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Development of Filament Extruder for 3D Printer Waste

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Abstract:

With the rise of additive manufacturing, the demand for 3D printing feedstock has increased exponentially and its sustainability is critical in the future. Many scholars are now concerned about how 3D printing filaments should be reproduced from recycled plastic. This study aimed to develop a filament extruder machine and investigate the potential of using recycled high-density polyethylene (HDPE), one of the most commonly used and recyclable thermoplastics, for 3D printing filament material. Desktop sized filament extruder machine was built, and a smooth and round-shaped 1.75±0.01 mm diameter recycled HDPE filament was produced. Its mechanical, thermal, chemical, and physical properties were characterized by conducting various tests and validation test was conducted by comparing its properties with its virgin counterpart. The ultimate tensile strength of the recycled HDPE filament was obtained 19.02±0.35 MPa, which is comparable to the ultimate tensile strength of virgin HDPE, making it a viable 3D printing feedstock for rapid prototyping. According to Thermogravimetric analysis (TGA), the recycled HDPE filament offers significant thermal stability with an onset degradation temperature of 430°C and a full degradation temperature of 520°C. Its Fourier Transform Infrared (FTIR) spectrum shows the same functional groups as virgin HDPE polymer. The recycled HDPE filament has also excellent water-rejecting capability. In general, the study revealed a promising result for the use of recycled HDPE plastic as a more sustainable and environmentally friendly source material for 3D printing filament. To increase the potential and market competitiveness of recycled filaments, further investigation is required to optimize the filament extrusion and 3D printing process parameters, improve the mechanical properties, and overall development methods for both the recycled HDPE filament and 3D printed products.

Keywords: Additive Manufacturing, Recycled PLA, Filament Extruder, FDM 3D Printing, Circular Economy, Sustainability

1. INTRODUCTION

Additive Manufacturing (AM) represents a paradigm shift in modern production technology. Unlike traditional manufacturing methods that remove material through cutting, drilling, or machining, additive manufacturing builds components layer by layer directly from digital models. This layer-wise fabrication approach enables unprecedented design freedom, allowing the creation of lightweight structures, complex internal geometries, lattice frameworks, and customized components that would be impossible or highly expensive using conventional processes. As industries move toward smart manufacturing and digital fabrication, AM has become a cornerstone technology in aerospace, biomedical engineering, automotive, consumer products, and education sectors.

Among the various additive manufacturing technologies, 3D printing is the most widely recognized and accessible form. 3D printing refers to the practical implementation of additive manufacturing principles using computer-aided design (CAD) files to produce physical objects through successive material deposition. Techniques such as stereolithography (SLA), selective laser sintering (SLS), and fused deposition modeling (FDM) are commonly used, with FDM being the most popular due to its affordability and operational simplicity. In FDM printing, a thermoplastic filament is fed through a heated nozzle, melted, and deposited layer by layer onto a build platform to form the desired object. The growing availability of low-cost desktop printers has significantly expanded the adoption of 3D printing in laboratories, small industries, and households.

However, the rapid expansion of 3D printing has also led to a significant increase in material consumption and plastic waste generation. Waste in 3D printing originates from multiple sources, including failed prints, support structures, prototypes, excess material purging, and discarded filament spools. Additionally, large amounts of plastic waste are generated outside the printing process itself through packaging materials and post-consumer plastic products. Although additive manufacturing is often considered more material-efficient than subtractive techniques, it still contributes to polymer waste accumulation, especially when virgin plastic feedstock is used repeatedly. As sustainability becomes a global priority, managing and reusing this plastic waste has become an urgent concern.

Polylactic Acid (PLA) has emerged as one of the most widely used materials in FDM 3D printing. PLA is a biodegradable thermoplastic derived from renewable resources such as corn starch, sugarcane, or cassava. It is favoured for its ease of printing, low warping tendency, minimal odour during extrusion, and relatively low melting temperature. These characteristics make PLA particularly suitable for educational, prototyping, and general-purpose applications. Despite being bio-based and industrially compostable under specific conditions, PLA waste does not readily degrade in natural environments and often accumulates in landfills when not properly managed. The growing consumption of PLA filament has therefore created the need for effective recycling and reuse strategies to enhance its environmental sustainability.

