International Journal for Multidisciplinary Research (IJFMR)
E-ISSN: 2582-2160 ● Website: www.ijfmr.com ● Email: editor@ijfmr.com

A Critical Review of the Discrepancies in PLA Recycling for 3D Printing

Abdul Rasheed Roshan[1], Faisal Abdul Qader[2], Syed Mubeen[3], Mohammed Mohfaaz[4], Abdullah Mansoor Ahmed[5]

[1,3,4]Student, Electronics and Communications Engineering Dept, Muffakham Jah College of Engineering and Technology, India
[2,5]Student, Mechanical Engineering Dept, Muffakham Jah College of Engineering and Technology, India

Abstract
This review examines the recycling of Polylactic acid (PLA) filament for 3D printing, focusing on mechanical and chemical property retention after repeated reprocessing. The study evaluates PLA waste from diverse sources, including PPE production, analyzing mechanical strength, molecular weight, and crystallinity changes across extrusion cycles. PLA recycling challenges include chain degradation, decreased tensile strength, and increased fluidity with repeated heating, though properties may be improved through polymer alloying. A detailed recycling system design is also proposed, incorporating temperature control, stepper motor regulation, and quality monitoring for efficient filament production. This system supports sustainable, high-quality PLA recycling for 3D printing applications.

Keywords: PLA Recycling, Renewable, Extrusion Cycles, Compression Molding, NMR Spectroscopy, Melt, Fluidity, Bio-polyester Chain Mobility, Thermal and Dimensional Stabilities, PID, MOSFET.

1. Introduction

The Main objective of PLA Recycling is to have a renewable source of a printable plastic that can be used as per need. In order to achieve this, it is necessary to analyse the inputs and the potential outputs of a system designed to include both the chemical properties and the physical attributes of the used PLA after it has been recycled.

Two types of waste were considered: a blend of different printing wastes (masks, visors, other components) of personal protective equipment coming from an association of Spanish corona makers, and PLA waste from a single known commercial source. Both types of materials were subjected to repeated extrusion cycles and processed into films by compression moulding. Samples were characterized after each cycle and their mechanical and viscosity properties evaluated. Diffusion Ordered NMR spectroscopy (DOSY) experiments were also carried out to estimate molecular weights [1].

The effect of the reprocessing cycles was also studied by the changes in the melt fluidity, which showed a significant increase after four reprocessing cycles. An increase in the bio-polyester chain mobility was also attained with the number of the reprocessing cycles that subsequently favoured an increase in crystallinity of PLA [1] [2].

The mechanical enhancement attained was related to the formation of branched and larger macromolecules by a mechanism of chain extension based on the reaction of the multiple glycidyl methacrylate (GMA)

groups present in PS*co*GMA with the hydroxyl (OH) and carboxyl (COOH) terminal groups of both bio-PET and r-PET. Furthermore, all the polyester blend pieces showed thermal and dimensional stabilities similar to those of neat
Bio-PET, remaining stable up to more than 400 °C [2] [3] [4].
PLA is supposed to finish its life in the compost, degrading into nature as time goes by from a span of two to ten months at the least, disregarding the creation of this type of material an idea is that it can be reused and refurbished and have a different chemical composition or different physical attributes altogether.
Having said that, it is necessary to have an understanding that the material that is being recycled may lose its original strength and other stronger discrepancies in regards to being refurbished and recycled.
It may or may not have to have the versatility and durability it once had, but looking forward it may have an alter effect and thereby create a new component altogether, in the essence and having an idea from alloying of two different types of metal, alloying of plastics can also have a betterment effect on the new material created, giving it more than usual versatility, durability and dexterity.

2. Analysis of the Physical and Chemical Structure of PLA plastics for 3D Printing:

Polylactic acid (PLA) is among the most popular polymers in FFF (Fused Filament Fabrication). It is a biodegradable and renewable thermoplastic polyester derived from renewable sources (mainly starch and sugar). It replaces conventional petrochemical based polymers, such as acrylonitrile butadiene styrene, and reduces oil consumption by 30–50%. [4] [5].
The findings of this study highlight how the mechanical properties of FFF printed components vary based on the internal fill pattern configuration, even when printed under similar conditions. Polylactic acid (PLA) is the most commonly used material for 3D printing [6].

