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Low-cost Device to Upcycling PET Plastic Bottle into 3D Printer Filament

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Abstract – *Plastic waste poses a significant environmental threat, particularly by clogging waterways and contributing to urban flooding. Plastic bottles, which require 450 to 1000 years to decompose, accelerate environmental degradation when not properly managed. In response, Indonesia's Ministry of Environment and Forestry (KLHK) promotes the 3R concept-Reuse, Reduce, and Recycle—as a sustainable strategy for waste utilization. With the advent of Industry 4.0, technologies such as 3D printing, especially via Fused Deposition Modeling (FDM), offer new pathways for sustainable manufacturing. One such innovation is the recycling of PET bottles into 3D printer filament, providing a low-cost alternative that reduces reliance on virgin materials and minimizes plastic waste. The integration of a mobile application adds further value by enabling users to configure and monitor the filament production process efficiently. To support a clean and sustainable environment, collaboration between government, industry, and the community is essential. Experimental tests on recycled PET filament show that filament diameter varies by extrusion speed: at 4 RPM it measures 1.6 mm, while other speeds yield approximately 1.7 mm. Optimal printing performance is achieved at 2 RPM with a temperature of 200°C and at 3 RPM with 210°C, demonstrating suitability for high-quality prints such as 3D vases and benchmarks made from recycled plastic bottles.*

Keywords – *Filament; Fused Deposition Model; Recycle; Polyethylene Terephthalate (PET); 3D printing.*

I. INTRODUCTION

WE are generating more plastic waste than ever before. Plastic packaging makes up about 40% of the plastic in the municipal solid waste stream [1]. Despite decades of effort to collect, sort, and recycle plastic packaging, most are destined for disposal in a landfill or waste-to-energy facility (e.g., incineration). Polyethylene terephthalate (PET) and high-density polyethylene (HDPE) bottles make up the majority of the plastic packaging recycled today [2].

Adopted in September 2015, the 12th goal of Sustainable Development Goals (SDGs) emphasizes sustainable consumption and production encompassing waste-related issues. Through the concept of 3R, the Ministry of Environment and Forestry (KLHK) aims to diminish plastic waste by emphasizing the principles of Reuse, Reduce, and Recycle (3R). Waste reduction is carried out by using reusable materials that are recycled and/or materials that are easily broken down by natural processes, collecting and handing back waste from products or packaging that have been used [3]. The management of plastic waste is a critical environmental challenge that requires a multifaceted approach. The 3R principle (Reduce, Reuse, Recycle) has been widely adopted as an effective strategy for plastic waste management [4–6]. Implementation of 3R in various settings, from schools to households, has shown promising results in reducing plastic waste and increasing environmental awareness [4, 7]. However, the success of 3R initiatives depends on factors such as attitude, subjective norms, perceived behavioral control, habits, and facilitating conditions [8]. Recent research suggests expanding the 3R concept to include ”recover” and ”redesign,” creating a 5R approach [9]. Additionally, exploring alternative materials like bioplastics and adopting a circular economy model are considered crucial steps towards sustainable plastic waste management [10].

Research on recycling plastic waste has explored various approaches, such as creating fiber-reinforced concrete [11], solar polymer heat exchangers [12], and other building materials [13]. However, converting

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plastic bottles into 3D printing filament offers a more versatile and sustainable solution. Unlike other methods that are often limited to specific industries, filament production supports a wide range of applications, from manufacturing to creative design. Additionally, it directly contributes to the circular economy by reducing the need for virgin plastics, minimizing waste, and promoting the efficient reuse of materials across various sectors.

The concept of Industry 4.0 was first introduced by the German government in 2013, marking the newest phase in industrial transformation. This revolution is characterized by improvements in connectivity, information transparency, technical support, and decentralized systems. A key development resulting from Industry 4.0 is the rise of 3D printing, also referred to as additive manufacturing [14]. 3D printing has been adopted in various industries, including medical applications [15], dentistry [16], and aerospace [17].

Its popularity stems from numerous benefits, including rapid production, cost-effectiveness, customization capabilities, and reduced material waste [18]. With the high demand for lightweight, more functional, and cost-efficient product systems, polymer-based composites have become "state of the art" in material system design and development for 3D print applications [19].

