provide a comprehensive and systematic evaluation of recycled PLA, including variability analysis and low-temperature performance, which remain limited in existing studies.

2. Materials and Methods

2.1. Materials

The material in study is PLA. Given that the main purpose of this paper is to access the viability of using recycled PLA in FDM AM, there were two different sources of PLA used for test specimen production: 100% virgin PLA sold by Bambu Lab (Shenzhen, China) [33] and recycled PLA acquired Sakata 3D Filaments (Granada, Spain) under the trade name ‘Re-Go&Print’ [34]. Both filaments had a diameter of 1.75 mm. According to technical specification provided by the virgin PLA manufacturer, optimal properties are achieved when the test specimens are printed in the *x-y* direction and tested this way. The same applies for both flexural and impact properties. Such mechanical properties can be consulted in Table 1 along with the normative standard used for the testing. For the results shown the manufacturer claims that a 220 °C temperature was used for the nozzle, and the heated bed was at 35 °C. The printing speed utilized was 200 mm/s and the test specimens had an infill rate of 100%. It should be noted that virgin and recycled PLA were sourced from different suppliers because the virgin PLA manufacturer does not produce or supply an identical commercially recycled equivalent. Thus, filaments from two distinct suppliers had to be utilized. Consequently, variations in baseline resin formulations and proprietary additives exist between the two brands, which may influence the absolute baseline mechanical properties independent of the recycling process itself.

Table 1. Mechanical properties of virgin PLA according to the manufacturer [33].

Property	Testing Method	Value
E (x-y)	ISO 527, GB/T 1040	2580 ± 220 MPa
E (z)	ISO 527, GB/T 1040	2060 ± 170 MPa
Tensile strength (x-y)	ISO 527, GB/T 1040	35 ± 4 MPa
Tensile strength (z)	ISO 527, GB/T 1040	31 ± 3 MPa
Breaking elongation rate (x-y)	ISO 527, GB/T 1040	12.2 ± 1.8%
Breaking elongation rate (z)	ISO 527, GB/T 1040	7.5 ± 1.3%
E_f (x-y)	ISO 178, GB/T 9341	2750 ± 160 MPa
Bending modulus (z)	ISO 178, GB/T 9341	2370 ± 150 MPa
Bending strength (x-y)	ISO 178, GB/T 9341	76 ± 5 MPa
Bending strength (z)	ISO 178, GB/T 9341	59 ± 6 MPa
Impact strength (x-y)	ISO 179, GB/T 1043	26.6 ± 2.8 kJ/m^2; 7.9 ± 1.2 kJ/m^2 (notched)
Impact strength (z)	ISO 179, GB/T 1043	13.8 ± 0.9 kJ/m^2
Glass transition temperature	DSC, 10º/min	60 °C

The recycled PLA was a 100% recycled filament from another supplier was used to test recycled PLA properties, without additives. The data provided by this manufacturer is summarized in Table 2. There was no specific information regarding printing parameters used in the test specimens that achieved such results, while the only information regarding them given by manufacturer was related to its infill rate, which is noted to be 100%.

Table 2. Mechanical properties of recycled PLA according to the manufacturer [34].

Property	Standard	Value
E	ISO 527-1	3500 MPa
Tensile strength	ISO 527-1	45 MPa
Tensile elongation	ISO 527-1	5%
Charpy notched impact	ISO 179-1eA	118 J/m

2.2. Specimen Geometry and Dimensions

The dimensions of the test specimens used for all tests performed in this thesis comply with ISO standards: tensile test (ISO 527-1), flexural test (ISO 178-1), and impact test/Charpy (ISO 179-1). The geometry and dimensions of the test specimens are shown in Figure 1.

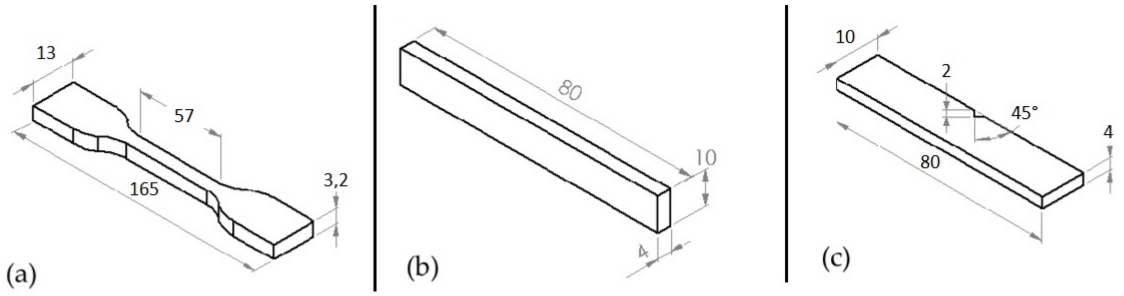

Figure 1. Dimensions of test specimens for: tensile testing (**a**), flexural testing (**b**), and Charpy testing (**c**).

Sixteen specimens were produced for tensile testing and sixteen for flexural testing to study the influence of virgin and recycled material on mechanical properties, as well as the influence of extrusion temperature. Twenty specimens were produced for Charpy testing. The reason behind using a higher number of specimens in this test involved studying the influence of the test temperature on the energy absorption capacity results. Table 3 summarizes all test conditions and variables studied in each test. Four repetitions were made for each variable in the tensile and flexure tests, and five for the Charpy tests.

Table 3. Summary table of the number of specimens and variables studied in each test.

Test	Extrusion Temperature of Test Pieces [°C]	Type of Material	Test Temperature [°C]	Number of Test Pieces Tested
Tensile	220, 237 and 255	Virgin PLA and recycled PLA	24.1 (room temperature)	16
Flexure	220, 237 and 255	Virgin PLA and recycled PLA	24.1 (room temperature)	16
Charpy	220, 237 and 255	Virgin PLA and recycled PLA	24.1 and −30.9	40

2.3. Fabrication and Printing Parameters

2.3.1. Fabrication Process and Printing Equipment

The study was conducted using a FDM 3D printer, the Bambu Lab X1-Carbon model from Bambu Lab; Shenzhen, China (Figure 2). This equipment, which was relatively modern at the time of use, has a build volume of 256 × 256 × 256 mm^3.

Figure 2. Bambu Lab X1-Carbon 3D printer (FDM) (**a**) and polyetherimide (PEI) build platform (**b**).

One of the main advantages of this printer is its fully enclosed design. This type of configuration allows for better control of the environment around the print bed, promoting slower and more uniform cooling of the material. This feature helped to reduce thermal deformation and improve the dimensional stability of the parts produced. The printer uses a 1.75 mm diameter filament and a standard 0.4 mm extrusion nozzle. The heated build base also plays an essential role in the adhesion quality of the first layers. In this study, a textured PEI base was used. This plate consisted of a thin 0.075 mm layer of PEI powder applied to both sides of a 0.5 mm stainless steel sheet. This configuration ensures excellent adhesion of the first layer and facilitates the parts' removal once cooled. According to the manufacturer, the material can withstand temperatures of up to 180 °C, which is confirmed by previous work showing that physical aging only occurs at temperatures above approximately 175 °C, even after 24 h of exposure to 190 °C [35].

