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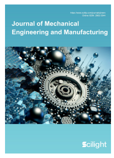

Article

Development of a Polymer Filament Extruder: Recycling 3D Printer Waste

André Guimarães [1,2,3,]*, Samuel Messias [3], João Lopes [3], José Salgueiro [3] and Daniel Gaspar [1,2,3]

1 CISeD–Research Centre for Digital Services, Polytechnic of Viseu, Campus Politécnico Santa Maria, Av. Cor. José Maria Vale de Andrade, 3504-510 Viseu, Portugal
2 CISE–Electromechatronic Systems Research Centre, Department of Electromechanical Engineering, University of Beira Interior, 6201-001 Covilhã, Portugal
3 Polytechnic Institute of Viseu, Department of Mechanical Engineering and Industrial Management, School of Technology and Management, 3504-510 Viseu, Portugal
* Correspondence: andre.m.guimaraes@ubi.pt or aguimaraes@estgv.ipv.pt

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Abstract: This article presents the development of a polymer filament extruder to recycle waste from 3D printing. As additive manufacturing grows within Industry 4.0, managing thermoplastic waste like PLA, ABS, and PET has become a key challenge. The proposed modular system includes a shredder, an extrusion unit, and a winding module to produce high-quality filaments with precise dimensions (1.75 ± 0.03 mm), ensuring compatibility with 3D printers. Aligned with circular economy principles, the system promotes material reuse and reduces environmental impact. Results confirm its technical and environmental feasibility, with potential for large-scale use. Future improvements may include recycling other polymers and using smart sensors and algorithms to optimize the process.

Keywords: additive manufacturing; polymer filament extrusion; circular economy in 3D printing; recycling; PLA recycling; sustainable materials engineering

1. Introduction

New technologies have evolved rapidly in recent years, playing an increasingly important role in modernizing and improving business processes [1]. Among these, 3D printing stands out as one of the most dynamic technologies, potentially becoming an essential tool in the era of Industry 4.0 [2]. However, using polymers in 3D printing brings greater responsibility concerning the lifecycle of these materials, as the process often generates a significant amount of unavoidable waste [3].

In this context, recycling becomes crucial to ensure resource sustainability and efficient waste management. Many materials used in 3D printing, such as PLA, ABS, PET, and other thermoplastics, have properties that, while advantageous for 3D printing, can complicate their reintegration into sustainable production cycles. Therefore, recycling waste generated during the 3D printing process is a key strategy to mitigate environmental impact and promote a circular economy in this sector [4].

Plastics remain valuable resources at the end of their lifecycle. In 2016, of the waste collected in the European Union, Norway, and Switzerland, 31.1% was recycled, 41.6% underwent energy recovery, and 27.3% was sent to landfills. For the first time, the amount of recycled plastic exceeded that disposed of in landfills [5,6]. Between 2006 and 2016, the volumes of plastic waste collected for recycling increased by approximately 80%. These numbers are encouraging, and now is the time to use recycled material not only for plastic bags but also for producing functional components. In polymer processing, 3D printing has emerged as the preferred technology for making functional components applicable in various fields, such as agriculture, biomedicine, uncrewed aerial vehicles (UAVs), bioprinting, membrane technology (selective barriers), aerospace, civil engineering, metal matrix composites, multi-material components, and food production [3,7–9].

This study focuses on creating an innovative solution for recycling waste generated by 3D printing. The main objective is to develop equipment that enables the reuse of this waste in the printing process, contributing to a more sustainable and efficient approach.

Building on previous work involving the development of a polymer shredder for waste generated by 3D printers [10], this study advances the state of the art by designing and constructing a complete, modular system that enables the closed-loop reuse of 3D printing waste. The novelty of this work lies in integrating a customized extrusion unit, designed explicitly for recycled PLA, and a controlled filament winding system, both supported by accessible components such as stepper motors and safety sensors. Unlike existing solutions, which often rely on commercially available extruders with limited adaptability, the proposed equipment was designed from the ground up, including the geometric modeling and dimensioning of the screw, to ensure process stability and high-quality filament production (1.75 ± 0.03 mm). This integrated and scalable solution contributes to circular economy goals and promotes sustainable practices in additive manufacturing.

2. Literature Review

2.1. 3D Printers Using Recycled Material

3D printing can be recognized as a clean manufacturing technology when using post-consumer recycled polymers to produce new components or parts [11]. Fused Deposition Modeling (FDM), one of the most popular types of additive manufacturing, utilizes a fused extrusion process to deposit thermoplastic polymer filaments in a predetermined pattern [4]. Among the polymers used in the FDM process, Polylactic Acid (PLA) and Acrylonitrile-Butadiene-Styrene (ABS) copolymers are the most widely referenced materials [12]. However, the use of these materials in the form of recycled filaments has been sparsely documented, particularly in their application as raw materials after the end of their lifecycle, i.e., post-consumption. Some challenges may arise due to the recycling process of these polymers [13].

2.2. Recycled Materials Used in 3D Printing

Recycled polymeric materials have gained prominence in 3D Printing as a sustainable and cost-effective alternative, aligning with the principles of the circular economy. Post-consumer or industrial plastic waste can be processed and transformed into new materials for Printing, reducing environmental impact and promoting resource reuse [4,14].

Creating polymer blends from recycled materials has proven to be a promising approach for economically reusing mixed waste streams [15]. Additionally, combining different polymers allows for simple adjustments to their mechanical properties or the enhancement of specific characteristics while maintaining other desirable qualities [16].