Over time, various types of 3D printing have evolved to meet diverse industrial needs. The different types of 3D printing include stereolithography (SLA), widely utilized since the 1980s, where a liquid material solidifies upon exposure to UV light; selective laser sintering (SLS), which operates similarly to SLA but employs powdered materials such as glass, nylon, and ceramics; fused deposition modeling (FDM), utilizing plastic materials for printing and known for being cost-effective, environmentally friendly, and relatively fast; and digital light processing (DLP), similar to SLA but differing in the light source. While SLA uses UV light, DLP employs a digital projector with digital illumination [20].

Generally, FDM employs a thermally regulated process, melting a thermoplastic filament before depositing it onto the platform [21]. Common materials like acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA) are favoured in FDM due to their thermal and rheological characteristics, facilitating easier part manufacturing [22]. Despite its benefits, 3D printing produces significant waste, often due to failed prints or discarded support structures. Additionally, the ease of creating components without machining or tools causes that many prints are used as disposable prototypes [23]. As the use of thermoplastic prints continues to rise with advancements in additive technology, the challenge of waste disposal becomes more pronounced.

Fused deposition modeling (FDM) is a 3D printing method based on material extrusion. In this process, heated material is extruded through a nozzle and deposited layer by layer, resulting in a completed printed composite part [24]. Recent studies have investigated the performance of waste PET as a material for 3D printing, comparing it to pure PET. The findings indicated that recycled PET is more suitable for 3D printing than pure PET. As a result, the waste 3D print PET filament was applied to prepare circuit boards [25]. Additionally, the filaments from electronic plastic waste exhibited a satisfactory level of flexibility compared to virgin plastic [26].

There has been considerable interest in utilizing 3D printing to alleviate supply chain congestion, particularly for small spare parts, with the rationale being that parts can be printed on demand, potentially reducing the need for physical inventory in warehouses while enabling quicker replenishment cycles for less frequently purchased parts [27].

II. RESEARCH METHODS

Based on the presented research, it is evident that utilizing plastic waste to create 3D printing filament holds the potential to address the global plastic waste issue. Therefore, this study aims to develop a filament-making machine using PET plastic bottle waste. The primary objective of creating this plastic bottle upcycling tool is to provide a cost-effective solution. Using plastic bottles as the filament source material is expected to lower the manufacturing costs compared to existing systems. An example of a 3D printing result can be seen in Figure 1.

Figure 1: Common 3D Print, Creality Ender 3

As illustrated in Figure 2, the functional block diagram shows how PET bottles are transformed into

3D printing filament. The process begins with the user placing a plastic bottle into the support column or pole, where it is sliced by a cutter. These plastic strips are then transferred into a heating chamber to be softened. A temperature sensor inside the chamber measures the heat level, and a microcontroller processes this data to control the heating system accordingly. Once the material is adequately softened, it is extruded and cooled by a DC fan before being wound using a gear mechanism. A smartphone functions as the control and monitoring interface for the entire system.

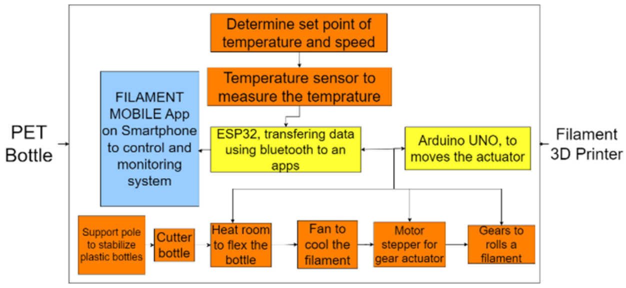


Figure 2: Functional block diagram of the PET bottle-to-filament transformation system.

i. *Device Characterization Overview*

The fabrication of the device includes several essential components that efficiently convert PET plastic bottles into filament suitable for 3D printing. The process starts with a bottle cutter that trims bottles into uniform strips. These strips are fed into a hotend extruder, which serves as the heating element. A thermistor inside the extruder measures the temperature continuously. This data is interpreted by an ESP8266 microcontroller, which then regulates the heating through a relay system to ensure optimal melting conditions.