2.3.2. Printing Parameters and Experimental Conditions

One of the main objectives of this study was to analyze and compare the behavior of virgin and recycled materials in AM, both in terms of their mechanical properties and their suitability for the manufacturing process. The evaluation focused on ease of extrusion, deposit stability, and the likelihood of failures occurring during the process, such as extrusion nozzle blockage. As previously indicated, the most decisive printing parameter for this work is the extrusion temperature, which has a direct influence on the quality of the print and the final properties of the parts. For virgin PLA, the generally recommended temperature range is between 190 and 220 °C [36]. However, some studies have shown that the tensile strength can increase proportionally with the extrusion temperature up to 240 °C [37]. In the case of recycled PLA, a higher temperature was required since the molecular structure of the polymer partially degrades after initial extrusion, which reduces its viscosity at low temperatures. A previous study [38] indicated that an increase of approximately 20% compared to the temperature used for virgin PLA is necessary to ensure proper extrusion of the recycled material. Based on these recommendations, three extrusion temperatures were selected for this research:

- 220 °C, common to both types of material (virgin and recycled);
- 237 °C and 255 °C, specifically applied to recycled PLA.

An infill density of 50% was selected for all tested samples to reflect typical practical printing conditions, balancing mechanical performance and material usage. The other printing parameters were set according to the conditions used in a previous study, to allow a direct comparison of the results. These parameters are detailed in Table 4.

Table 4. Common printing parameters for all produced samples.

Parameter	Value/Description
Extrusion nozzle diameter (mm)	0.4
Layer height (mm)	0.4
Infill density (%)	50
Infill pattern	Rectilinear
Printing speed—first layer outline (mm/s)	50
Printing speed—first layer infill (mm/s)	105
Printing speed—outer wall of intermediate layers (mm/s)	200
Printing speed—inner wall of intermediate layers (mm/s)	300
Printing speed—infill of intermediate layers (mm/s)	250
Printing speed—last layer (mm/s)	200
Printing direction	*x-y*

After the test pieces were produced, measurements were taken with a digital calliper with 0.01 mm resolution to obtain the nominal envelope cross-section of each specimen. In accordance with mechanical engineering conventions for FDM cellular structures, stress values were calculated based on this overall envelope cross-section rather than the net material cross-section. This reflects practical application design, where structural spaces are volume-constrained. To verify internal infill consistency and ensure that printing temperatures did not introduce under- or over-extrusion anomalies, all printed specimens were weighed. The real density ($\rho_{apparent}$) was also calculated as the ratio of the sample mass to its total geometric volume. Table 5 presents all obtained results, whose coefficient of variation (CoV) is shown between parentheses. The minor variance in mass guarantees highly stable and repeatable infill rendering for all batches.

Table 5. Cross-section, mass, and $\rho_{apparent}$ of the printed specimens.

Specimen Type	Configuration/Temperature	Cross Section (mm^2)	Mass (g)	Average $\rho_{apparent}$ (g/cm^3)
Tensile	Virgin PLA (220 °C)	15.71 ± 0.11 (0.70%)	4.51 ± 0.41 (9.09%)	0.867
	Recycled PLA (220 °C)	16.03 ± 0.23 (1.43%)	4.48 ± 0.23 (5.13%)	0.862
	Recycled PLA (237 °C)	16.22 ± 0.36 (2.22%)	4.56 ± 0.31 (6.80%)	0.877
	Recycled PLA (255 °C)	16.07 ± 0.31 (1.93%)	4.59 ± 0.42 (9.15%)	0.883
Flexural	Virgin PLA (220 °C)	39.89 ± 0.65 (1.63%)	2.77 ± 0.11 (3.97%)	0.866
	Recycled PLA (220 °C)	40.30 ± 0.49 (1.22%)	2.73 ± 0.37 (13.55%)	0.853
	Recycled PLA (237 °C)	40.12 ± 0.59 (1.47%)	2.79 ± 0.31 (11.11%)	0.872
	Recycled PLA (255 °C)	39.97 ± 0.45 (1.13%)	2.80 ± 0.22 (7.86%)	0.875
Charpy	Virgin PLA (220 °C)	40.20 ± 0.54 (1.34%)	2.71 ± 0.30 (11.07%)	0.847
	Recycled PLA (220 °C)	39.91 ± 0.60 (1.50%)	2.74 ± 0.15 (5.47%)	0.856
	Recycled PLA (237 °C)	38.86 ± 0.81 (2.08%)	2.68 ± 0.12 (4.48%)	0.838
	Recycled PLA (255 °C)	40.12 ± 0.93 (2.32%)	2.74 ± 0.18 (6.57%)	0.856

2.4. Test Details

In this section, the equipment and test setup used for tensile, flexural, and Charpy testing are presented. The machine used for tensile testing was a Shimadzu Autograph AG-X (serial number I22004500220) with a maximum load capacity of 100 kN (Figure 3a). The test speed was 5 mm/min for both tensile and flexural tests. Such a device allows for both tensile and flexural testing by adapting two different sets of tools on its opposing grips. In the specific case of tensile testing two wedge grips were fastened, one to the top moving part of the machine and another to the bottom fixed part of this equipment. This grip had a threaded mechanism that allowed for their opening or closing when the test specimens were to be positioned. Additionally, during the elastic phase of the material being tested, a manual strain gauge type extensometer was also used to allow for longitudinal displacement measurement between reference points, aiming to estimate the longitudinal strain in the elastic loading part. The testing equipment and the used strain gauge extensometer were certified by Catim (certification numbers LMD20155012525/10 and LMD201550125255/20, respectively) and had their last calibration on 20 November 2015. For flexural testing, the same Shimadzu machine was utilized with the appropriate adjustments to the tools fastened to the grips (Figure 3b). A small structure was bolted to the stationary side of the equipment. Such structure had two “L” shaped supporting points with width of 14 mm and a radius of 3 mm machined on its corners to prevent any the testing specimens from being damaged and possibly changing flexural properties results. The moving grip also had a punch device bolted to it with a radius of 5 mm that was going to press the testing specimen against the above mentioned two supporting points.

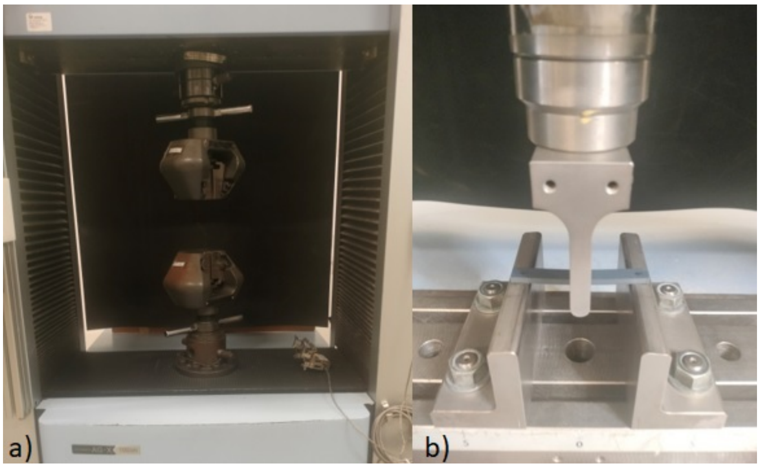

Figure 3. Shimadzu Autograph AG-X testing machine in the tensile (**a**) and flexural (**b**) testing arrangements.

