Design of a PET bottle recycling machine for sustainable 3D printing filament production

Diseño de una máquina de reciclaje de botellas PET para la producción sostenible de filamento para impresión 3D

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Abstract: The increasing demand for affordable materials for additive manufacturing has generated growing interest in sustainable alternatives for 3D printing filament production. This study presents the design of a PET bottle recycling machine intended to transform post-consumer polyethylene terephthalate (PET) waste into sustainable filament for fused deposition modeling (FDM) 3D printers. The proposed system integrates mechanical shredding, thermal extrusion, temperature control, and filament winding mechanisms to obtain recyclable filament with potential application in rapid prototyping and low-cost manufacturing environments. The research addresses both economic and environmental challenges associated with conventional filament production by promoting circular economy strategies and reducing plastic waste generation. The machine design includes the selection of mechanical components, electronic control systems, sensors, actuators, and thermal regulation elements required to ensure stable extrusion conditions and acceptable filament quality. Additionally, the study discusses the operational stages of the recycling process, including PET collection, cleaning, shredding, extrusion, cooling, and filament spooling. Mechanical performance, thermal stability, and compatibility with common FDM 3D printers are considered as critical evaluation criteria for the recycled filament. The proposed design contributes to sustainable engineering practices by encouraging plastic reuse, reducing dependence on virgin polymer materials, and supporting environmentally responsible additive manufacturing processes. The project demonstrates the technical feasibility of converting PET bottle waste into functional 3D printing filament through an accessible and low-cost recycling approach, providing opportunities for educational, industrial, and prototyping applications.

Keywords: PET recycling; Sustainable filament; Additive manufacturing; 3D printing; Circular economy; Recycled polymers;

Sustainable engineering; FDM filament.

Resumen: La creciente demanda de materiales asequibles para manufactura aditiva ha generado un interés creciente en alternativas sostenibles para la producción de filamento para impresión 3D. Este estudio presenta el diseño de una máquina recicladora de botellas PET destinada a transformar residuos posconsumo de tereftalato de polietileno (PET) en filamento sostenible para impresoras 3D de modelado por deposición fundida (FDM). El sistema propuesto integra mecanismos de trituración mecánica, extrusión térmica, control de temperatura y enrollado de filamento con el fin de obtener filamento reciclable con potencial aplicación en entornos de prototipado rápido y manufactura de bajo costo. La investigación aborda tanto los desafíos económicos como ambientales asociados con la producción convencional de filamentos mediante la promoción de estrategias de economía circular y la reducción de la generación de residuos plásticos. El diseño de la máquina incluye la selección de componentes mecánicos, sistemas electrónicos de control, sensores, actuadores y elementos de regulación térmica necesarios para garantizar condiciones estables de extrusión y una calidad aceptable del filamento. Adicionalmente, el estudio analiza las etapas operativas del proceso de reciclaje, incluyendo la recolección, limpieza, trituración, extrusión, enfriamiento y bobinado del PET. El desempeño mecánico, la estabilidad térmica y la compatibilidad con impresoras 3D FDM convencionales se consideran criterios críticos de evaluación del filamento reciclado. El diseño propuesto contribuye a las prácticas de ingeniería sostenible al fomentar la reutilización del plástico, reducir la dependencia de materiales poliméricos vírgenes y apoyar procesos de manufactura aditiva ambientalmente responsables. El proyecto demuestra la viabilidad técnica de convertir residuos de botellas PET en filamento funcional para impresión 3D mediante un enfoque de reciclaje accesible y de bajo costo, ofreciendo oportunidades para aplicaciones educativas, industriales y de prototipado.

Palabras clave: reciclaje de PET; filamento sostenible; manufactura aditiva; impresión 3D; economía circular; polímeros reciclados; ingeniería sostenible; filamento FDM.