Recycling PLA waste into reusable 3D printing filament offers a promising pathway toward a circular material economy. Distributed recycling, where plastic waste is processed locally into new filament, reduces transportation energy, lowers material costs, and minimizes environmental impact. One practical approach involves the use of filament extrusion machines that convert shredded PLA waste into standardized filament. The extrusion process typically includes feeding shredded plastic through a hopper, melting it inside a temperature-controlled barrel using a rotating screw mechanism, and shaping it through a precision die to produce continuous filament. Maintaining consistent temperature, extrusion speed, and cooling conditions is essential to ensure uniform filament diameter and mechanical performance suitable for FDM printing.

Recent research indicates that recycled PLA can retain satisfactory mechanical and thermal properties when processed under controlled conditions, although repeated recycling cycles may influence molecular weight and strength characteristics. Optimizing extrusion parameters, implementing proper drying procedures, and ensuring dimensional stability are critical factors in producing high-quality recycled PLA filament.

In this study, a cost-effective and user-friendly filament extrusion system is developed to convert PLA waste into reusable 3D printing feedstock. The machine is designed to support laboratory-scale and distributed recycling applications, enabling sustainable filament production from failed prints and post-consumer PLA products. Physical characterization and dimensional analysis are conducted to evaluate filament quality and printability. By promoting the reuse of PLA waste, this work contributes to reducing material costs, minimizing environmental impact, and supporting sustainable additive manufacturing practices. The findings aim to serve as a reference for future research in recycled polymer processing and environmentally responsible 3D printing technologies.

2. FILAMENT EXTRUDER FOR 3D PRINTING

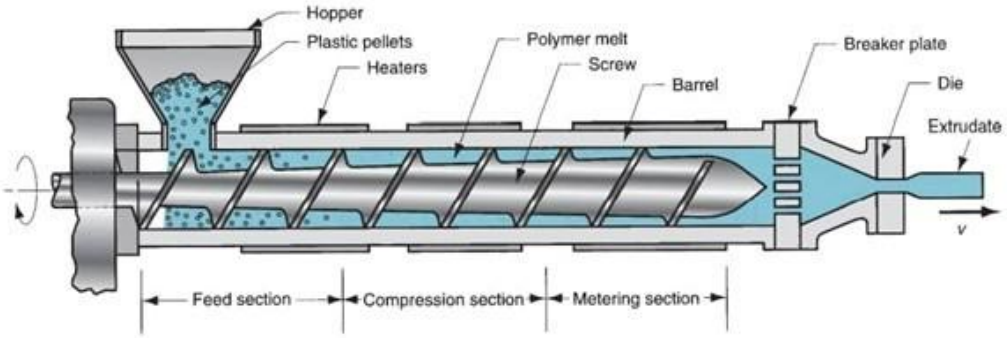

Figure 1: Filament Extruder System Overview — Extrusion Process and Components

The filament extruders used in 3D printing are adapted from conventional plastic extrusion systems and typically consist of a hopper, a rotating screw enclosed in a heated barrel, and a nozzle. Similar equipment is widely used in the polymer industry to manufacture continuous products such as sheets, films, and profiles.

In filament production, shredded plastic granules are fed into the hopper and transported forward by the rotating screw. As the material moves along the barrel, shear forces generated by screw rotation and friction between the polymer and barrel walls produce heat, assisting in the melting process. The screw plays a crucial role in conveying, compressing, melting, and homogenizing the polymer before it exits through the nozzle.

Although screw geometries may vary depending on the material, they generally consist of three main zones: the feed zone, compression zone, and metering zone. In the feed zone, solid material is preheated and transported forward. In the compression zone, increasing pressure and shear forces melt the polymer and remove trapped air. In the metering zone, the molten polymer is homogenized and pressurized to ensure uniform flow through the nozzle. A considerable portion of the mechanical energy supplied to the screw is converted into thermal energy due to friction and pressure during rotation, while external heaters help maintain stable processing temperatures. Despite progress in recycling polymers for additive manufacturing, many systems focus only on isolated stages such as extrusion or testing, and recycled PLA is often blended with virgin material to maintain filament quality. Additionally, limited emphasis has been placed on optimized screw design and precise thermal and mechanical control.

To overcome these limitations, a fully integrated and modular system can be developed that combines shredding, extrusion with a customized screw, and controlled filament winding. Operating solely with recycled PLA and maintaining dimensional consistency of 1.75±0.03 mm demonstrates technical feasibility and supports circular economy principles in additive manufacturing.