The Charpy testing device used was a small portable one with a manual pendulum system (Figure 4), specifically designed for plastics testing as described by the manufacturer. It was produced by Hounsfield, an English manufacturer and, as such, the measuring units it shows were shown in lb/ft. After testing the results conversion to international units was made with the help of a set of tables provided by Hounsfield, available with the machine. This device allows for different impactors to be used. Given the material type being tested, the mass of 0.125 lb was preselected to use and access which of these would provide more appropriate results during testing. For low-temperature impact testing (−30.9 °C), the specimens were conditioned using liquid nitrogen. The samples were immersed in a container filled with liquid nitrogen, and their temperature was monitored using a thermocouple to ensure accurate measurement. Once the target temperature was reached, the specimens were quickly removed using pliers and immediately positioned in the Charpy testing device. The time between removal and testing was minimized to reduce temperature fluctuations. This procedure allowed reliable testing at sub-zero temperature conditions.

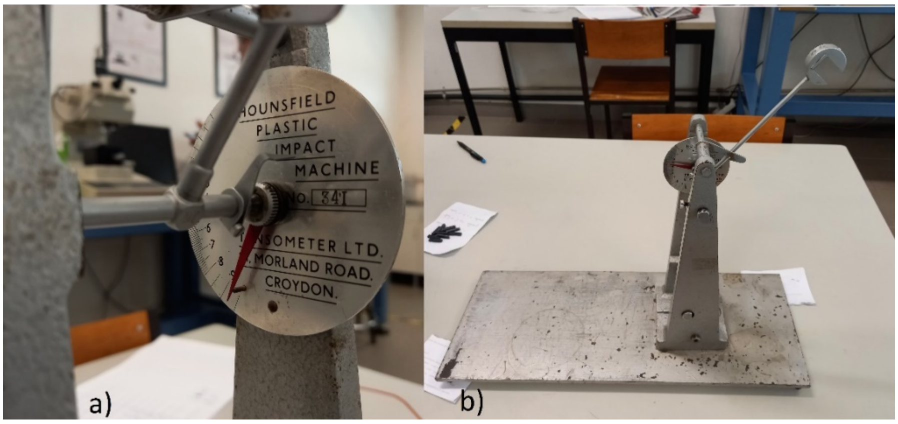

Figure 4. Charpy testing device: visual scale for toughness measurement (**a**) and overall view of the equipment (**b**).

3. Results

3.1. Tensile Tests

To compare the mechanical behavior of virgin and recycled PLA materials, tensile tests were performed under identical conditions. All results, including *E*, yield stress, tensile strength, and strain at break, were compiled in Table 6 (CoV between parentheses) and corresponding combined σ-ε presented in Figure 5. This approach allows a clear and direct comparison between the virgin PLA and the recycled PLA printed at different temperatures (220 °C, 237 °C, and 255 °C). The analysis of these combined results provides a global view of how recycling and printing temperature affect the tensile performance of PLA, particularly in terms of stiffness, strength, and ductility. It should be noted that no visible signs of thermal degradation, such as discoloration or surface irregularities, were observed in all printed specimens for all tests carried out in this work, especially at the highest extrusion temperature (255 °C), which suggests that the material remained stable under the selected processing conditions.

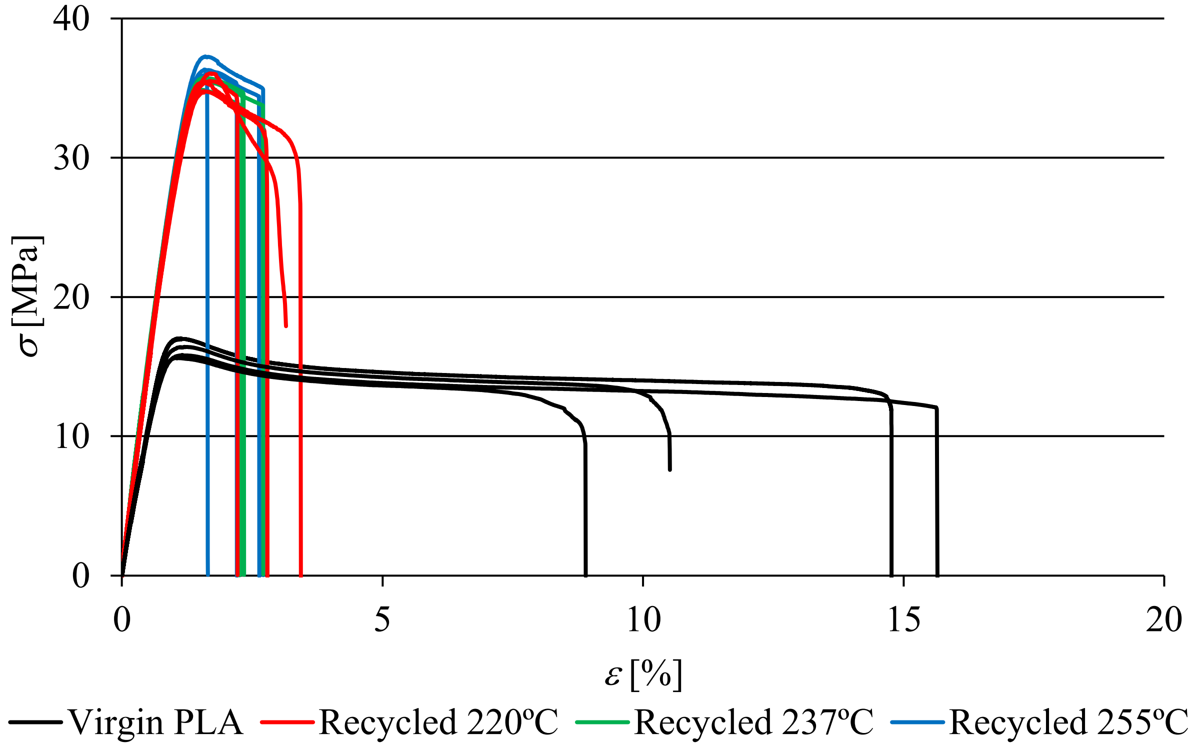

Figure 5. Combined σ-ε curves of virgin and recycled PLA from tensile tests at different printing temperatures (220 °C, 237 °C, and 255 °C).

Table 6. Mechanical properties obtained from tensile tests of virgin and recycled PLA at different printing temperatures (220, 237 and 255 °C).