Material Under Different Exposures:

A. Material under UV Radiation:

The samples were exposed to UV irradiation using a Mikrolux Chirana device equipped with a 125 W mercury discharge lamp, with exposure times of 20 hours at 400 mm and 100 hours. The samples were rotated periodically to ensure uniform illumination from both sides.
After 20 hours of exposure, the ABS samples, particularly those in lighter shades, showed slight yellowing, while the surface of the PLA samples became sticky. No noticeable changes were observed in the PETG or ASA samples.
After 100 hours of exposure, the colour changes in the ABS samples became more pronounced, especially in the Fillamentum ABS material and slight changes were also visible in the ASA samples [5] [6].

B. Material under Elevated Temperature:

Another set of samples was placed in the furnace for 100 h at a temperature of 60 °C. This temperature was chosen because there would be no significant shape deformation of the samples and thus it would be possible to test their mechanical properties.
At the same time, this is the glass transition temperature range for PLA material. For the remaining materials, this is the temperature below the glass transition temperature [6].

C. Material under different Ambient Temperatures:

The final aging method involved placing the samples outdoors for 98 days. They were situated in a sheltered location, where they were exposed to varying temperature, sunlight, and
humidity conditions.
During the testing period, air temperatures ranged from −5°C at night to 10°C during the day, and humidity

levels varied between 30% and 97%. The samples underwent aging for a total of 2400 hours. The cumulative duration of direct sunlight during this period was approximately 294 hours.

3. General Outlining of the PLA Filament Recycling System

To create a PLA recycling system that melts PLA waste and extrudes it into filament, let's outline each step in detail:

Loading the PLA Waste:

Process: Start by placing the PLA waste (e.g., scraps, failed prints) into a hopper or funnel positioned above an extrusion chamber.

Design Note: The hopper should have a wide opening to accommodate various shapes of PLA scraps and funnel them effectively into the extrusion chamber.

Feeding Mechanism (Screw Extruder with Stepper Motor):

Process: As the PLA waste enters the extrusion chamber, a screw (auger) driven by the stepper motor pushes the PLA forward through the chamber.

Motor Control: A stepper motor, paired with a driver, will provide precise control of the screw's rotation, ensuring a steady feed of PLA into the heating zone.

Speed Control: You'll likely need to adjust the motor speed depending on the amount and thickness of the PLA, so you can maintain a smooth extrusion flow.

Heating and Melting Zone:

Process: The PLA reaches a heating zone where a heating element, such as a nichrome wire coil or cartridge heater (like those used in 3D printer hot ends), gradually melts it.

Temperature Control: The temperature should be carefully controlled to around 180200°C, the ideal range for PLA. This is managed by a thermistor or thermocouple to measure the actual temperature.

A PID controller (proportional integral derivative controller) for precise temperature regulation, which ensures stable melting without overheating. [7]

A MOSFET (Metal Oxide Semiconductor Field Effect Transistor) or relay switches the heating element on or off based on the temperature reading.

Melted PLA Flow and Nozzle Extrusion:

Process: The melted PLA is pushed forward by the screw through a nozzle, which defines the diameter of the extruded filament. Common diameters for 3D printing filament are 1.75 mm or 2.85 mm.

Quality Control: Sensors like optical or laser based systems can monitor the filament's diameter as it exits the nozzle, ensuring consistency in the filament's thickness.

Cooling Zone: As the filament exits the nozzle, it must cool down quickly to retain its shape. Small cooling fans or a water bath can help solidify the filament.

Filament Pulling and Winding Mechanism:

Process: A pair of rollers (one of which may be connected to a second stepper motor) gently pulls the filament as it exits the cooling zone. These rollers maintain tension and ensure smooth, even extrusion.

Control System: The motor driving these rollers needs to match the extrusion rate to avoid stretching or compressing the filament, so adjusting its speed to match the PLA feed rate is crucial.

Winding the Filament:

Process: After cooling, the filament needs to be wound onto a spool for convenient storage and use.