PLA is frequently recovered from print supports or discarded parts and is among the most commonly used recycled polymers. Recycled ABS is also widely utilized, although it requires greater control during processing due to its thermal properties [17–19].

Recycled polymers can be used in the form of filaments or directly as particles, such as flakes or pellets, in printing systems that support Fused Particle Fabrication (FPF) [20,21]. Despite environmental advantages, recycled materials may experience some degradation in mechanical properties after multiple processing cycles. However, technological advancements, such as the addition of reinforcements or the use of specialized equipment, have mitigated these limitations, making recycled polymers an increasingly viable and accessible option in 3D Printing [7,14,21].

2.3. Production of 3D Printing Filaments Using Recycled Materials

The production of 3D printing filaments from recycled material derived from 3D printer waste is emerging as a sustainable and innovative solution to combat plastic waste [22]. This process involves collecting waste generated during printing operations, such as discarded supports, defective parts, or leftover filaments, which are shredded and transformed into new raw materials [23].

Plastic waste, such as PLA and ABS, undergoes a grinding process to be reduced to smaller particles, which are then melted and extruded into reusable filaments. This cycle significantly reduces the amount of discarded plastic, promoting a circular economy [24].

Despite environmental advantages, recycled material may experience degradation in mechanical properties due to repeated heating and extrusion cycles. To address this issue, additives are often incorporated to enhance the performance of recycled filaments, ensuring their quality and functionality [4,16,23,24].

The production of recycled filaments reduces the environmental impact of 3D printing and lowers production costs, making the technology more accessible and sustainable for domestic, educational, and industrial users. This method represents a significant step in integrating sustainability into modern additive manufacturing practices [11,25].

Studies such as [23] highlight the production of recycled PLA filaments from 3D-printed waste and biocomposites reinforced with micro- and nanocellulose. The process involved shredding, sieving, and air-cleaning the waste, followed by drying to remove moisture and impurities. The materials were mixed in specialized equipment, pressed into thin sheets, and extruded to form filaments. To improve quality, recycled PLA was blended with virgin PLA in specific proportions, optimizing mechanical and thermal properties. The filament diameter was carefully controlled to ensure compatibility with 3D printers. The result was a high-quality recycled filament with performance comparable to commercial alternatives, demonstrating a sustainable and efficient solution for PLA waste reuse.

Another study [24] focused on a process where shredded material was fed into an extruder, melted, and transformed into filaments with the aid of a fan for stabilization. A precision control system, including laser sensors and a tensioning device, adjusted the filament diameter in real time to maintain a consistent 1.75 mm ± 5%. After extrusion, the filament was cooled and uniformly wound onto a spool using a winding system to prevent tangling. The temperature and material flow were adjusted according to the type of plastic, PLA or ABS, to ensure quality and consistency. This process enabled the production of recycled filaments with properties comparable to commercial ones, promoting sustainability and cost reduction.

In the work of [26], filaments were also produced using an extruder designed to transform thermoplastic materials into filaments with consistent diameters. The process involved melting the material, which was then shaped and extruded into formats suitable for 3D printers. To ensure quality, the system featured precise temperature control and production adjustments to maintain uniform filament diameter. Various tests were conducted to optimize the performance and consistency of the final product. This method allowed for producing sustainable, high-quality filaments, reducing costs and providing a more economical and environmentally friendly alternative.

2.4. Filament Extruder for 3D Printing

According to studies by [23,24,26], the extruders used for the production of filaments for 3D printers are based on conventional plastic extrusion equipment, in this case consisting of a screw system, as illustrated in Figure 1. This type of equipment is widely used in the polymer industry to manufacture profiles, sheets, or plastic films [27].

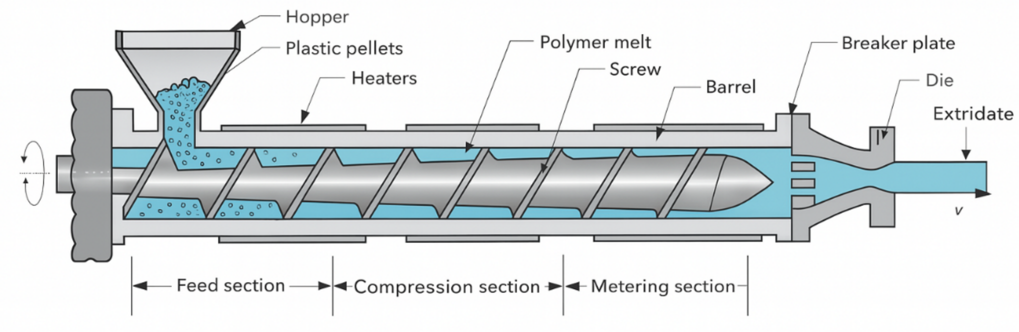

Figure 1. Diagram of a Plastic Extruder [28].

The plastic, previously shredded as described by [10], is placed into the hopper as granules. As it descends through the hopper, the plastic granules come into contact with the screw, whose rotational movement cuts the polymer molecules, generating energy in the form of heat and facilitating the material's melting process [29,30].

After melting, the plastic is transported and homogenized before exiting through the nozzle. Thus, the screw is the most crucial component of this type of system, as it performs the functions of compression, cutting, and homogenization of the polymer [31]. Screws may have different geometries depending on the polymer being processed, but they all include a feed zone, a compression zone, and a metering zone [32].

In the feed zone, the plastic from the hopper is preheated and transported to the compression zone. In this stage, the polymer, subjected to intense shear forces, melts, while the air between the particles is removed due to the generated pressures. In the metering zone, the polymer is homogenized and compressed until it reaches the necessary pressure to be pumped through the nozzle [33–35].