	Manufacturer (Virgin)	Manufacturer (Recycled)	Virgin PLA	Recycled PLA (220 °C)	Recycled PLA (237 °C)	Recycled PLA (255 °C)
E (MPa)	2580 ± 220 (8.53%)	3500	2130.68 ± 77.57 (3.64%)	2958.00 ± 53.43 (1.81%)	3090.38 ± 123.5 (4.00%)	2961.03 ± 9.45 (0.32%)
Yield stress (MPa)	-	-	7.78 ± 1.80 (23.21%)	23.85 ± 0.46 (1.94%)	22.80 ± 1.52 (6.68%)	26.06 ± 1.72 (6.59%)
Tensile strength (MPa)	35 ± 4 (11.43%)	45	16.23 ± 0.54 (3.35%)	35.43 ± 0.45 (1.27%)	35.43 ± 0.34 (0.95%)	36.42 ± 0.52 (1.41%)
Strain at break (%)	-	-	12.46 ± 2.83 (22.69%)	2.87 ± 0.37 (12.97%)	2.41 ± 0.18 (7.37%)	2.30 ± 0.42 (18.36%)

Figure 5 shows all σ-ε curves and highlights marked differences between the materials. Virgin printed PLA has significantly higher ductility, with a deformation capacity up to eight times higher than that of recycled PLA. Conversely, recycled PLA has over twice the tensile strength, confirming the improved mechanical properties of the material induced by the recycling process. A moderate decrease in strain at break with increasing extrusion temperature is also visible, suggesting a progressive embrittlement of the material. Table 6 also allows for a comparison of the mechanical performance of printed PLA with that of materials supplied by the manufacturer. The manufacturer's virgin PLA has a *E* of 2580 ± 220 MPa (CoV = 8.53%) and a yield stress of 35 ± 4 MPa (CoV = 11.43%), while the manufacturer's recycled PLA has higher values, with a reported *E* of 3500 MPa and a yield stress of 45 MPa. This initial difference between virgin and recycled materials is partially reflected in the printed test specimens, where recycled PLA consistently shows a higher *E* and higher tensile strength. Direct comparison between the printed materials confirms that the tensile strength of the virgin PLA print remains significantly lower than that of the recycled PLA, representing less than half its value. Furthermore, the CoV of printed recycled PLA are generally lower than those of virgin PLA, a result that contradicts some trends reported in the literature, where recycled PLA is often described as more variable [29,39]. The *E* values also show several important trends. The printed virgin PLA has a *E* approximately 17% lower than that of the manufacturer, presumably because of the printing process or possible heterogeneity in the batch of virgin material. Printed recycled PLA, on the other hand, has a higher *E* than virgin PLA, also slightly higher than the manufacturer's recycled material. These observations are consistent with certain studies that associate the increased stiffness of recycled PLA with molecular restructuring induced by recycling cycles. Furthermore, the influence of printing temperature on *E* remains low:

between 220 °C and 255 °C, the variation is very limited (approximately 3 MPa), with a maximum observed at 237 °C. CoV analysis confirms better reproducibility of the mechanical properties for recycled PLA, particularly at 220 °C and 255 °C, compared to virgin printed PLA. The slight increase in CoV observed at 237 °C could be related to local variations in interlayer adhesion or microscopic defects. Overall, the low dispersion observed for recycled PLA suggests good structural homogeneity of the material used. Finally, the results associated with the elastic limit confirm the general trends observed. The manufacturer's virgin material has a yield stress approximately 4.5 times higher than that of printed virgin PLA, and on average 1.4 times higher than that of printed recycled PLA. It should be noted that differences in mechanical properties may be influenced not only by the recycling process but also by variations in base resin formulation between different suppliers.

Between the results obtained on recycled PLA at different temperatures, the results of the tensile tests on recycled PLA printed at 220 °C confirm the expected evolution of the material after recycling, i.e., oven virgin PLA with an increase in *E* (38.8%), yield stress (206.6%) and tensile strength (118.3%), and a reduction of strain at break (77.0%), in line with the trends reported in the literature [40]. A comparison with virgin PLA reveals a higher *E* and significantly reduced ductility, approximately five times lower, confirming that the material is stiffer but also more brittle due to the molecular changes induced by recycling. All test specimens failed during testing, and the values for *E* and tensile strength show very low dispersion (CoV of 1.46% and 2.00%), indicating good reproducibility and satisfactory mechanical homogeneity. The yield stress shows slightly greater variability (CoV of 6.68%), probably related to local microstructural variations or slight fluctuations in the flow of material during printing, while the deformation at break remains the most dispersed property (CoV of 12.97%), reflecting the increased brittleness of a polymer that has undergone thermal or chemical degradation. Contrary to what is usually suggested in the literature, which indicates more uniform behavior for virgin PLA [29], the results obtained here show greater consistency for recycled PLA, possibly linked to homogenization of the material during melting in the recycling process. For the tensile tests carried out on recycled PLA printed at 237 °C, all other printing parameters being identical to those used at 220 °C, the results were overall similar. Thus, over virgin PLA, the changes were an increase in *E* (45.0%), yield stress (193.1%), and maximum stress (118.3%), and a reduction in strain at break (80.7%). The dispersions were acceptable, with higher values over 220 °C for *E* and yield stress 4.00% and 6.68%), and lower values for the tensile strength and strain at break (0.95% and 7.37%, respectively). For the recycled PLA test specimens printed at 255 °C, results were very similar. Table 6 highlights the excellent consistency of the mechanical properties of recycled PLA printed at 255 °C and the minor differences compared to 220 °C and 237 °C (over virgin PLA, the variations were an increase in *E* (39.0%), yield stress (235.0%), and maximum stress (124.4%), and a reduction in strain at break (81.5%)). *E* has an extremely low CoV (0.32%). The elastic limit, with a CoV of 6.59%, also remains within satisfactory values for a series of four tests. The tensile strength is notable for its high homogeneity (CoV of 1.41%), reflecting uniform melting of the material and good interlayer cohesion at this printing temperature. However, strain at break remains the most variable property (CoV of 18.36%), probably due to microscopic defects such as voids or irregular adhesion between layers, which can cause premature breakage. Overall, recycled PLA printed at 255 °C exhibits good mechanical stability and high print quality, despite slightly more dispersed ductility. Bergaliyeva et al. [41] analyzed the thermal, morphological, and mechanical behavior of 3D-printed PLA blends combining virgin and recycled material in varying proportions. The tensile strength increased with higher recycled fractions, rising from 44.2 MPa for virgin PLA to 52.6 MPa for blends with the highest recycled content. These findings indicate that recycling can enhance the mechanical performance of PLA-based parts, although the resulting material exhibits distinct structural characteristics compared to purely virgin PLA.

To complement the mechanical analysis, Figure 6 illustrates the fracture characteristics of one specimen from each test series, while Figure 7 presents all the samples after tensile testing, highlighting their respective fracture zones. Although some specimens did not fracture exactly at the mid-length of the gauge section, all failures occurred within the constant cross-section region of the specimens. This finding ensures that the stress state remained uniform and that the results are valid according to standard tensile testing criteria. The observed variability in fracture location is attributed to local heterogeneities typical of FDM-processed materials, such as interlayer defects or minor voids, which can locally initiate failure without compromising the overall validity of the test.