1. INTRODUCTION

Plastic waste accumulation has become one of the main environmental challenges worldwide due to the extensive consumption of polymer-based products and the limited efficiency of conventional recycling systems (Rahman et al., 2022). Among the most commonly discarded plastic materials, polyethylene terephthalate (PET) bottles represent a significant percentage of municipal solid waste because of their widespread use in beverage packaging and consumer products (Cruz Sanchez et al., 2021). In recent years, the increasing concern regarding environmental sustainability has promoted the development of recycling technologies capable of transforming plastic waste into value-added products (Singh et al., 2020).

At the same time, additive manufacturing technologies, particularly fused deposition modeling (FDM) 3D printing, have experienced rapid growth in educational, industrial, and prototyping applications (Gebler et al., 2020). However, the elevated cost of commercial filament materials continues to represent an economic limitation for many users, especially in academic environments and small-scale manufacturing systems. This situation has motivated the search for alternative and sustainable filament production methods based on recycled polymer materials (Pakkanen et al., 2021).

In this context, PET recycling has emerged as a promising strategy for the production of low-cost filament suitable for 3D printing applications. Recycled PET materials offer advantages such as availability, reduced environmental impact, and potential compatibility with additive manufacturing processes when adequate thermal and mechanical treatment conditions are achieved (Tao et al., 2021). Several studies have demonstrated that recycled PET can be processed into filament with acceptable mechanical and thermal properties for rapid prototyping applications (Cruz Sanchez et al., 2021).

The present study proposes the design of a PET bottle recycling machine capable of converting post-consumer PET waste into sustainable 3D printing filament. The system integrates mechanical, thermal, and electronic components to perform shredding, extrusion, temperature regulation, and filament winding operations. The project seeks to contribute to sustainable engineering practices by promoting circular economy principles, reducing plastic waste generation, and facilitating access to affordable additive manufacturing materials (Núñez-Cacho et al., 2022).

Furthermore, the proposed design aims to support educational and technological innovation initiatives related to sustainable manufacturing and environmentally responsible engineering solutions. The development of accessible PET recycling technologies may contribute to reducing dependence on virgin polymer materials while encouraging the implementation of recycling-oriented production systems in academic and industrial environments. Similar sustainable engineering approaches have been reported in technological innovation studies developed by Arencibia Pardo et al. (2023), highlighting the importance of integrating sustainability principles into engineering education and applied manufacturing processes.

1.1. Problem Context

The rapid expansion of additive manufacturing technologies has increased the global demand for thermoplastic filament materials used in fused deposition modeling (FDM) systems. Commercial filaments such as PLA, ABS, and PETG have become essential materials in prototyping, engineering design, educational laboratories, and small-scale manufacturing processes. However, the elevated cost of these materials represents a significant economic limitation for students, researchers, and small industries seeking affordable manufacturing alternatives.

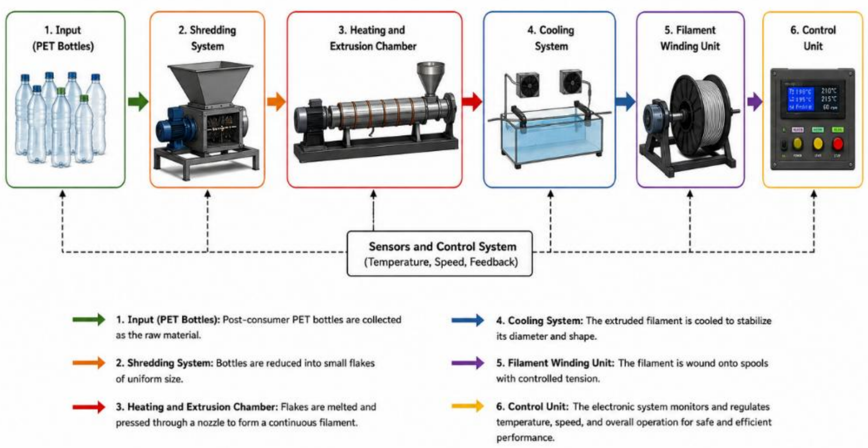

Figure 1. *General architecture of the PET recycling machine.*

Simultaneously, plastic waste generation continues to increase worldwide, particularly regarding polyethylene terephthalate (PET) bottles used in beverage packaging. According to recent environmental studies, PET waste constitutes an important fraction of urban solid residues due to its high consumption and inadequate recycling management in many regions (Kumar et al., 2021). Although PET possesses excellent recyclability characteristics, large quantities of this material still end up in landfills or natural ecosystems, generating severe environmental impacts.