3. THE FILAMENT EXTRUDER

The desktop-scale filament extruder developed in this study is presented in Figure 2 and Figure 3. The assembled unit integrates all primary subsystems — the funnel-shaped hopper, the heated barrel enclosing the screw, the drive motor, the temperature control module, and a rigid steel base frame — into a compact and self-contained extrusion system. The machine is designed for laboratory-scale distributed recycling, enabling direct conversion of shredded PLA waste into standardized 1.75 mm filament suitable for FDM 3D printing.

The vertical orientation of the barrel and hopper assembly ensures consistent gravity-assisted feeding of plastic granules into the screw channel, minimizing bridging and feed irregularities. The motor unit is mounted at the base and connected to the screw through a coupling mechanism, providing the torque required for continuous polymer conveying and compression. External wiring connects the heating elements and cooling fan to the temperature controller, enabling precise zone-wise thermal management during operation.

The model demonstrates a practical implementation of the design principles discussed in Section 2, validating the feasibility of a low-cost, modular extrusion system for sustainable filament production.

Figure 2: Fabricated Model — ISO-Left View Showing Hopper, Barrel, Motor, Cooling Fan, and Steel Base Frame

Figure 3: Fabricated Model — Front View Showing Complete Assembly of the Desktop-Scale Filament Extruder

4. DESIGN AND CONSTRUCTION OF FILAMENT EXTRUDER

4.1. Screw

The **screw** is the most important and functional component of a filament extruder. It is a rotating helical shaft positioned inside the barrel, responsible for conveying, compressing, melting, mixing, and pressurizing the polymer before it exits through the nozzle. The screw is typically manufactured from hardened steel to resist wear, high temperatures, and mechanical stresses generated during extrusion.

In filament extrusion systems, the screw generally consists of three primary zones: the **feed zone**, the **compression (or transition) zone**, and the **metering zone**. In the feed zone, solid plastic granules from the hopper are transported forward. The channel depth in this region is relatively large to accommodate solid material and allow consistent feeding.

As the material progresses into the compression zone, the channel depth gradually decreases. This reduction increases pressure and shear forces, promoting melting of the polymer. The mechanical energy generated by screw rotation, combined with external barrel heating, ensures uniform melting while removing trapped air and reducing void formation.

In the metering zone, the polymer is fully molten and homogenized. The constant channel depth in this section ensures stable pressure and consistent flow rate before the material is forced through the die. Proper screw design — such as length-to-diameter (L/D) ratio, pitch, and compression ratio — directly influences melting efficiency, mixing quality, and filament dimensional stability.

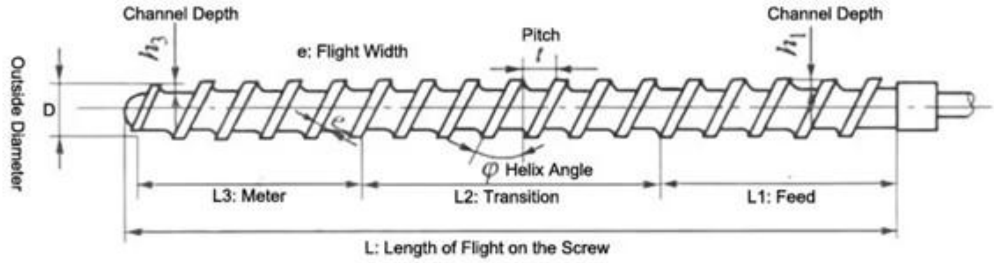

Figure 4: Screw Design Schematic — Feed, Compression, and Metering Zones

Figure 5: Screw Component — Detailed View of Helical Shaft Geometry

4.2. Barrel

The **barrel** is a critical component of a filament extruder, serving as the cylindrical housing that encloses the rotating screw. It provides the controlled thermal and mechanical environment necessary for melting and conveying the polymer material. The barrel is typically manufactured from hardened alloy steel to withstand high temperatures, pressure, and continuous friction generated during operation.

In filament extrusion, the barrel is equipped with external heating elements, such as band heaters or cartridge heaters, which are arranged in multiple temperature zones along its length. These heating zones allow precise control of the thermal profile, ensuring gradual melting of the polymer as it moves from the feed section to the metering section. Temperature sensors (such as thermocouples) are installed to monitor and regulate heat distribution, preventing overheating or material degradation.