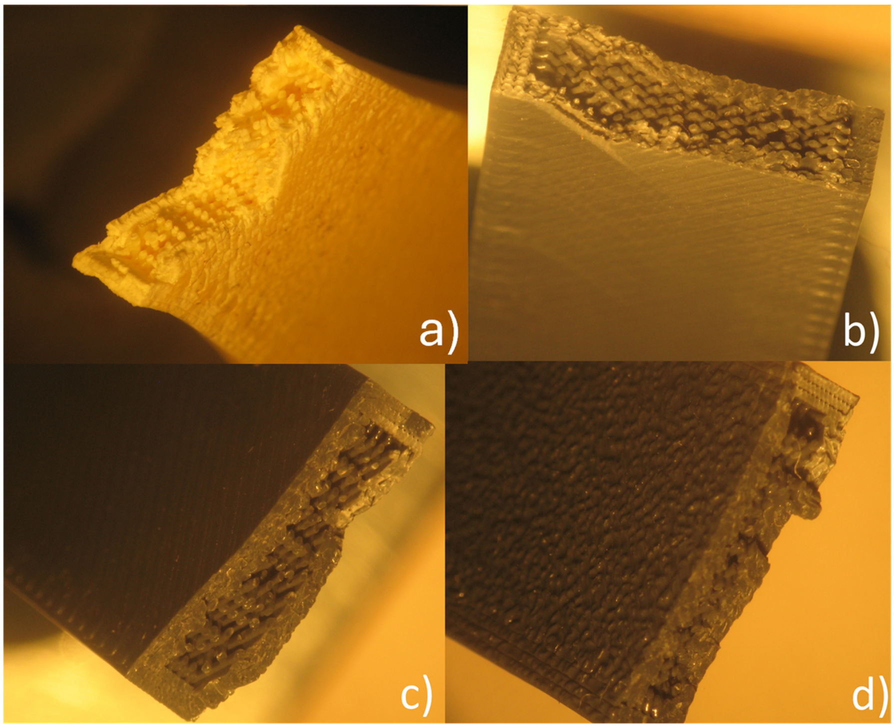

Figure 6. Fracture surfaces of tensile PLA specimens: virgin PLA (**a**) and recycled PLA printed at 220 °C (**b**), 237 °C (**c**), and 255 °C (**d**).

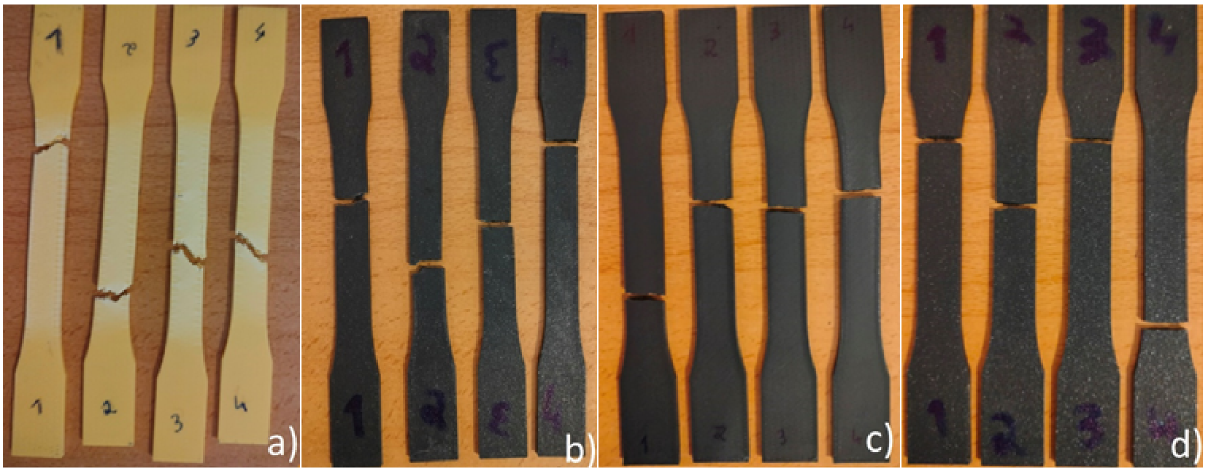

Figure 7. Tensile PLA specimens after testing: virgin PLA (**a**) and recycled PLA printed at 220 °C (**b**), 237 °C (**c**), and 255 °C (**d**).

Virgin PLA test specimens exhibit significantly more ductile behavior at fracture than those made from recycled material. This difference can be explained by the morphology of the fracture surfaces: the new PLA samples exhibit macroscopically irregular failure pathway, typical of tough virgin resin and characteristic of ductile fracture, while the recycled PLA test pieces show smoother and more homogeneous surfaces, associated with a clean and perpendicular macro-crack orientation, typical of brittle fracture. This fracture occurs because the embrittled recycled matrix favors rapid and collinear trans-track cleavage over wavy inter-filament shearing path variations. The printing temperature appears to have a limited influence on the fracture mode of recycled PLA. Only two specimens printed at 220 °C and one specimen printed at 237 °C show slight surface irregularities, while none of the test pieces printed at 255 °C showed this behavior, confirming the tendency toward more brittle fracture with increasing extrusion temperature. These clear differences in fracture surface morphology between virgin and recycled PLA highlight the transition from ductile to brittle behavior induced by the recycling process.

3.2. Bending Tests

The bending tests were performed on 16 specimens manufactured at different extrusion temperatures to characterize the mechanical behavior of virgin and recycled PLA under bending stress. During each test, the applied load and displacement of the loading point were recorded, enabling the construction of σ-ε curves for all samples (Figure 8). The results obtained, summarized in Table 7, include E_f, yield stress, and bending strength for each material and printing temperature. These data will serve as the basis for a detailed discussion of the effects of material origin and extrusion temperature on mechanical properties in the following paragraphs.

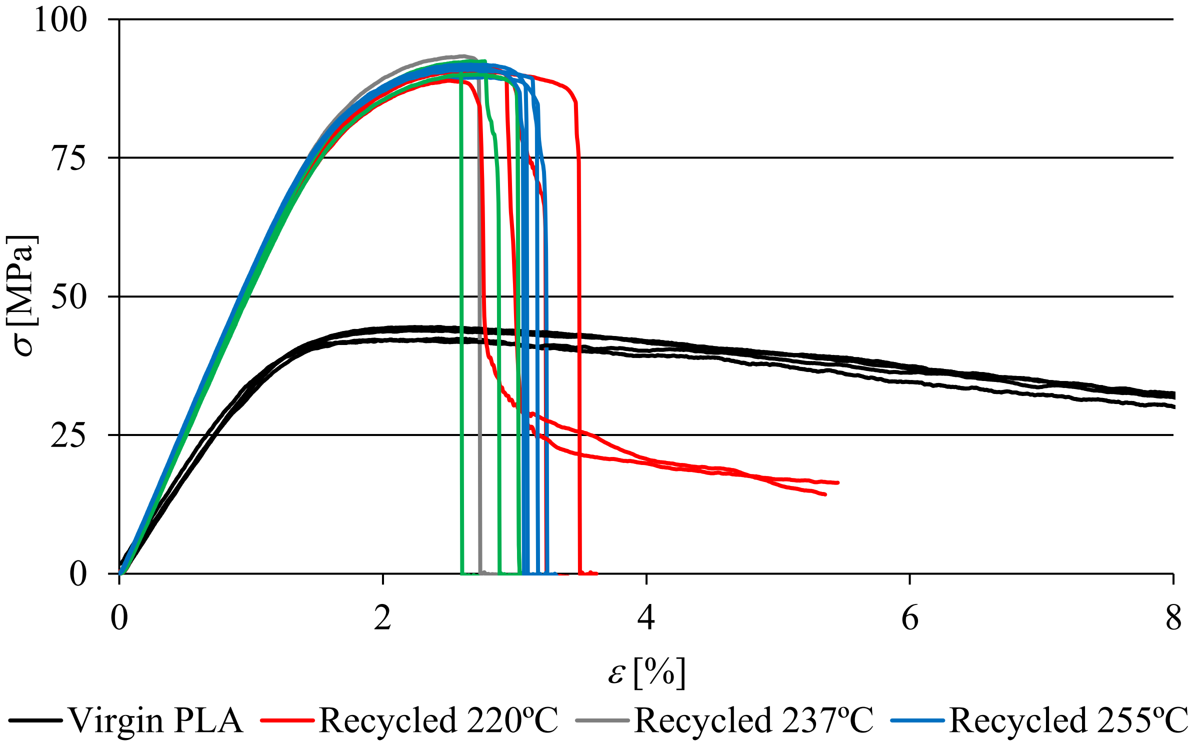

Figure 8. Combined σ-ε curves of virgin and recycled PLA from bending tests at different printing temperatures (220 °C, 237 °C, and 255 °C).