Recent advances in sustainable manufacturing have highlighted the importance of integrating circular economy principles into engineering processes. Circular economy strategies promote material reuse, waste reduction, and resource optimization through closed-loop production systems (Núñez-Cacho et al., 2022). In this context, transforming PET bottle waste into 3D printing filament represents an environmentally responsible alternative capable of reducing both production costs and plastic pollution.

Several studies have demonstrated the feasibility of manufacturing recycled PET (rPET) filament for additive manufacturing applications. Research conducted by Singh et al. (2020) reported that recycled PET materials can achieve suitable mechanical and thermal properties for FDM printing when adequate extrusion parameters are employed. Similarly, Cruz Sanchez et al. (2021) indicated that recycled polymer-based filaments contribute significantly to sustainable manufacturing and waste valorization processes.

The present project addresses these challenges through the design of a PET bottle recycling machine intended to produce sustainable filament for 3D printing applications. The proposed system seeks to integrate mechanical recycling, thermal extrusion, and electronic control technologies into a low-cost engineering solution suitable for educational and prototyping environments.

Additionally, the project aligns with sustainable engineering approaches focused on technological innovation, resource optimization, and environmental responsibility. Recent engineering studies associated with sustainable manufacturing and intelligent systems developed by Arencibia Pardo and collaborators have emphasized the importance of integrating technological innovation with sustainable industrial practices in educational and productive sectors (Arencibia Pardo et al., 2023).

2. MACHINE DESIGN AND DEVELOPMENT

2.1. Mechanical Components

The proposed recycling machine incorporates several mechanical subsystems designed to transform PET bottle waste into usable 3D printing filament. The system includes shredding, extrusion, cooling, and winding stages that operate sequentially to ensure continuous filament production.

The shredding mechanism is responsible for reducing PET bottles into small plastic flakes suitable for thermal processing. Stainless steel cutting blades and a compact mechanical transmission system are considered to ensure durability and operational efficiency. Proper particle size reduction is essential for achieving stable melting and extrusion conditions during filament production (Rahman et al., 2022).

The extrusion subsystem constitutes the core of the machine. This stage includes a heated barrel, extrusion screw, nozzle system, and thermal insulation components capable of maintaining controlled melting temperatures for PET processing. The extrusion process converts shredded PET into continuous filament by applying controlled pressure and thermal energy. Temperature stability is a critical factor because PET requires relatively precise thermal conditions to avoid degradation and ensure dimensional consistency.

The cooling subsystem is designed to stabilize the filament diameter immediately after extrusion. Controlled cooling improves dimensional precision and contributes to the mechanical stability of the final filament product. Finally, the winding mechanism collects the produced filament onto spools compatible with standard FDM 3D printers.

2.2. Sensors and Electronic Control System

The machine incorporates electronic control systems intended to regulate operational parameters and improve process stability. Temperature sensors, motor controllers, heating resistors, and rotational speed regulation mechanisms are integrated into the system to ensure safe and efficient operation.

Temperature control represents one of the most important variables in PET filament manufacturing. Inadequate thermal regulation may generate inconsistent filament diameters, polymer degradation, or insufficient extrusion quality. Therefore, the proposed system integrates digital temperature sensors and microcontroller-based control systems capable of maintaining stable extrusion temperatures.

The electronic system also includes speed control mechanisms for the extrusion motor and winding subsystem. Synchronization between extrusion speed and winding speed is necessary to maintain uniform filament diameter during production. Recent studies on recycled polymer extrusion systems indicate that automated control improves filament quality and reduces production variability (Tao et al., 2021).