As shown in Figure 3, the flowchart of the system provides a step-by-step sequence of the filament production. The operation begins by powering on the device and placing a plastic bottle on the support column. The user sets the desired parameters (temperature and speed) through a mobile application. Once the bottle is inserted and heated, filament begins to emerge. If it does not, the user can fine-tune the temperature. After extrusion begins, the filament is guided to a spool for winding.

Eventually, the filament is fully produced, and the process can be repeated for the next bottle. The smartphone interface allows users to monitor and adjust production variables remotely, offering flexibility and ease of use. The estimated cost to build the device is under IDR 2,000,000, providing an affordable method to recycle plastic waste into usable filament.

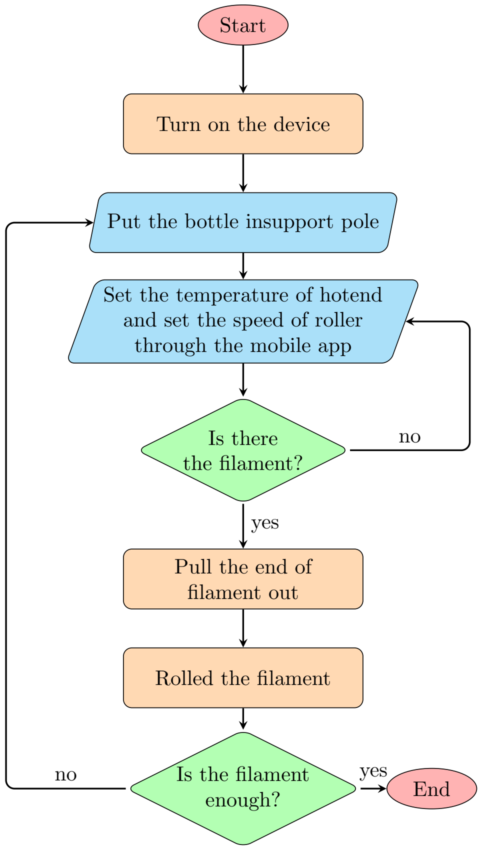


Figure 3: Flowchart of the PET filament fabrication process controlled via smartphone interface.

The system is designed to maintain a consistent filament diameter, critical for accurate 3D printing. It supports adjustable temperatures from 60°C to 210°C, accommodating a range of material behaviors. Filament diameter consistency is crucial for 3D printing quality, with temperature control playing a significant role. Studies have shown that heating temperature affects filament diameter consistency in HDPE and LDPE extrusion [28]. Optimal temperatures for consistent filament production were found to be 220°C for HDPE and 190°C for LDPE. Process parameters, including temperature and extrusion rate, can be adjusted to achieve high diameter consistency and low tolerances [29, 30]. Improved print head designs and temperature control systems can enhance temperature control accuracy, reducing errors from 28% to 6.2% [31]. Filament extruders have been developed to produce 1.75 mm diameter filaments from recycled materials, operating at temperatures between 350–370°C [32]. Constant temperature control systems in 3D printers can help maintain optimal printing conditions and reduce material consumption [33].

Furthermore, the motor speed can be tuned from 1 to 10 RPM, giving users control over production speed for either detailed prints or rapid prototyping. These features make the system user-friendly and effective for home or small-scale manufacturing environments.

Figure 4 illustrates the comprehensive block diagram of the entire system, incorporating sensors, actuators, and IoT components. These elements collectively enable the device to detect temperature, control extruder motion, and provide remote monitoring. The actuator mechanism involves an Arduino Uno connected to a stepper motor and an A4988 motor driver, which orchestrate the movement of the extrusion process.

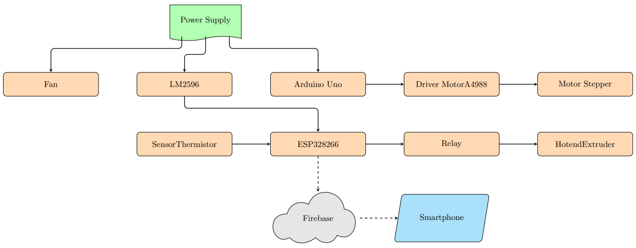


Figure 4: System block diagram including sensor, actuator, and IoT modules.

ii. Schematic Diagram

As depicted in Figure 5, this schematic system diagram illustrates the relationships and interactions between various components of the device. Temperature and speed monitoring and control are the two primary output parameters generated through collaboration among interconnected modules. This system aims to ensure consistent filament quality that meets predefined standards by managing and monitoring both temperature and extrusion speed.