Table 7. Mechanical properties obtained from the bending test of virgin and recycled PLA at different printing temperatures (220, 237 and 255 °C).

	Manufacturer (virgin)	**Virgin PLA**	**Recycled PLA (220 °C)**	**Recycled PLA (237 °C)**	**Recycled PLA (255 °C)**
E_f (MPa)	2370 ± 150 (6.33)	3669.65 ± 88.21 (2.40%)	5255.50 ± 14.20 (0.27%)	5262.20 ± 86.08 (1.64%)	5436.05 ± 56.76 (1.04%)
Yield stress (MPa)	59 ± 6 (10.17)	20.16 ± 10.19 (50.53%)	63.29 ± 8.51 (13.44%)	74.66 ± 5.13 (6.88%)	63.90 ± 2.20 (3.44%)
Bending strength (MPa)	-	43.25 ± 0.97 (2.25%)	90.40 ± 0.90 (1.00%)	91.96 ± 1.21 (1.31%)	90.89 ± 0.82 (0.91%)

Figure 8 reveals two main trends. First, virgin PLA has significantly lower bending strength, with maximum stress values less than half those observed for recycled PLA. Second, varying the extrusion temperature of recycled PLA does not cause significant changes in the bending strength, suggesting good mechanical stability of the material when exposed to temperature variations within the range studied (220–255 °C). Table 7 shows that, in terms of E_f, virgin PLA exhibits an average value of 3669.65 MPa, which is lower than that of recycled PLA, with values ranging from 5255.50 to 5436.05 MPa depending on the printing temperature. A slight increase in E_f is observed with increasing extrusion temperature, indicating a moderate but positive effect of processing temperature on the stiffness of recycled PLA. Furthermore, the low variability of the results for recycled PLA (CoV ≤ 1.64%) reflects better mechanical homogeneity compared to virgin PLA, whose CoV for elastic stress reaches 2.40%. Examination of the yield stress and bending strength values also shows that recycled PLA has higher strength than virgin PLA. The yield stress values vary with the printing temperature, suggesting that there is an optimal temperature of around 237 °C to maximize the bending strength of recycled PLA (74.66 MPa).

Finally, the results highlight the reliability of the measurements for recycled PLA, with very low coefficients of variation for the bending strength (0.91–1.31%), while virgin PLA shows greater variations, particularly for the bending strength recorded during the tests, making these values less representative. In summary, the comparative analysis confirms that recycled PLA has superior mechanical performance to virgin PLA, with higher stiffness and strength, as well as better homogeneity. The extrusion temperature slightly influences E_f and the elastic stress, and an optimal value appears to be around 237 °C to maximize the material's strength. These observations highlight the value of recycling PLA for applications requiring reliable and stable mechanical performance.

Considering the recycled PLA specimens at three different temperatures, initially the data for recycled PLA printed at 220 °C reveal a significant difference after recycling, i.e., over virgin PLA. The properties' variations were as follows: increase in E_f (43.2%), yield stress (213.9%), and bending strength (109.0%). In view of these results, over virgin PLA, significant improvements were attained, inclusively an over two-fold improvement in the bending strength. After testing, it was found that all test specimens recycled at 220 °C broke during testing. E_f and the bending strength had negligible dispersion, with CoV of 0.27% and 1.00%, respectively, showing the mechanical homogeneity between specimens on these properties. On the other hand, the yield stress data led to higher variability (CoV of 13.44%), as it was found for the tensile test data. Once again, the CoV results were much more consistent that those obtained for virgin PLA, which was previously associated with material homogenization taking place during recycling. These results show that, despite the recycled nature of the material, the test specimens extruded at 220 °C exhibit stable and reproducible mechanical behavior. The low E_f and bending strength dispersion indicates good homogeneity of the samples, and the measured properties remain within the expected limits for this type of PLA. The recycled PLA at 237 °C, with all other printing parameters unchanged over 220 °C, showed proximal results to those at 220 °C. Comparing the relevant data over virgin PLA, the property increases were 43.4% for E_f, 270.3% for the yield stress, and 112.6% for the bending strength. The maximum dispersion between the measured data was smaller than that for 220 °C. The CoV's were 1.64% for E_f, 6.88% for the yield stress, and 1.31% for the bending strength. The bending strength remains generally satisfactory compared to the reference values reported in the literature [29]. At 255 °C, the recycled PLA test data was also identical to the previous recycling temperatures. Always compared to virgin PLA, all three measured quantities increased, in this case by 48.1% (E_f), 217.0% (yield stress), and 110.2% (bending strength). These results show that recycled PLA extruded at 255 °C retains stable and uniform mechanical behavior in terms of both stiffness and bending strength. The low variability of the measured values highlights the reproducibility of the printing process at this temperature and the consistency of the material's mechanical properties, confirming the robustness and reliability of recycled PLA when processed at high extrusion temperatures. Comparing the three recycling temperatures, despite the small variations, the highest E_f was achieved at 255 °C, while 237 °C recycling temperature provided the maximum bending strength.

A series of photographs of the test specimens after the flexural tests is presented in Figures 9 and 10, providing a visual complement to the previously discussed quantitative data. These images provide a better understanding of the fracture modes observed for the different specimens and confirm the highlighted trends.

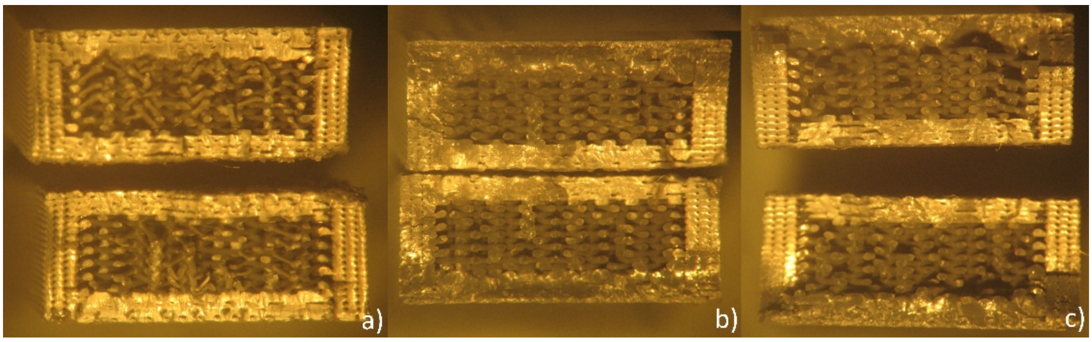

Figure 9. Fracture surfaces of flexural recycled PLA specimens: (**a**) recycled PLA printed at 220 °C, (**b**) recycled PLA printed at 237 °C, and (**c**) recycled PLA printed at 255 °C.