Furthermore, the machine design incorporates safety mechanisms such as thermal protection systems and emergency stop controls to reduce operational risks and improve user safety.

2.3. Sustainable Manufacturing Approach

The proposed project contributes to sustainable manufacturing through the implementation of recycling-oriented engineering strategies. The conversion of PET bottle waste into functional 3D printing filament promotes material reutilization and reduces dependence on virgin polymer production.

From an environmental perspective, the recycling of PET bottles reduces plastic waste accumulation and decreases the environmental burden associated with conventional disposal practices. Additionally, recycled filament production contributes to reducing the carbon footprint associated with the manufacturing and transportation of commercial thermoplastic materials.

Recent studies have demonstrated that sustainable additive manufacturing technologies can significantly reduce material waste compared to traditional subtractive manufacturing processes (Gebler et al., 2020). Similarly, circular economy-based engineering approaches promote the development of environmentally responsible production systems with long-term sustainability benefits.

The present machine design also possesses educational relevance because it encourages the integration of sustainable engineering concepts into academic environments. Educational institutions can employ recycling-based additive manufacturing systems to support technological innovation, environmental awareness, and practical engineering training.

Research developed in engineering education and technological innovation environments has emphasized the importance of integrating sustainable technological solutions into applied engineering processes (Arencibia Pardo et al., 2022). These approaches support the development of engineering competencies associated with sustainability, automation, and manufacturing innovation.

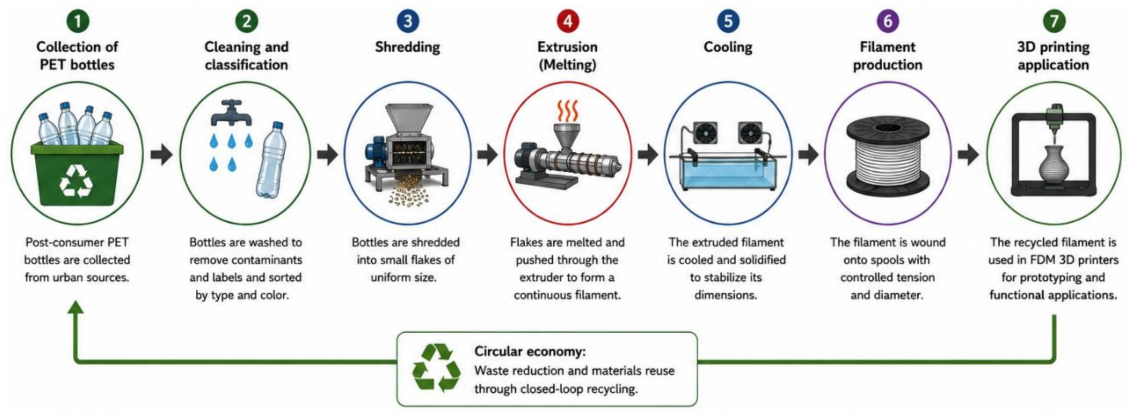

Figure 2. *Sustainable PET recycling process for 3D printing filament production.*

2.4. Filament Testing and Evaluation

The quality of recycled PET filament constitutes a critical factor for successful implementation in FDM 3D printing applications. Therefore, the proposed project considers several evaluation criteria associated with filament performance, dimensional stability, and printer compatibility.

Mechanical resistance tests are necessary to evaluate the structural behavior of the recycled filament under tensile and flexural loading conditions. These analyses help determine whether the recycled material possesses sufficient strength for prototyping applications.

Thermal stability evaluations are also essential because recycled PET materials may experience thermal degradation during repeated processing cycles. Differential thermal behavior can influence extrusion quality, adhesion characteristics, and final print performance.

Dimensional consistency represents another critical parameter. Standard FDM printers typically require filament diameters of 1.75 mm or 2.85 mm with minimal dimensional variation. Consequently, extrusion stability and cooling control are essential for obtaining acceptable printing performance.