A significant portion of the energy supplied to the screw is used to increase the plastic's temperature as a result of the pressures created by the screw's rotational movement and the friction between the plastic and the barrel walls. The heating elements positioned along the barrel serve primarily to provide part of the heat required to melt the plastic and to stabilize its temperature [33,36].

Despite the progress in using recycled polymers in additive manufacturing, several shortcomings persist in existing studies. Most approaches either focus on isolated steps, such as filament extrusion or mechanical characterization, or rely on commercially available systems with limited adaptability and control. Moreover, virgin PLA must be blended with recycled material in many cases to achieve acceptable filament quality and dimensional consistency [23,25]. There is also a lack of detailed engineering studies addressing the geometric design of the extrusion screw and the thermal and mechanical control of the extrusion process. In this context, the present study contributes scientifically by designing, dimensioning, and constructing a fully integrated and modular system that includes shredding, extrusion with a customized screw, and precision filament winding. The system operates with recycled PLA alone and maintains dimensional stability (1.75 ± 0.03 mm), demonstrating technical robustness and alignment with circular economy principles.

3. Materials and Methods

For the development of the filament extruder for 3D printers, a detailed analysis was conducted on the critical phases of the extrusion process and the fundamental components involved.

3.1. Project Requirements Analysis

Initially, the essential technical requirements for the project were defined, including:

- Filament diameter: 1.75 mm, according to industry standards.
- Production capacity: Minimum of 1 kg/h of filament, meeting the demand for continuous production.
- Electrical supply: Compatible with 220V AC, according to the available infrastructure.
- Speed control: Adjustable screw rotation speed to accommodate different materials and processing conditions.

The diameter of 1.75 mm was chosen as it is one of the most commonly used standards in commercial FDM 3D printers, ensuring compatibility and broader usability of the recycled filament. This standard also facilitates more stable extrusion and retraction behavior than thicker filaments (e.g., 2.85 mm), which require greater torque and more robust heating systems.

3.2. Screw Design

The screw, considered the critical component in extrusion, was designed based on the following fundamental geometric parameters:

- Diameter (D): Determines the volumetric capacity and material transport efficiency.
- Channel width (b) and channel depth (h): Influence the flow and internal pressure during extrusion.
- Thread angle (θ): Affects transport efficiency and the uniformity of the melted material.
- Pitch (Ls): Defines the distance between consecutive threads, impacting the extrusion rate.
- Thread thickness (e) and clearance between the screw and barrel (δ): Crucial for minimizing losses and ensuring uniformity in processing.

An L/D ratio of 20 was selected based on established guidelines for screw design in polymer extrusion, particularly for semi-crystalline materials like PLA [37]. This ratio ensures sufficient residence time for melting and homogenization while maintaining compact equipment dimensions suitable for small-scale recycling systems.

The thread angle of 17.6° is widely adopted in thermoplastic extrusion due to its proven effectiveness in balancing shear, compression, and forward transport [37]. This angle is particularly suitable for medium-viscosity polymers such as molten PLA.

3.3. Motor Sizing

The motor was selected to provide the appropriate power required for the extrusion process, ensuring:

- Power: To maintain continuous and stable operation.
- Speed control: Enabling fine adjustments for different materials and operating conditions.

The NEMA34 closed-loop stepper motor was selected to provide high torque at low rotational speeds (up to 40 rpm), ensuring stable screw movement and precise control of extrusion rate. Its closed-loop control also avoids step loss and provides better consistency under variable load, essential for processing recycled polymers with inconsistent flow behavior.

4. Development and Sizing of the Extruder

According to [37], the commonly used thread angle is 17.6°. This value was determined empirically, as it delivers good results for most polymers, as illustrated in Figure 2.

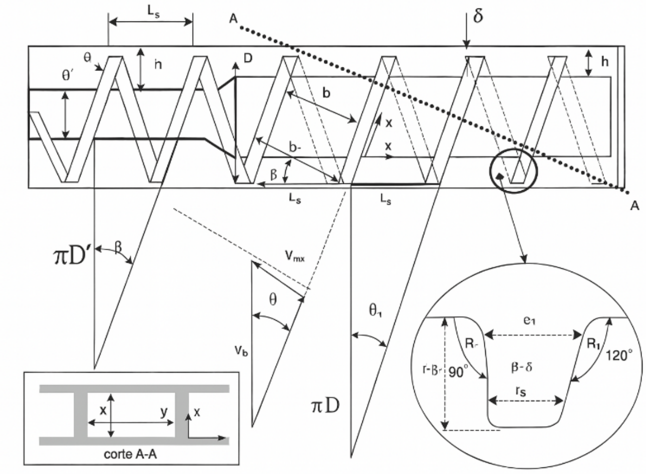

Figure 2. Schematic of the screw's geometric parameters [37].

The channel height can be determined using the diagram in Figure 3 based on the diameter "*D*" and the type of polymer. Considering a screw with a nominal diameter of 20 mm and PLA as a semi-crystalline polymer [38], the channel height is calculated as 6 mm for the feed zone and approximately 1.8 mm for the metering zone.