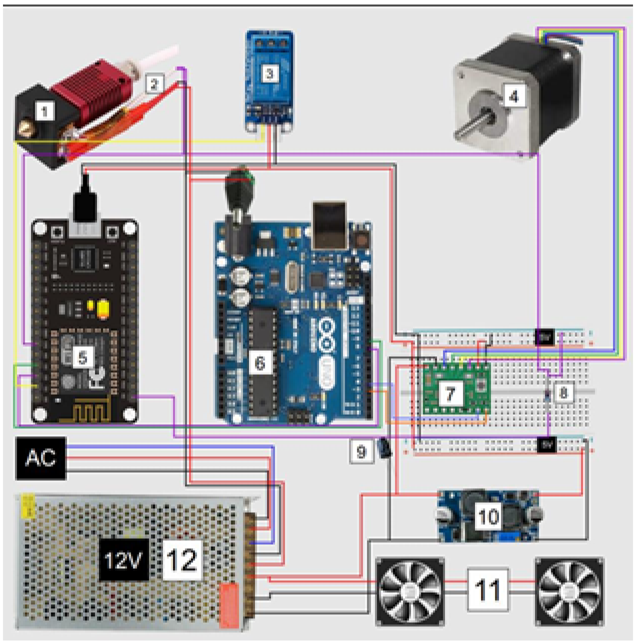
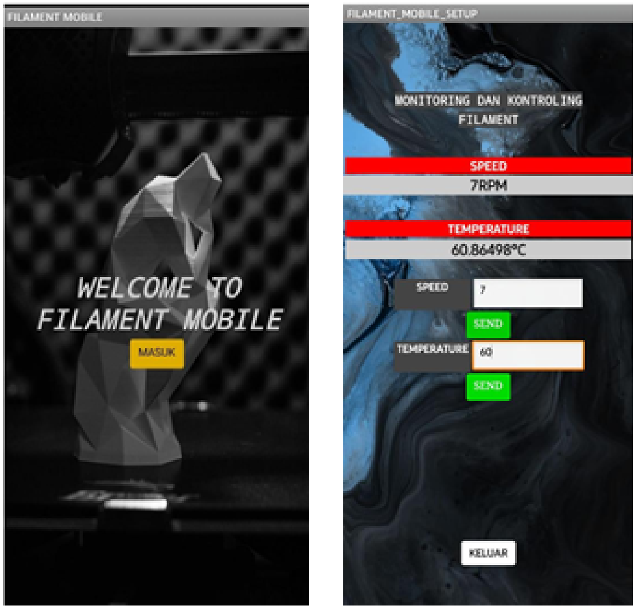


Figure 5: Schematic diagram showing sensor-actuator integration and control logic.

At the core of this system is the Arduino Uno, which serves as the master microcontroller, responsible for coordinating the actuators and processing sensor input. To facilitate wireless control, the system integrates NodeMCU ESP8266, enabling Bluetooth communication. The stepper motor used is Nema 17, selected for its high torque performance at moderate RPM levels. For temperature sensing, a thermistor is employed due to its compatibility with heating areas and suitability for embedded systems. In addition, an infrared-based speed sensor is utilized for reliable, low-cost speed detection. The system is powered through a 12V input, and a step-down converter supplies appropriate voltages to the microcontroller and sensors.

iii. Graphical User Interface (GUI) Display on Android Using MIT App Inventor

The integration of the NodeMCU ESP8266 with the Firebase platform enables real-time communication of control and sensor data. As illustrated in Figure 6, the Android application interface, developed using MIT App Inventor, interacts with Firebase to receive and transmit operational data from the device seamlessly.


FILAMENT MOBILE

WELCOME TO
FILAMENT MOBILE

FILAMENT_MOBILE_SETUP

MONITORING DAN KONTROLING
FILAMENT

SPEED
7RPM

TEMPERATURE
60.86498°C

SPEED 7

TEMPERATURE 60

(a) **(b)**

Figure 6: Graphical User Interface (GUI): (a) Initial App Display, (b) Setup Screen of Filament Mobile.