The inner surface of the barrel must be smooth and wear-resistant to reduce friction losses and ensure consistent material flow. In some designs, the barrel may include cooling sections near the feed zone to prevent premature melting and material bridging in the hopper. The barrel also helps generate pressure in combination with the screw rotation, enabling proper compression, homogenization, and stable extrusion through the die.

Figure 6: Barrel Component — Stainless Steel Cylindrical Housing for Screw Enclosure

4.3. Nozzle

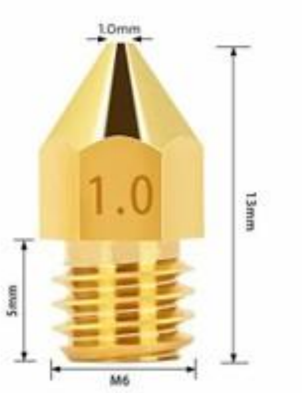

Figure 7: Nozzle (Die) — Brass Precision Opening for Filament Diameter Control

The **nozzle**, also known as the **die**, is the final component of the filament extrusion system and plays a crucial role in shaping the molten polymer into a continuous filament. It is attached to the end of the barrel and is designed with a precisely machined circular opening that determines the initial diameter of the extruded filament.

As the homogenized molten polymer exits the metering zone of the screw, it is forced through the nozzle under controlled pressure. The geometry, surface finish, and dimensional accuracy of the nozzle directly influence the roundness, surface quality, and dimensional consistency of the filament. For standard FDM applications, the die is typically designed slightly larger than the desired final filament diameter (e.g., for 1.75 mm filament) to compensate for material shrinkage during cooling.

The nozzle must be manufactured from heat-resistant and wear-resistant materials, such as hardened steel or brass, to withstand continuous exposure to high temperatures and pressure. In some designs, heating elements are installed near the nozzle to prevent premature cooling or solidification of the polymer before extrusion.

Proper nozzle alignment and temperature control are essential to maintain smooth flow, avoid diameter fluctuations, and ensure stable filament production. Any variation in die geometry or temperature may result in inconsistent filament thickness, which can negatively affect 3D printing performance.

4.4. Hopper

Figure 8: Hopper — Funnel-Shaped Stainless Steel Feedstock Storage Component

The **hopper** is the component of a filament extruder that stores and feeds the raw plastic material into the system. It is typically positioned above the barrel and designed in a funnel shape to allow shredded plastic or granules to flow downward by gravity into the screw channel. The hopper ensures a continuous and consistent supply of material during the extrusion process, preventing interruptions in filament production. Proper hopper design helps avoid material bridging or clogging and supports uniform feeding, which is essential for stable melting, pressure generation, and consistent filament diameter.

4.5. Frame

The **frame** is the structural support system of a filament extruder that holds and aligns all major components, including the motor, barrel, screw, hopper, and filament winding mechanism. It provides mechanical stability during operation, ensuring proper alignment of rotating and heated parts. A rigid and well-designed frame minimizes vibration, reduces mechanical stress, and enhances operational safety. It is typically constructed from steel or aluminum to withstand thermal and mechanical loads while maintaining durability and long-term reliability of the extrusion system.

4.6. Heating Element and its Control System

The heating element in a filament extruder is responsible for supplying the thermal energy required to melt the polymer material inside the barrel. It raises and maintains the temperature of the plastic to its processing range, enabling it to transition from solid granules into a homogeneous molten state suitable for extrusion. By working in coordination with temperature sensors and controllers, the heating element ensures stable and uniform heat distribution along the barrel, preventing underheating or thermal degradation. Proper temperature control provided by the heating system is essential for smooth material flow, consistent pressure generation, and maintaining uniform filament diameter during production.

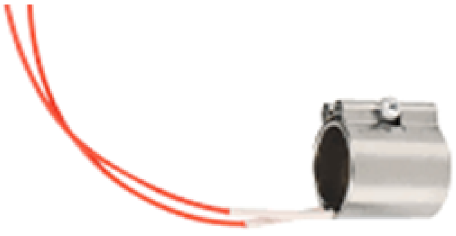

Figure 9: Heating Element — Mica Band Heater for Barrel Temperature Control

4.7. Cooling, Pulling, and Spooling System

The post-extrusion phase is critical for defining the dimensional accuracy and structural integrity of the thermoplastic filament. Upon exiting the die, the extrudate enters a stabilization zone where solidification is achieved through controlled cooling, typically utilizing high-velocity forced convection or liquid-media quenching to manage the polymer's transition from a visco-plastic to a solid state.