Compatibility tests with commercial FDM printers may also be performed to evaluate extrusion continuity, layer adhesion, surface quality, and print precision. Previous investigations have shown that recycled PET filament can achieve acceptable printing performance under optimized extrusion conditions (Pakkanen et al., 2021).

Table 1: *Main components of the proposed PET recycling machine.*

Component	Function	Material / Specification
Shredder blades	Reduces PET bottles into small flakes	Stainless steel (AISI 420), thickness: 6 mm
Extrusion screw	Conveys, melts and homogenizes PET material	Stainless steel (AISI 304), diameter: 25 mm, L/D ratio: 24:1
Heating resistors	Provides thermal energy for melting PET	Ceramic band heaters, 800–1000 W, 220 V
Temperature sensor	Monitors the temperature of the extrusion barrel	Type K thermocouple, range: 0–400 °C
DC motor (extruder)	Drives the extrusion screw	24 VDC, 120–200 W, adjustable speed
Cooling system	Reduces filament temperature and stabilizes diameter	Water bath with 2 axial fans, 12 VDC
Filament spooler	Collects and winds the filament continuously	DC motor with speed control, adjustable tension
Control system	Regulates temperature, speed and overall operation	Microcontroller (Arduino Mega), LCD display, PID control

2.5. Economic and Environmental Impact

The proposed recycling machine offers potential economic advantages by reducing dependence on commercial filament materials. The reutilization of PET bottle waste may significantly decrease filament production costs, especially in educational institutions and small-scale manufacturing laboratories.

From an environmental perspective, the system promotes waste valorization and contributes to reducing plastic pollution through local recycling strategies. The integration of recycling technologies into additive manufacturing processes aligns with current sustainable development objectives and environmentally responsible engineering practices.

Additionally, the implementation of low-cost recycling systems may encourage the adoption of sustainable manufacturing technologies in developing regions where access to commercial additive manufacturing materials remains limited.

Table 2: *expected technical and environmental benefits of the propused system.*

Parameter	Conventional Filament (Virgin Material)	Recycled PET Filament System (This Project)	Expected Impact
Material cost (USD/kg)	20 – 35	4 – 8	60 – 80% cost reduction
Plastic waste generation	High (non-recycled PET bottles)	Low (reuse of post-consumer PET)	Significant reduction of plastic in landfills
Raw material consumption	High (virgin polymer dependence)	Low (recycled PET bottles)	Lower demand for fossil-based resources
Energy consumption	High (polymer production + transport)	Moderate (local recycling process)	Reduced energy footprint
Environmental impact	High (carbon footprint and pollution)	Lower (emissions and pollution)	Contribution to climate change mitigation
Educational accessibility	Medium (high material cost limits access)	High (affordable and locally produced)	Promotes learning and innovation
Circular economy contribution	Linear system (take–make–dispose)	Closed-loop system (reuse and recycle)	Strengthens circular economy principles

3. CONCLUSIONS

The present study proposed the design of a PET bottle recycling machine intended to produce sustainable filament for 3D printing applications through mechanical recycling and thermal extrusion processes. The project integrates mechanical, thermal, and electronic subsystems capable of transforming post-consumer PET waste into functional filament suitable for additive manufacturing applications.

The proposed system contributes to sustainable engineering practices by promoting circular economy principles, reducing plastic waste generation, and facilitating access to low-cost filament materials. The incorporation of temperature control systems, extrusion mechanisms, and automated operational components improves process stability and supports the production of recyclable filament with potential educational and industrial applications.

The project also demonstrates the technical feasibility of integrating recycling technologies with additive manufacturing processes in order to reduce environmental impact and encourage responsible material utilization. Furthermore, the implementation of sustainable manufacturing systems within educational environments may strengthen engineering competencies related to technological innovation and environmental sustainability.

Future work may include experimental validation of filament mechanical properties, optimization of extrusion parameters, implementation of automated quality control systems, and evaluation of long-term operational performance under real manufacturing conditions.

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