Figure 6(a) displays the app's initial interface upon launch, where users are greeted by the "Filament Mobile" logo and can access the application via a login button. Once logged in, users are directed to the setup screen (Figure 6(b)), which allows real-time monitoring of temperature and speed. Input boxes are provided for adjusting these parameters, and an exit button allows users to close the application easily.

During development, the app is tested using a web emulator provided by MIT App Inventor. This testing approach allows rapid iterations without requiring installation on a physical device, thus improving development efficiency. The real-time data exchange enables users to optimize filament production directly via their smartphones, enhancing system responsiveness and interactivity.

iv. Device Design

Figure 7 presents the visual design of the complete filament maker device. This design emphasizes compactness, modularity, and mobility. Ergonomic handles are included to increase comfort and maneuverability during operation. The overall structure ensures ease of use, as well as straightforward maintenance and assembly.

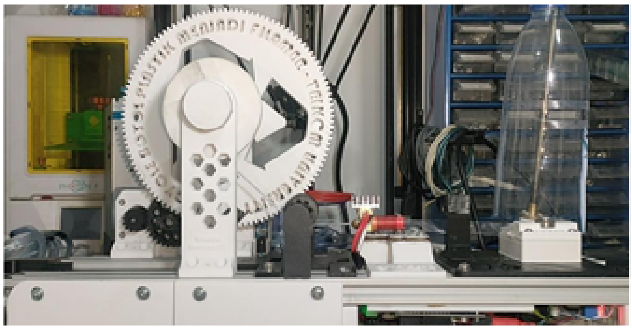


Figure 7: 3D visualization of the complete filament maker device.

As shown in Figure 8, the gear component of the device was designed using Autodesk Fusion 360 and printed with a higher infill density of 50% to improve strength. The rest of the components utilized approximately 25% infill. The gear required approximately 12 hours of continuous 3D printing.

Figure 8: Gear component design using Autodesk Fusion 360.

The final prototype matches the design specification in terms of both dimension and functionality. Its lightweight and efficient form factor makes it suitable for portable use. The modular assembly approach simplifies installation, upgrading, and component replacement, while ergonomic features enhance user comfort throughout the operation.

III. RESULTS AND DISCUSSION

The purpose of testing in this study includes several evaluation criteria, particularly from economic and technical perspectives. Economically, the goal is to ensure the production cost of the tool remains affordable so that the selling price is competitive and accessible. The use of low-cost and easily available materials, such as PET plastic bottle waste, aligns with this criterion.

From a technical standpoint, the method of operation should be simple and straightforward, ensuring users can operate the device with minimal training. Simple operation reduces the risk of user error and enhances operational efficiency. The design must strike a balance between simplicity and functionality to ensure effectiveness. Moreover, the process of converting PET plastic bottles into filament must be efficient and avoid unnecessary complexity to maintain productivity. Based on the decision matrix, the selected solution for development incorporates a bottle cutter as the main mechanism for slicing plastic bottles.

i. Motor Stepper and Motor Driver

The stepper motor was tested using the A4988 driver to evaluate its ability to control speed and rotation direction under different voltages and signal conditions. Tests ranged from 1 to 10 RPM. All speeds were achieved successfully, with a minor exception at 9 RPM, which required an additional 1 minute and 1 second. However, this variation did not significantly affect overall device performance. The A4988 driver demonstrated consistent reliability and stability during testing.

ii. Hotend Extruder and Relay

The hotend extruder functions as both the heating tool and filament former. Temperature regulation is achieved through a thermistor that reads real-time temperature values. Once the preset threshold is reached, the relay automatically disables the heater to prevent overheating. The heating process is managed within predefined temperature intervals: 60°C, 90°C, 120°C, 150°C, 180°C, and 210°C. When any of these thresholds is reached, the relay disconnects power, and reconnects as the temperature falls below the set value, maintaining stable filament extrusion conditions. This cycle provides a robust mechanism for continuous, automated temperature control throughout the filament manufacturing process.

iii. Quality of Service (QoS)

Quality of Service (QoS) refers to the measurement of overall system performance as perceived by the user, especially in data communication between microcontrollers and cloud services such as Firebase. QoS was evaluated using three parameters: throughput, packet loss, and delay.