Spooler: A third motor can drive a spool that winds the filament neatly. A sensor may also guide the filament back and forth across the spool to ensure even distribution.
Auto-Cut off: If the spool reaches full capacity, the system can have a sensor to stop extrusion automatically.

User Interface and Monitoring:

Temperature and Motor Control: An LCD or touchscreen interface can display the current temperature, motor speeds, and status updates, allowing for real time adjustments.
Safety and Alerts: Alerts can indicate any issues, like overheating or a jam in the screw mechanism, to help prevent damage.

Summary Flow:

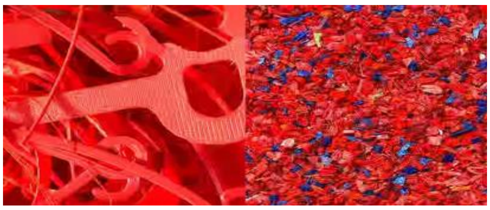
1. Load PLA scraps in the hopper.
2. The stepper motor drives a screw to feed PLA into the heating zone.
3. The heater melts PLA, with temperature maintained by a PID controller.
4. Melted PLA is extruded through a nozzle, and the filament is cooled.
5. Pulling rollers guide the filament, keeping tension consistent.
6. The cooled filament is wound onto a spool by the spooler motor.
7. The user interface displays current settings, status, and allows for adjustments.

4. Alloying of Recycled Plastics

This method holds promise for applications beyond just immiscible polymer blending; it could also be useful in recycling waste plastics without the need for sorting or compatibility.
Alloying, by its very definition, means the merging of different types of plastics for creating new properties and for the need of experimenting and analysing the newly made composition in regard to the current use in the market [8].
Different composition is however appreciated if its leaning towards sustainability and the sustenance of the nature in the long run, by creating a somewhat related structure of a plastic to that of a dissolvable and reusable composition, an alloying abled plastic, meaning a component which can be further alloyed with other such material can be created and used. [9]

5. A Possible Design for a System for Recycling 3D Printable PLA

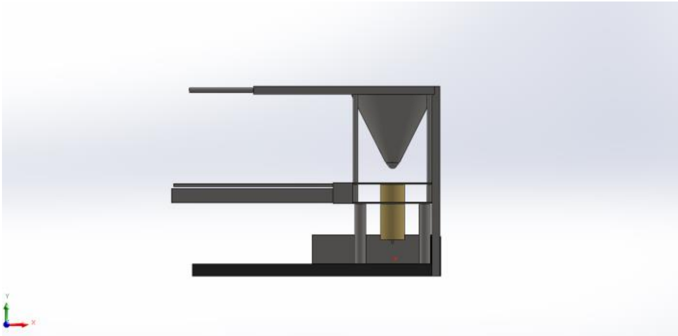
Since the dimensional accuracy, tensile strength, and friction properties of the samples were analysed and compared for printing temperatures ranging from 200 °C up to 240 °C [10].
The subjected heat to the already printed products by the PLA filament need to be heated a little over the described temperature in order to reach the moulding melting point of the shredded filament.
Although that is the required temperature, it is also necessary to have the printed parts shredded into little bits in order to have the surrounding temperature reach the moulding plastic stage. The following figure shows the state the previously printed part needs to be in, in order to go through the process.



(Shredded state of a 3D printed Products) (Figure-1)

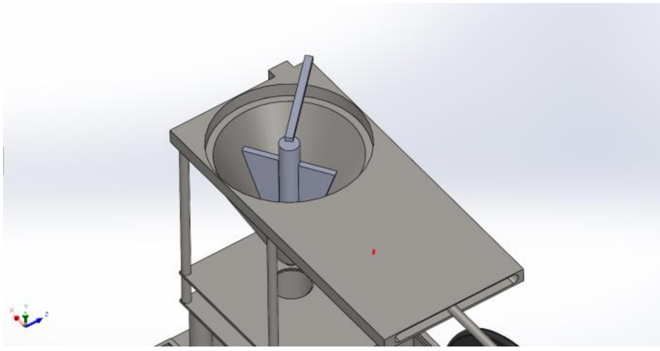
A Possible CAD model of the system:

In regards to designing a system that can sustain temperatures and the ambient controls to have the shredded material melted and molded into a new filament in order to be reused, a system was designed so as to have an abject understanding of the situation and solution that was the objective.