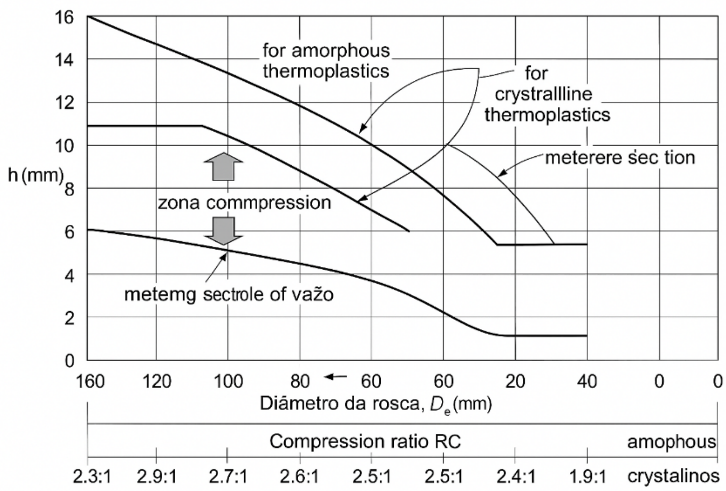

Figure 3. Diagram for determining the screw channel height [37].

According to [37], the lengths of the three characteristic zones differ. The feed zone constitutes approximately 15% of the total screw length, the compression zone 25%, and the metering zone about 60%. The total length of the screw can be determined by the L/D ratio. This parameter is significant as it is used to characterize the type of screw and its application. Assuming an L/D ratio of 20 and a nominal screw diameter of 20 mm, the total screw length is calculated as:

$$L/D = 20 \Leftrightarrow L = 400 \text{ mm}$$

Another important parameter refers to the clearance between the screw and the barrel. This clearance must be sufficient to allow the screw to rotate without colliding or making contact with the internal surface of the barrel.

However, it should not exceed a limit that would allow molten plastic to escape, as this would reduce compression and increase component wear. Typically, this parameter is set between 0.15 and 0.20, depending on the screw size as shown in Table 1.

Table 1. Clearances used between the screw and barrel [37].

Diameter (mm)	Channel at Feed hi (mm)	Channel at End hf (mm)	CR hi/hf	Clearance: Screw and Barrel (mm)	Complement
30	4.3	2.1	2.0:1	0.15	
40	5.4	2.6	2.1:1	0.15	Pitch: Ls = D to 0.7 D
60	7.5	3.4	2.2:1	0.15	
80	9.1	3.8	2.4:1	0.20	L/Ls ~ 20
100	10.7	4.3	2.5:1	0.20	
120	12	4.8	2.5:1	0.20	e ~ 0.1 D
>120	Máx. 14	Máx. 5.6	Máx. 3:1	0.25	

- Nominal screw diameter D = 20 mm;
- External screw diameter $De = D - \delta \rightarrow De$ = 19.7 mm;
- Channel height in the feed zone $h1$ = 6 mm;
- Channel height in the metering zone $h2$ = 1.8 mm;
- Length of the feed zone $L1 = 0.15 \times L \rightarrow L1$ = 60 mm;
- Length of the compression zone $L2 = 0.25 \times L \rightarrow L2$ = 100 mm;
- Length of the metering zone $L3 = 0.6 \times L \rightarrow L3$ = 240 mm.

Thus, the following screw profile was obtained, as illustrated in Figure 4:

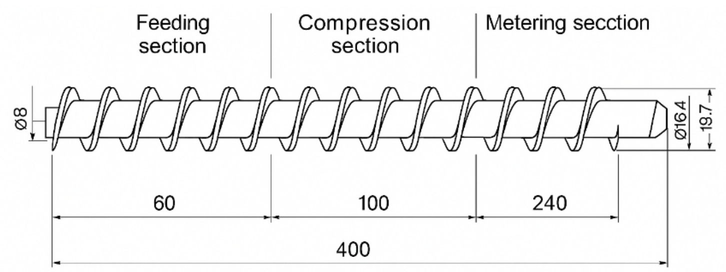

Figure 4. Screw profile according to the determined parameters.

With the screw profile defined, it is necessary to determine and verify whether the flow rate meets the requirements. This value can be calculated using Equation (1) [28]:

$$Q_d = 0.5\pi^2 D^2\, N\, h \sin\theta \cos\theta \quad (1)$$

However, this value is only valid in the absence of any restrictions on the polymer's exit, which is not the case, as it is known in advance that the nozzle, with an orifice diameter of 1.75 mm, will limit material flow [28].

Due to this restriction, the material cannot exist freely, forming back pressure that reduces the output flow rate. This reduction in flow is known as the back pressure flow rate Qb, as defined by Equation (2) [28].

$$Q_b = \frac{p\pi D h^3 \sin\theta^2}{12\eta L} \quad (2)$$

N: Screw rotation speed (rev/s)

η: Density of molten polymer (kg/m^3)

p: Pressure at the screw tip (Pa)

L: Total screw length (m)

Therefore, the actual output flow rate Qx, as shown in Equation (3), corresponds to the difference between the theoretical flow rate Qd and the back pressure flow rate Qb.

$$Q_x = Q_d - Q_b \quad (3)$$

The output flow rate Qx, as shown in Equation (4), can also be described as a function of the dimensions and shape of the nozzle [28].

$$Q_x = K_s p \tag{4}$$

where Ks = Shape factor of the nozzle.

For a nozzle with a circular orifice, the parameter Ks can be described according to Equation (5):

$$K_s = \frac{\pi D_d^4}{128\eta L_d} \text{ [28]} \tag{5}$$

where,

D_d: Nozzle orifice diameter (m)

η: Nozzle orifice length (m)

The pressure generated at the screw tip depends on the polymer's viscosity, the screw's dimensions, and the pressure gradient along the barrel. As illustrated in Figure 5, the operating pressure "p". The intersection between the nozzle characteristic curve and the extruder characteristic curve determines "p".