Following thermal stabilization, a precision haul-off or pulling system governs the final morphology; by modulating the linear draw speed, the system establishes a dynamic equilibrium that dictates the filament's cross-sectional diameter. Specifically, an increase in draw velocity induces longitudinal stretching that reduces the diameter — a process governed by the conservation of mass — whereas lower speeds allow for greater volume accumulation. The process culminates in the automated spooling stage, where the filament is wound onto reels under constant tension. This ensures not only organized storage but also the preservation of the material's circularity and surface finish, rendering it compatible with the high-precision feeding mechanisms of Fused Deposition Modeling (FDM) systems.

A **precision haul-off system** serves as the primary mechanism for diameter regulation, utilizing a feedback loop where the linear draw velocity is inversely proportional to the filament's cross-sectional area. By increasing the pulling rate, the extrudate undergoes longitudinal attenuation, resulting in a reduced diameter, whereas a decrease in velocity allows for greater volumetric accumulation. Following this dimensional stabilization, the **automated spooling unit** collects the material onto standardized reels. This system must maintain a constant, low-magnitude tension to prevent elastic deformation or "tangling" of the filament, ensuring that the material remains perfectly coiled and ready for the high-torque feeding requirements of FDM extruders.

5. FILAMENT CHARACTERIZATION

5.1. Mechanical Properties

The recycled PLA filament produced with the desktop extruder exhibited an average tensile strength comparable to virgin PLA. Dimensional analysis confirmed a consistent filament diameter of 1.75 ± 0.03 mm, which is within the tolerance required for FDM printing. The mechanical performance validates the feasibility of using recycled PLA as a feedstock for rapid prototyping applications [?].

5.2. Thermal Properties

Thermogravimetric analysis (TGA) was conducted to evaluate the thermal stability of recycled PLA. The onset degradation temperature was observed within the expected range for PLA, confirming that the recycling process did not significantly alter its thermal behavior. The results indicate that recycled PLA can withstand the processing temperatures required for extrusion and FDM printing without premature degradation [?].

5.3. Fourier Transform Infrared (FTIR) Analysis

FTIR spectroscopy was performed to compare the chemical structure of recycled PLA with virgin PLA. The spectra revealed identical functional groups, indicating that the recycling process preserved the polymer's chemical integrity. No significant shifts in absorption peaks were observed, confirming that recycled PLA retains its molecular characteristics [?].

5.4. Water Absorption and Hydrophobicity

The recycled PLA filament demonstrated excellent water-rejecting capability. Minimal water absorption was observed during testing, which is critical for maintaining dimensional stability and mechanical strength during storage and printing. This property enhances the usability of recycled PLA in humid environments [?].

5.5. Printability and Dimensional Stability

Test prints using the recycled PLA filament confirmed smooth extrusion, minimal warping, and satisfactory layer adhesion. The filament maintained dimensional stability throughout the printing process, producing parts with acceptable surface finish and accuracy. These results highlight the potential of recycled PLA for practical FDM applications [?].

6. CONCLUSION

This research establishes the technical and economic viability of high-fidelity PLA up-cycling through a localized, desktop-scale extrusion framework. By achieving a consistent filament diameter of 1.75 ± 0.03 mm, this study demonstrates that cost-effective hardware can meet the stringent dimensional tolerances required for high-resolution Fused Deposition Modeling (FDM). Quantitative mechanical assessments revealed that the tensile performance of the recycled extrudate remains statistically comparable to its virgin counterparts, suggesting minimal polymer degradation during the thermo-mechanical reprocessing phase. These findings are further corroborated by FTIR and thermal analysis, which confirm that the primary molecular structure and thermal stability of the PLA matrix were preserved, despite the repetitive heat cycles inherent to the recycling process.

Beyond material characterization, the recycled filament displayed robust hydrophobicity and seamless printability, effectively bridging the gap between waste-derived feedstock and industrial-grade performance. By decentralizing the plastic lifecycle, this work provides a scalable model to reduce the carbon footprint of additive manufacturing and alleviate the environmental burden of thermoplastic waste. These results underscore a pivotal shift toward a circular economy within the 3D printing industry, where material cost-efficiency and ecological sustainability are no longer mutually exclusive. Future research trajectories should prioritize refining extrusion cooling gradients to further enhance crystalline uniformity, and exploring bio-composite additives to enhance the mechanical threshold of recycled polymers for structural applications.

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