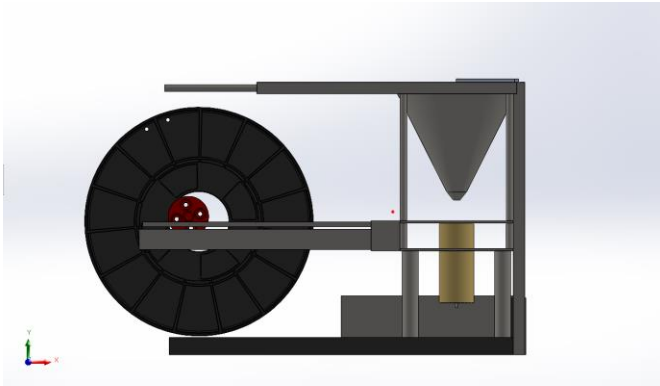
(Holder and Heat Compartment) (Figure-2)

The funnel takes the work of the holder where the rotatory device makes sure that the opening of the funnel does not get clogged, then the heating compartment takes the shredded PLA of the previous 3-D prints and then gets pushed through the slim nozzle of about 2mm diameter.



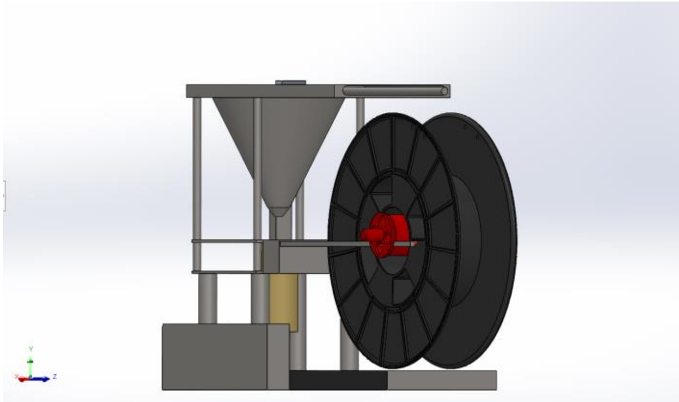
(Rotating Element for Shredded PLA) (Figure-3)

The rotating part helps the shredded shrapnel from getting stuck in the opening towards the heating compartment. Having this would help in the free flow of the system and conditional rotation towards the shredded pieces as well.



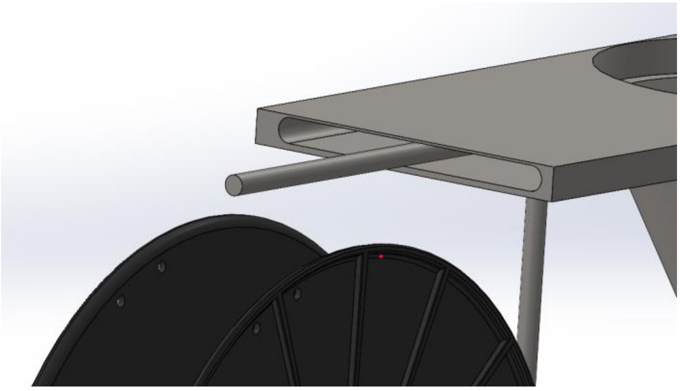
(Heat Compartment with nozzle for PLA Recreation) (Figure-4)

The Heat sink here heats the shredded PLA into its mouldable form in order to re-iterate into the subjective 2mm cylindrical wire that needs to be casted again, the nozzle helps in have the moulded form, injected outside the heated compartment, cooling it to the ambient temperature and its resting phase.



(Spool where the re-iterated PLA is collected) (Figure-5)

The spool collects the PLA and has it collected uniformly and gets distributed over the collecting surface. The whole system of movements is controlled by electronics of relevant nature and therefore have everything automated.



(Sliding Rod for Equal Distribution) (Figure-6)

The Sliding Rod is controlled by the axis thereafter being controlled by a motor and electronics in order to have the PLA be distributed evenly over the collecting surface of the spool.

6. Involvement of Electronics and other Relevant Itinerary

A. Stepper Motor Control for PLA Feeding [11] [12]

Purpose:

The stepper motor drives the screw in the extrusion chamber, which pushes the PLA waste toward the heating zone at a steady rate.