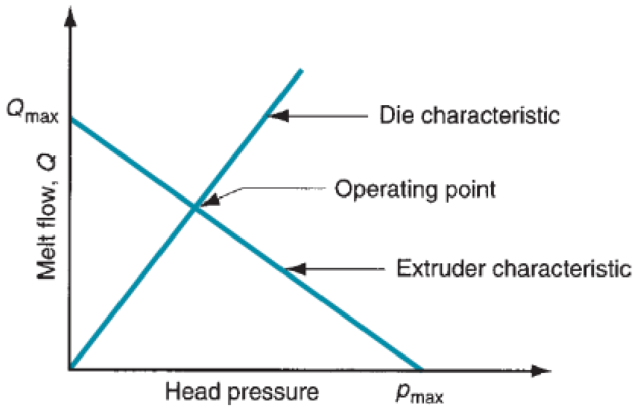

Figure 5. Characteristic curves of the extruder and nozzle [28].

The intersection of the two curves can be determined using the system of equations, as shown in Equation (6):

$$\begin{cases} Q_x = Q_{max} - \left(\frac{Q_{max}}{p_{max}}\right) p \\ Q_x = K_s p \end{cases} \tag{6}$$

where the maximum pressure is the pressure the screw can exert if the nozzle is completely blocked, and it can be determined using Equation (7):

$$p_{max} \frac{6\pi\, D\, N\, L\, \eta\, \cot\theta}{h^2} \tag{7}$$

The maximum rotational speed for a conventional screw is approximately 60 rpm. Thus, a value of 40 rpm (0.67 rev/s) is assumed. The viscosity of molten PLA is approximately 150 Pa·s [39].

Based on the equations mentioned earlier, the following results were obtained:

$$Q_{max} = Q_d = 2.287 * 10^{-6}\ \text{m}^3/\text{s}$$

$$p_{max} = 1.327\ \text{MPa}$$

$$K_s = 3.07 * 10^{-13}\ \text{m}^5/\text{Ns}$$

$$\begin{cases} Q_x = 0.001246\ \text{m}^3/\text{h} \\ p = 1.126\ \text{MPa} \end{cases}$$

Determining the mass flow rate yields the following:

$$\rho_{PLa} = \frac{m}{Q} \rightarrow m = 1.41\ \text{Kg/h}$$

The mass flow rate meets the established design requirements, validating the screw's geometric parameters.

Finally, the screw's driving power can be calculated using Equation (8) [37]:

$$p_{max}\frac{6\pi\ D\ N\ L\ \eta\ \cot\theta\ P_o = \dot{\mathrm{m}}.C_p(-T_{Prohibited} + T_{Exit}) + \dot{\mathrm{m}}H_f + \Delta p\frac{\dot{\mathrm{m}}}{\rho}}{h^2} \quad (8)$$

where,

$\dot{\mathrm{m}}$: Mass flow rate (kg/h).

Cp: Specific heat (J/kg/K).

Tprohibited: Plastic temperature at the hopper prohibited (°C).

Texit: Plastic temperature at the hopper exit (°C).

ρ: Density (kg/m^3).

Hf: Heat of fusion (J/kg).

Δp: Pressure difference (Pa).

According to the referenced literature, the following values were obtained for the previously mentioned parameters:

$$\dot{\mathrm{m}} = 1.41\ \mathrm{kg/h}$$

$$C_p = 1800\ \mathrm{J/Kg/K}\ [40]$$

$$H_f = 35000\ \mathrm{J/Kg}\ [41]$$

$$\rho_{PLA\ molten} = 1130\ \mathrm{Kg/m^3}$$

$$\rho_{PLA\ \mathrm{solid}} = 1240\ \mathrm{Kg/m^3}$$

Establishing:

$$T_{Prohibited} = 20\ °\mathrm{C}\ e\ T_{Exit} = 230\ °\mathrm{C}$$

It is obtained:

$$P_o = 162.15\ \mathrm{W}$$

Assuming 90% efficiency for the electric motor and transmission, the required motor power is calculated as:

$$P_{motor} = 180.2\ \mathrm{W}$$

A closed-loop NEMA34 stepper motor with 12 N·m torque was chosen for the application in question, as illustrated in Figure 6. This type of motor is selected due to its ease of speed adjustment, high torque at low rotation, and low cost.

Figure 6. NEMA 34 stepper motor.

5. Extruder Assembly

The extruder's and its components' development and design were carried out using Autodesk Inventor (2020) software [42]. This program enabled the creation of detailed technical drawings, functional simulations, and structural analyses, ensuring the performance, efficiency, and safety required for the polymer recycling process. Additionally, it facilitated the creation of virtual prototypes, optimizing the design and reducing errors before manufacturing.

The extrusion device, illustrated in Figure 7, is based on a conventional plastic injection system but with specific adaptations. The process begins with feeding a screw conveyor through a hopper, which directs the granular material into the system. As the screw rotates, it transports the material through a cylinder heated by electric resistances. During this journey, the solid plastic heats up upon contact with the cylinder walls, reaches its glass transition temperature, and melts, acquiring the consistency of a highly viscous liquid.

At the cylinder's end, a high-pressure zone is generated, forcing the molten plastic to pass through an orifice called a nozzle, where it takes the desired shape for subsequent use.

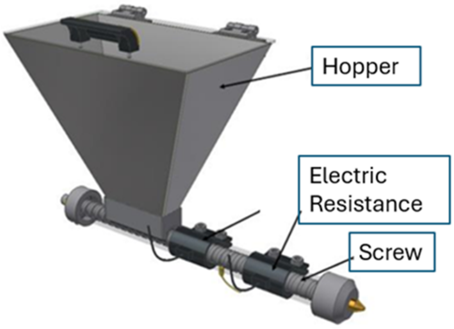

Figure 7. Hopper, screw, and electric resistance.