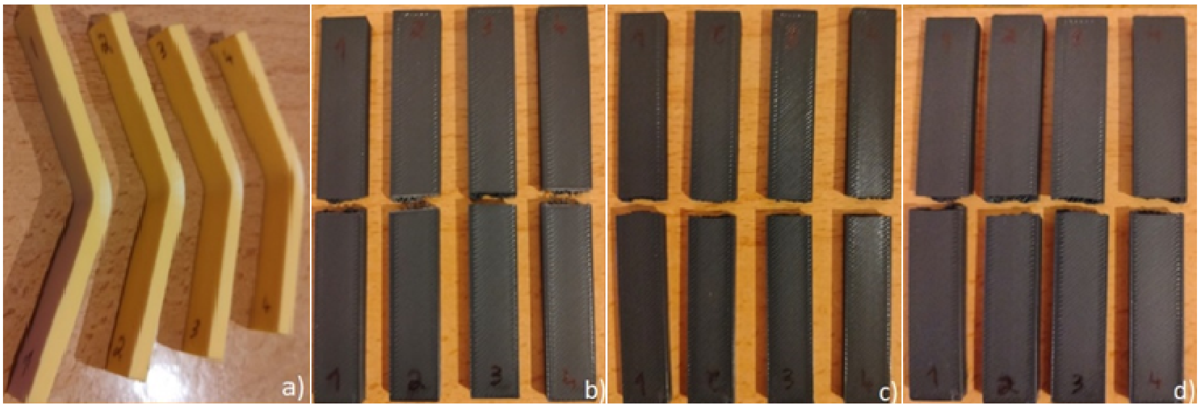

Figure 10. Flexural PLA specimens after testing: virgin PLA (**a**) and recycled PLA printed at 220 °C (**b**), 237 °C (**c**), and 255 °C (**d**).

As shown in the figures, the recycled PLA test specimens mainly exhibit brittle fractures, characterized by relatively smooth and homogeneous surfaces. This is consistent with the presented mechanical data, where recycled PLA showed higher stiffness and strength but low plastic deformation capacity. A more detailed observation of Figure 9 indicates that samples printed at 220 °C exhibit slightly more irregular areas, suggesting higher ductility, while specimens printed at 237 °C and 255 °C show more regular fracture surfaces, confirming the brittle nature of the material. These minor differences can be attributed to better interlayer cohesion achieved at higher printing temperatures, thus limiting deformation before fracture. However, as shown in Figure 10a, the virgin PLA specimens did not break during the flexural test but exhibited significant deformation, which is consistent with the previously observed low stiffness and lower strength. This behavior indicates a significantly more ductile behavior. Thus, although recycled PLA offers superior strength and stiffness, its fracture mode remains predominantly brittle, unlike virgin PLA, which can undergo significant plastic deformation before breaking. Overall, the photographic observations corroborate the trends identified in the quantitative analyses: recycled PLA exhibits superior mechanical performance in terms of stiffness and maximum stress, while virgin PLA shows greater ductility. These results illustrate the trade-off between strength and plasticity, influenced by the origin of the material and the printing temperature. Karayer et al. [42] examined the influence of recycling and post-processing on the bending mechanical response of FDM-printed PLA under varying infill densities, layer thicknesses, and build orientations. Scanning electron microscopy (SEM) observations revealed that although higher infill promoted improved interlayer bonding, recycled PLA exhibited a greater tendency toward brittle fracture, in contrast to the more ductile features observed in sterilized specimens, which corroborates the finding of the present paper.

3.3. Fracture Tests

Given the added variable of temperature, two sets of results are shown for each testing temperature. All specimens were tested with the 0.125 lb impactor. The obtained results are visually presented by testing temperature in Figure 11 for 24.1 and −30.9 °C, and the respective details in Table 8, to highlight the influence of testing temperature in energy absorbing capabilities of virgin PLA and recycled PLA printed at three different temperatures.

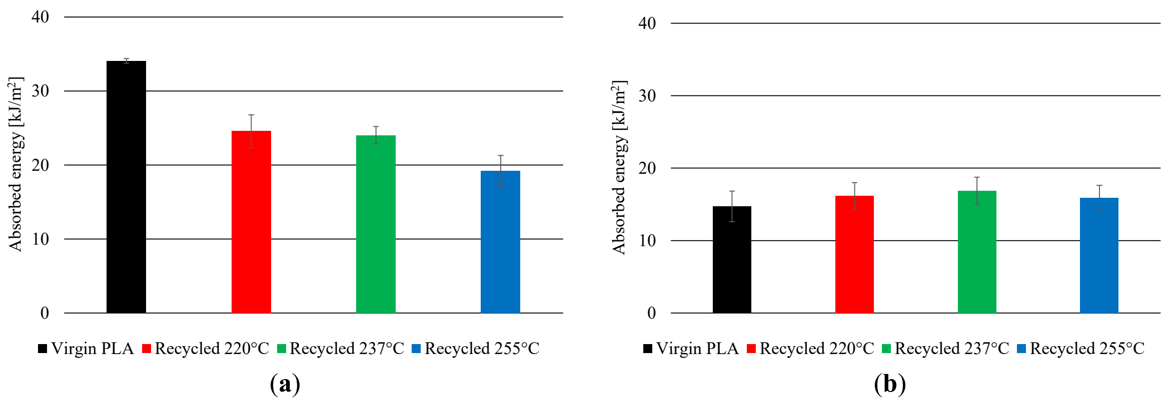

Figure 11. Comparison of absorbed energy at 24.1 °C (**a**) and −30.9 °C (**b**).

Table 8. Absorbed energy obtained from the Charpy test of virgin and recycled PLA at different printing temperatures (220, 237 and 255 °C), tested at 24.1 °C and −30.9 °C.

Temperature	Material	Absorbed Energy (kJ/m^2)	Standard Deviation (kJ/m^2)	CoV (%)
24.1 °C	Virgin PLA	34.08	0.31	0.91
	Recycled PLA (220 °C)	24.57	2.23	9.06
	Recycled PLA (237 °C)	24.04	1.17	4.87
	Recycled PLA (255 °C)	19.21	2.08	10.80
−30.9 °C	Virgin PLA	14.72	2.11	14.36
	Recycled PLA (220 °C)	16.15	1.85	11.45
	Recycled PLA (237 °C)	16.86	1.89	11.23
	Recycled PLA (255 °C)	15.89	1.73	10.87

The fracture behavior at −30.9 °C cannot be directly correlated with the tensile or flexural stress-strain curves, as these tests involve different loading conditions and failure mechanisms. Tensile and flexural tests describe the quasi-static response at room temperature, whereas low temperature Charpy testing reflects impact behavior under restricted molecular mobility, where failure is governed primarily by crack initiation and propagation rather than large scale plastic deformation. Therefore, any comparison between these tests should be considered qualitative and based on overall ductility and energy absorption capacity inferred from tensile behavior.

Between testing temperatures, virgin PLA has the best energy absorption capabilities at 24.1 °C. Between the recycled test specimens the group printed at 220 °C has the highest energy absorbed, closely followed by the group printed at 237 °C and lastly test specimens printed at 255 °C. This data leads to conclude that the higher the printing temperature for recycled PLA the lower its energy absorption properties will be. Moreover, while 237 °C is not the printing temperature maximizing energy absorption of recycled PLA, it is the one that maximizes test specimens' consistency, with an average CoV of 4.87%. Testing at low temperature (−30.9 °C) shows very different results from the data collected at 24.1 °C. Virgin PLA is no longer the material with the best energy absorption properties at −30.9 °C, nor recycled PLA printed at 220 °C. Recycled PLA printed at 237 °C is the one that shows the best results of Charpy testing at negative temperature compared with the other test specimens in analysis. Given how close its energy absorption values are at 24.1 °C to recycled PLA printed at 220 °C, it can be said that, overall, recycled PLA printed at 237 °C has the best energy absorption properties between all the recycled test specimens.