This control ensures a consistent flow of material, which is crucial for achieving a uniform filament diameter in the extrusion process.

Stepper Motor and Driver Circuit:

A stepper motor (commonly a NEMA 17 for 3D printing applications) is controlled by a stepper motor

driver like an A4988 or DRV8825.The microcontroller sends precise pulses to the stepper motor driver, dictating the motor's speed and direction.
Driver Current Limiting: The driver's current limiting is adjusted based on the motor's
requirements, preventing overheating while ensuring adequate torque for feeding the PLA.

Speed Control:

The stepper motor's speed (RPM) is adjusted through the microcontroller's pulse frequency, controlling how fast the PLA is fed.
By setting the speed based on the microcontroller's programming, you ensure that the extrusion rate matches the PLA melting rate, preventing clogs or gaps in the filament.

Microcontroller Commands:

The microcontroller (like an ESP32 or Arduino) generates commands to:
Start and stop the stepper motor.
Adjust the motor speed as per the material flow needs.
Control feedback based on sensor inputs, like diameter consistency.

B. Microcontroller for System Management [12] [13]

Core Control:

The microcontroller (ESP32, Arduino, etc.) acts as the central brain of the system, coordinating between the stepper motor, heating element, temperature sensors, and other peripherals.

Sensor Integration:

The microcontroller reads data from temperature sensors (such as thermistors or thermocouples) placed near the heating element.
It processes this data to adjust the heating element's power, ensuring the temperature remains within the optimal range for PLA melting.

Feedback Loop:

The microcontroller is programmed with a PID control algorithm that adjusts the heating element's power based on real time temperature data.
This feedback loop ensures that the temperature remains stable, preventing
Under-heating (which would cause clogs) or overheating (which could degrade PLA quality).

User Interface Management:

The microcontroller is connected to an LCD or touchscreen display, allowing users to set temperature, extrusion rate, and motor speed.
The interface could also provide real time feedback on current temperature, motor speed, and filament quality.

C. Temperature Control and Adjustment [14] [15]

Heating Element:

The heating element, such as a nichrome wire or cartridge heater, heats the PLA in the melting chamber. It requires precise control to maintain a steady temperature of around 180200°C, which is optimal for PLA.

Temperature Sensor:

A thermistor or thermocouple placed close to the heating element monitors the temperature. The sensor reads the current temperature and sends this data to the microcontroller, forming the basis of the feedback control loop.

PID Controller:

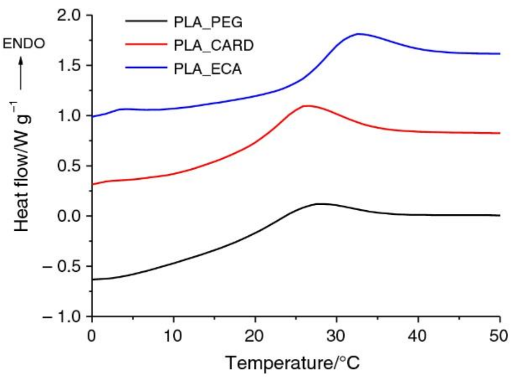
The microcontroller is programmed with a PID (Proportional Integral Derivative) control algorithm, which processes temperature sensor data and adjusts the power to the heating element accordingly. This control loop helps to maintain a stable temperature by making incremental adjustments:
Proportional to how far off the current temperature is from the set point.
Integral for accumulated past temperature errors.
Derivative for the rate of temperature change.

4. Power Control:

A MOSFET (metal–oxide–semiconductor field effect transistor) or relay is used to control the heating element's power. The microcontroller adjusts the MOSFET's gate or relay to modulate the current supplied to the heater. This allows precise control over the heating element's power, ensuring steady heating without temperature fluctuations.

5. Material Based Settings:

User Input: The interface allows the user to specify the type of material (e.g., PLA) to set the correct temperature range automatically.
Temperature Profiles: If different types of PLA or other thermoplastics are used, the microcontroller can store and retrieve different temperature profiles, adjusting heating as per material requirements.