The nozzle's primary function is precisely calibrating the filament diameter during extrusion. Typically, 3D printers operate with filaments measuring 1.75 ± 0.03 mm, a value that the nozzle must ensure. This precision is crucial for filament compatibility with printing equipment and the quality of the printed parts' quality.

The screw is driven by a stepper motor, with transmission carried out via a toothed belt, as shown in Figure 8. This motor was chosen for its advantages: simplicity of operation, ease of adjustment, high precision, and the ability to provide high torque even at low speeds. These characteristics make it the ideal solution for the precise control required in the extrusion process.

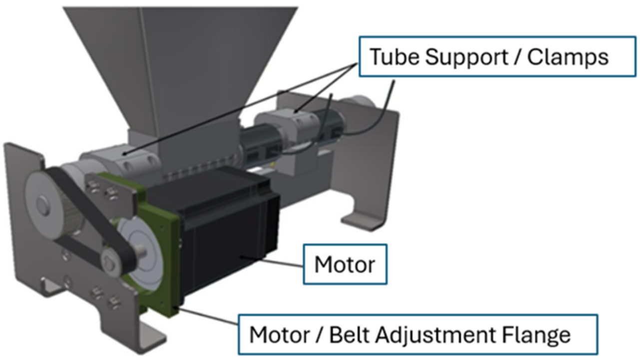

Figure 8. Motion transmission system.

To ensure safety during equipment operation and prevent access to hazardous areas, all moving parts were properly safeguarded. The hopper cover includes a PILZ brand inductive safety sensor that automatically stops the equipment if opened (Figure 9). Additionally, the transmission system is protected by a cover, preventing accidental contact with moving parts and ensuring compliance with safety standards

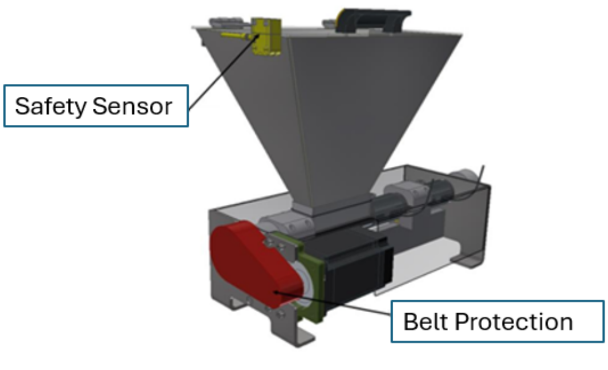

Figure 9. Safety and protection systems.

The final stage of the process is winding, which involves cooling, guiding, and rolling the solidified filament onto reusable spools. The filament exits the extruder while still hot, flexible, and with a rubber-like consistency. To ensure proper winding and maintain the calibrated diameter, cooling it gradually and synchronizing the winding process with the extruder's operation is essential.

When the filament exits the nozzle, it is malleable and can be damaged if handled directly. Therefore, it can fall freely, enabling gradual cooling that provides enough rigidity for handling without altering its diameter (Figure 10).

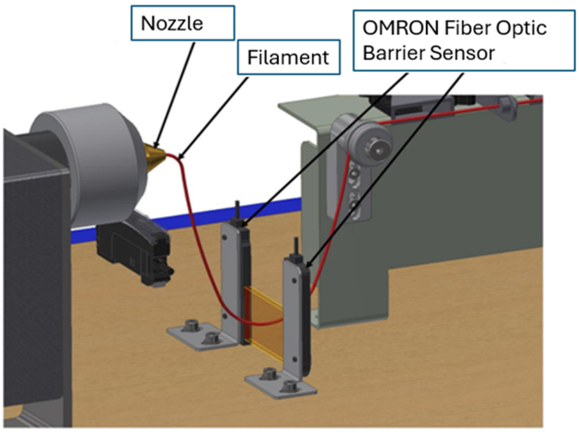

Figure 10. Filament movement at the extruder exit.

As illustrated in Figure 11, an OMRON laser barrier sensor detects the filament's presence and activates the winder motor during this descent phase. This motor pulls the material, initiating its controlled and precise winding, ensuring the uniformity of the filament on the spools.

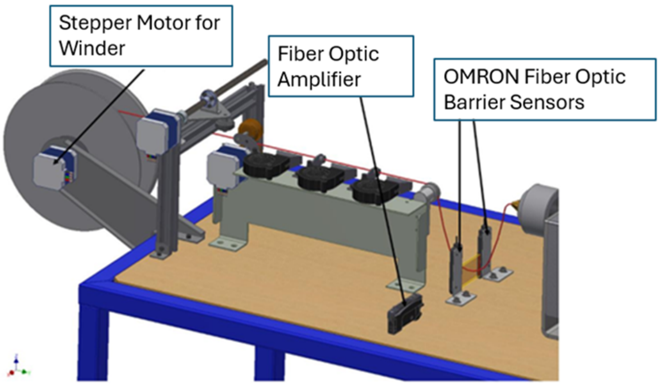

Figure 11. Filament movement to the winder.

On its way to the winder, the filament is cooled in a controlled manner by three adjustable-speed fans (Figure 12). This process prevents the still-malleable filament from sticking to itself during winding. However, the cooling should not reach ambient temperature. The filament must attain an intermediate temperature, allowing it to adapt to the spool without the risk of cracks or defects. This thermal balance is crucial to ensure the filament's quality, integrity, and uniformity for subsequent use in 3D printers.