Between different materials, the following conclusions were taken:

- Virgin PLA: The results at 24.1 °C were considered robust, since the scatter was minimum (CoV = 0.91%). Virgin PLA can absorb a much higher amount of energy at 24.1 °C than at −30.9 °C, more than the double (+131.5%). Another important characteristic is that virgin PLA tested at negative temperature has a much higher CoV (14.36%) than at room temperature.
- Recycled PLA printed at 220 °C. With a similar tendency to virgin PLA, recycled PLA printed at 220 °C has a better energy absorption capacity at 24.1 °C than at −30.9 °C. However, the difference is shortened since the material tested at room temperature only absorbs 52.1% more energy than the same material tested at −30.9 °C. Another important note is that CoV is still higher for test specimens tested in negative temperatures (11.45%) but is much more similar to its value at 24.1 °C (9.06%).
- Recycled PLA printed at 237 °C: Higher energy absorption capabilities and lower CoV of the material at 24.1 °C than at −30.9 °C (42.6% higher), equal to 220 °C. An important observation of this set of specimens is that CoV at 24.1 °C is much lower than any other group of recycled specimens (4.87%). This could point towards the existence of an optimal processing temperature for energy absorption properties maximization situated near 237 °C. At −30.9 °C, CoV = 11.23%.
- Recycled PLA printed at 255 °C: The absorbed energy is still higher at 24.1 °C than at −30.9 °C (by 20.9%), although the two values have approached much more. Is also important to note a similar CoV for both testing temperatures (10.80% and 10.87% for 24.1 °C and −30.9 °C, respectively).

After the Charpy testing was completed the fractured halves of the test specimens were collected and sorted in a way that allowed to observe the surface of the test specimens and deduce which type of rupture occurred in each one. Figure 12 shows representative test specimen halves of all materials and temperatures. After close inspection of Figure 12 it is noticeable that virgin PLA test specimens show a more irregular fracture surface than recycled ones. This leads to conclude that the dominant fracture more in virgin PLA Charpy testing was ductile since the material can absorb more energy due to having a higher plastic deformation than its recycled counterpart, which exhibits a more brittle behavior.

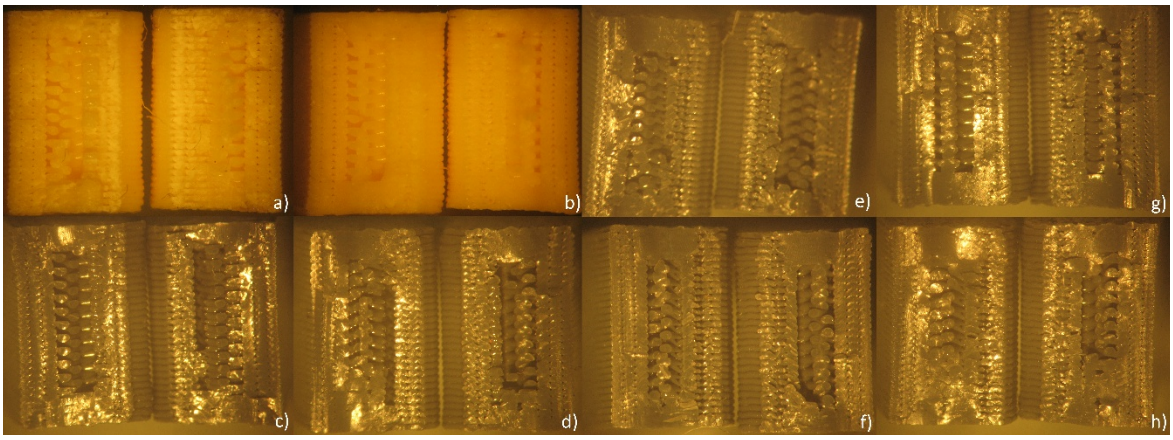

Figure 12. Fracture surfaces of Charpy PLA specimens: virgin PLA at 24.1 °C (**a**), virgin PLA at −30.9 °C (**b**), recycled PLA (220 °C) at 24.1 °C (**c**), recycled PLA (220 °C) at −30.9 °C (**d**), recycled PLA (237 °C) at 24.1 °C (**e**), recycled PLA (237 °C) at −30.9 °C (**f**), recycled PLA (255 °C) at 24.1 °C (**g**), and recycled PLA (255 °C) at −30.9 °C (**h**).

4. Conclusions

This work assessed the feasibility of using recycled PLA in FDM additive manufacturing by examining its tensile, flexural, and impact behavior under controlled printing conditions. The results showed that recycled PLA can deliver mechanical performance that is comparable to virgin PLA, but in many cases superior, provided that the application does not rely heavily on ductility. Recycled PLA consistently exhibited higher E and E_f, as well as higher tensile and bending strengths, regardless of the printing temperature used. These gains are likely associated with molecular rearrangements and partial chain scission occurring during the recycling process, which tend to increase stiffness but reduce deformability. As a result, all recycled PLA samples showed markedly lower strain at break and more brittle fracture behavior than their virgin counterparts. Despite this increased brittleness, the mechanical response of recycled PLA was found to be highly reproducible, with generally low CoV across specimens. The printing temperature had only a modest influence on stiffness and strength, but it played a more noticeable role in toughness. For room-temperature Charpy testing, recycled PLA printed at 220 °C showed the highest impact absorption among the recycled groups, though still below virgin PLA. At sub-zero temperatures, however, the trend shifted: recycled PLA printed at 237 °C demonstrated the best impact performance and the most consistent results, suggesting that this temperature provides a balanced compromise between structural stiffness and interlayer cohesion. It should be noted that the optimization points specifically aim to identify the processing window for the studied recycled formulation to balance interlayer bonding against thermal degradation, rather than establishing a universal absolute temperature baseline for all commercial PLA brands. Overall, the obtained findings confirm that recycled PLA is a viable and reliable material for FDM, particularly in applications where stiffness and strength are prioritized over ductility or high impact resistance. Recycled PLA has thus potential as a sustainable and cost-effective alternative to virgin filament, contributing to waste reduction in additive manufacturing without compromising the functional performance required in many engineering applications. While brittleness remains a limiting factor, optimizing printing parameters, especially extrusion temperature, can partially mitigate this behavior.

Author Contributions

M.A.R.V.E.: investigation, data curation, visualization, writing original draft; R.D.S.G.C.: methodology, data curation, visualization, supervision; H.B.: data curation, visualization, writing—reviewing and editing; J.I.P.S.: data curation, visualization, writing—reviewing and editing. All authors have read and agreed to the published version of the manuscript.

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Informed Consent Statement

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Data Availability Statement

Not applicable.

Conflicts of Interest

The authors declare no conflict of interest. Given the role as Senior Consulting Board Member, Raul D. S. G. Campilho had no involvement in the peer review of this paper and had no access to information regarding its peer-review process. Full responsibility for the editorial process of this paper was delegated to another editor of the journal.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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