(Figure-7)

D. Summary of Electronics Operation Flow:

1. Controlled by the microcontroller.
2. Temperature sensors monitor the heating chamber temperature, feeding data to the microcontroller.
3. The microcontroller's PID algorithm adjusts the heater's power to maintain optimal PLA melting temperature.
4. Motor speed is synchronized with the extrusion rate, set and adjusted through the user interface.
5. The user interface displays system status and allows adjustments, enabling the user to control extrusion temperature, speed, and monitor system conditions.

This integrated control of the stepper motor, heating element, and user interface ensures the PLA melts and extrudes smoothly, yielding high quality recycled filament.

Materials	ABS	PLA	PLA-CF
Print Temperature	230	195	195
Temperature of print bed	90	60	60
Print Speed	30	30	30

Print layer thickness	0.2	0.2	0.2
Print orientation	[0-90]	[0-90]	[0-90]
Print Nozzle diameter	0.4	0.4	0.4
Print condition	Print in a closed cabin		

(Table-1)

References

1. "Hidalgo Carvajal D, Muñoz ÁH, Garrido González Recycled PLA for 3D Printing: A Comparison of Recycled PLA Filaments from Waste of Different Origins after Repeated Cycles of Extrusion.," September 2023.
2. Fico D, Rizzo D, De Carolis V, Montagna F, Esposito Corcione C, "“Sustainable Polymer Composites Manufacturing through 3D Printing Technologies by Using Recycled Polymer and Filler", Polymers (Basel)," September 2022.
3. Agüero A, Morcillo MDC, QuilesCarrillo L, Balart R, Boronat T, Lascano D, Torres Giner S, Fenollar O, "“Study of the Influence of the Reprocessing Cycles on the Final Properties of Polylactide Pieces Obtained by Injection Molding" Polymers (Basel)," November 2019.
4. MontavaJorda S, Lascano D, QuilesCarrillo L, Montanes N, Boronat T, MartinezSanz AV, Ferrandiz-Bou S, TorresGiner S, ""“Mechanical Recycling of Partially BioBased and Recycled Polythylene Terephthalate Blends by Reactive Extrusion with Poly (styrenecoglycidyl methacrylate)", Polymers (Basel)," January 2020.
5. Bergaliyeva S, Sales DL, Delgado FJ, Bolegenova S, Molina SI,“Manufacture and Characterization of Polylactic Acid Filaments Recycled from Real Waste for 3D Printing”, Polymers.," 2023.
6. Sedlak J, Joska Z, Jansky J, Zouhar J, Kolomy S, Slany M, Svasta A, Jirousek J, "“Analysis of the Mechanical Properties of 3DPrinted Plastic Samples Subjected to Selected Degradation Effects."," Febuary 2021.
7. Subramanyam, M V & Satyaprasad, K & P V, Gopi krishna rao
8. bpf.
9. Qu, Jinping & Huang, Zhaoxia & Yang, Zhitao & Zhang, Guizhen & Yin, Xiaochun & Feng, Yanhong & He, Hezhi & Gang, Jin & Wu, Ting & He, Guangjian & Cao, Xianwu. , ""“IndustrialScale Polypropylene–Polyethylene Physical Alloying Toward Recycling” Engineer,” 2021.
10. Frunzaverde D, Cojocaru V, Ciubotariu CR, Miclosina CO, Ardeljan DD, Ignat EF,, "“The Influence of the Printing Temperature and the Filament Color on the Dimensional Accuracy, Tensile Strength, and Friction Performance of FFFPrinted PLA Specimens”, Polymers (Basel).," May 2022.
11. Arefin, Tanu Kabir, Humayun & Chowdhury "“Simple Discussion on Stepper Motors for the Development of Electronic Device”, 5. 1089-1096.," 2014.
12. Chang, Xinyi, "“Design and analysis of three types of stepper motor drive Circuits”, Theoretical and Natural Science," 2023.
13. egr.
14. Dinwiddie, Ralph & Love, Lonnie & Rowe, John, "“Real-time Process Monitoring and Temperature Mapping of a 3D Polymer Printing Process”,".
15. Ismailov, Alisher Jo`rayev, Zafar, "“Study of arduino microcontroller board”.," 2022.