The puller consists of a stepper motor and two rollers, which are crucial in the winding process. Its primary function is continuously pulling the filament and maintaining appropriate tension on the spool, ensuring uniform winding and preventing the filament from unspooling or overlapping, as illustrated in Figure 13. This precise tension control is essential for ensuring the quality and functionality of the filament in 3D printing applications.

Filament overlap during winding increases the spool's volume, reducing its storage capacity and potentially causing jams that compromise the 3D printing process and the final product. An adjustable guiding system was implemented to prevent these issues, tailored to the spool's width and the filament's thickness. With each spool rotation, the system moves the filament laterally by a distance equal to its diameter (1.75 mm), ensuring uniform and organized winding, as shown in Figure 14. This mechanism maximizes the spool's capacity and prevents overlaps.

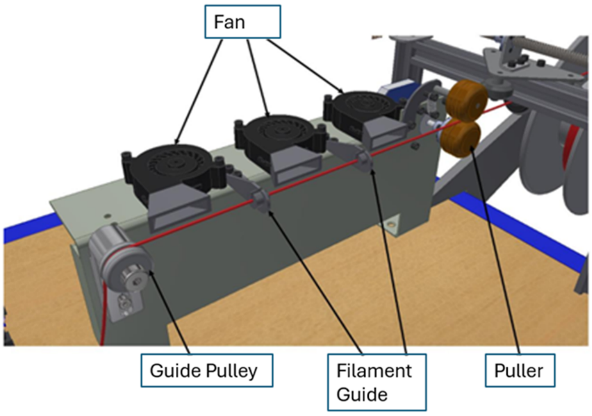

Figure 12. Filament cooling system.

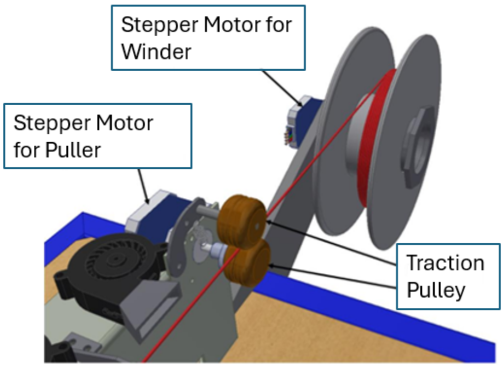

Figure 13. Filament traction system.

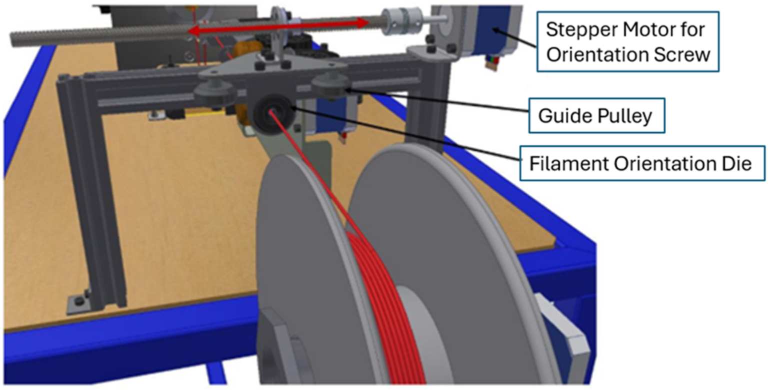

Figure 14. Filament guiding system.

After filling the entire width of the spool, the guiding system automatically reverses the direction of lateral movement. This mechanism ensures uniform and organized filament winding across multiple layers, preventing misalignments or overlaps that could affect quality. This continuous process maximizes spool utilization efficiency and preserves the filament's integrity for future use in 3D printers, as illustrated in Figure 15.

Figure 16 presents the layout of the final equipment for PLA recycling, consisting of three main modules: the shredder, which reduces the material into fragments; the extruder, which converts the fragments into reusable filaments; and the winding module, which rolls the filament onto spools ready for use. This system was designed to ensure an efficient and continuous process, from shredding to the production of filaments for 3D printing, representing the final solution of this work.

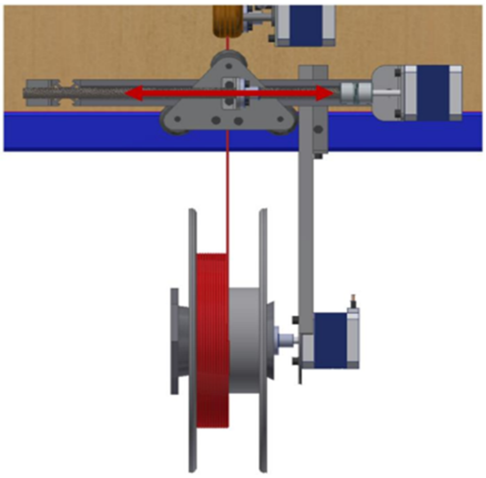

Figure 15. Filament guiding system.

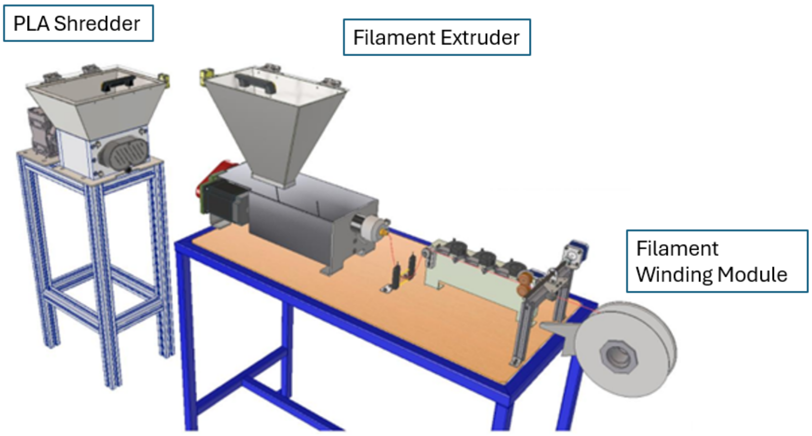

Figure 16. PLA recycling equipment layout.

6. Discussion

The development of the filament extruder addresses critical aspects of sustainability and the circular economy by enabling the reuse of 3D printing waste through a modular system that integrates shredding, extrusion, and winding. From a technical perspective, the proposed design demonstrates coherence between engineering calculations and operational feasibility.

The stability of the filament diameter (1.75 ± 0.03 mm) suggests that the geometric design of the extrusion screw was adequate, particularly the selected L/D ratio of 20 and the distribution of the feed, compression, and metering zones. This configuration ensured sufficient residence time and pressure for melting and homogenization, as theoretically supported by [27,37]. Unlike commercial screw profiles, which are often optimized generically, the present design was tailored explicitly for semi-crystalline PLA, with proper clearance and pitch values that contribute to stable throughput.

The choice of a 12 N·m closed-loop NEMA34 stepper motor proved theoretically effective in maintaining rotational stability under backpressure conditions. This is consistent with findings by Abeykoon et al. [35], who emphasize the importance of torque control and rotational precision in minimizing pulsation and flow instability during polymer extrusion. Although real extrusion tests were not performed, the dimensioning aligns with values reported for comparable small-scale systems.

The controlled cooling system, consisting of three adjustable fans, allowed for gradual thermal reduction without introducing thermal shock or diameter variation. This is a key aspect in ensuring filament dimensional stability during winding, as refs. [25,26] described. The coordinated action of the puller and guide system, synchronized with the extrusion rate, helps prevent filament overlap and deformation, a common challenge in manual or semi-automatic systems.

Compared with similar low-cost systems [23,26], the present solution offers notable improvements by fully integrating automation and control components, such as inductive safety sensors, a laser detection system, and synchronized motion systems. These features enhance user safety and operational consistency, a limitation frequently noted in DIY or open-source extruders.

Despite these strengths, the system's real performance still requires experimental validation. Mechanical and thermal testing of the extruded filaments is necessary to determine their suitability for functional or load-bearing applications, as degradation from multiple heating cycles can affect mechanical properties [24]. Furthermore, as highlighted by Byrley et al. [27], the environmental impact of polymer extrusion includes the emission of volatile organic compounds (VOCs) and ultrafine particles. Although the small scale of the system minimizes its footprint, energy consumption and emissions should be quantified in future implementations, and mitigation measures (e.g., HEPA filters or air recirculation systems) may be warranted.

Lastly, the system's modularity and open design facilitate adaptability to other polymers. However, variations in melting behavior, viscosity, and degradation profiles across materials like ABS or PETG may require adjusting process parameters or redesigning the screw profile accordingly, a topic suitable for future optimization studies.

7. Conclusions

Developing the filament extruder for recycling 3D printing waste has demonstrated technical feasibility and environmental relevance. The integrated system, comprising a shredder, a screw-based extruder, and a controlled winding unit, effectively transformed PLA waste into high-quality filaments with a consistent diameter of 1.75 ± 0.03 mm, suitable for standard FDM 3D printers.

The custom-designed extrusion screw, explicitly tailored for recycled PLA, ensured a stable and continuous flow. At the same time, using a NEMA34 closed-loop stepper motor allowed precise speed control, contributing to uniform filament diameter. The cooling and winding subsystems further ensured the filament's structural integrity and compatibility with reuse.

These results confirm that it is possible to design and build a low-cost, modular system capable of recycling thermoplastic waste locally, supporting circular economy practices in additive manufacturing. The study also demonstrates that high-quality filaments can be produced without blending with virgin material, a limitation identified in previous studies.

In conclusion, the developed system presents a scalable and adaptable solution for sustainable 3D printing. Future research should explore economic viability in industrial contexts, the adaptation of the system for other polymers (e.g., ABS, PETG), and the integration of intelligent sensors and control algorithms to optimize process parameters in real time.

Despite the promising design and theoretical validation, several limitations must be acknowledged. The system was developed and explicitly dimensioned for PLA, a widely used thermoplastic in 3D printing; however, no experimental tests were conducted within the scope of this study. As such, its actual performance with PLA and with other polymers like ABS or PETG remains to be experimentally verified. Furthermore, a detailed cost, benefit analysis was not performed, and economic viability may vary depending on application context, component availability, and usage scale. No mechanical or thermal characterization of the extruded filament was carried out, nor were potential environmental impacts, such as energy consumption and VOC emissions, quantified. Future work should address these aspects and consider integrating advanced technologies to enhance process control, energy efficiency, and environmental sustainability.

Author Contributions

Conceptualisation: A.G., S.M., J.L., J.S. and D.G.; methodology: A.G., S.M., and J.L.; validation: A.G., J.S. and D.G.; formal analysis: A.G., S.M., J.L., J.S. and D.G.; investigation: A.G., S.M. and J.L.; data curation: A.G., S.M., J.L., J.S., and D.G..; writing original draft preparation: A.G., and S.M.; writing review and editing: A.G., J.S. and D.G..; visualisation: A.G. and S.M.; supervision: A.G., J.S. and D.G.; project administration: A.G. and S.M.; funding acquisition: A.G. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare that they have no competing interests.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper

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