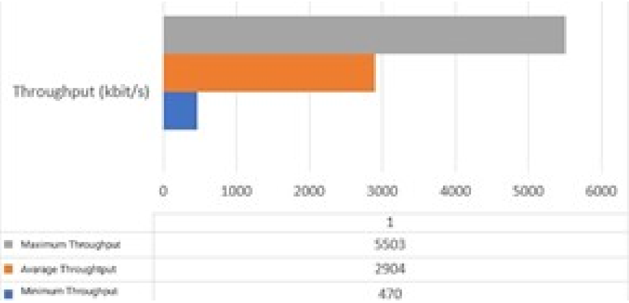


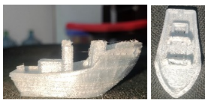
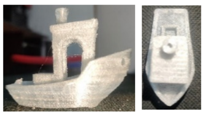
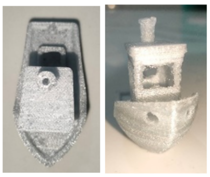
Figure 9: Throughput test results between device and Firebase.

Throughput is defined as the maximum rate at which the system can process requests [34]. It is calculated based on the number of tasks completed within a specified time frame [35]. The throughput test involved three sessions of data transmission with five samples per session (totaling 15 samples). As shown in Figure 9, the highest throughput was recorded in session 1 at 5503 Kbit/s, while the lowest was in session 3 at 470 Kbit/s. The average throughput across all sessions was 2904 Kbit/s. Higher throughput indicates better system performance in data handling and communication.

Packet loss in communication systems can occur due to network congestion, limited node memory, or buffer overflows [36]. In our testing, the communication between the device and Firebase showed no packet loss, with a consistent 100% packet delivery rate across all three sessions. This result indicates excellent reliability and data integrity during operation.

Delay refers to the latency between data transmission and reception across the network. In distributed systems, it includes transmission delay on the medium and data delivery to the task layer [37]. Delay was tested across three sessions, with five samples each (15 samples in total). The minimum delay was 379 ms (session 2), while the maximum reached 1427 ms (session 3). The average transmission delay was approximately 762.64 ms. This delay is considered acceptable for non-real-time monitoring applications, such as those used in this system.

Table 1: Bency Ship Testing

Speed	Best Temperature Result	3D Bency Test Result
1 RPM	210°C	
2 RPM	200°C	
3 RPM	210°C	
4 RPM	180°C	

iv. Temperature Testing

The process of calibrating a thermistor temperature sensor is carried out to correct inaccuracies in its readings. The Steinhart–Hart method is used to calibrate the sensor, establishing a more linear relationship between the measured temperature and the actual value recorded by a digital thermometer. This calibration improves the accuracy and reliability of thermistor readings.

After calibration, testing is conducted in five temperature sessions with ten samples each, totaling 50 data points. This evaluation ensures that the thermistor performs consistently across various conditions, supporting reliable operation during real-world filament production.

v. Filament Testing

Filament testing involves evaluating various operational parameters, such as cutting speed and heating temperature, to optimize 3D print quality. The process includes preparing plastic bottles, setting machine speeds and temperatures, and producing sample filaments for print testing.

In this experiment, filaments were printed at temperatures between 180°C and 210°C and extrusion speeds of 1–4 RPM. These ranges were selected based on preliminary observations that indicated optimal output. Figure 10 illustrates the visual difference in print resolution between PLA and recycled PET filament. PLA exhibited smoother layers and less warping, while PET suffered from noticeable shrinkage during cooling. Time required for filament production at each speed was recorded as follows:

Figure 10: 3D Benchy test using PLA filament and recycled PET for comparison.

1. RPM: 49 minutes 55 seconds
2. RPM: 23 minutes 49 seconds
3. RPM: 16 minutes 7 seconds
4. RPM: 13 minutes 24 seconds

This data helps determine optimal speed-temperature combinations for efficient production. Overall, filaments printed at 2 RPM and 200°C, and at 3 RPM and 210°C, provided the best results for both 3D Vase and 3D Benchmark models.

IV. Results and Discussion

A series of trials using recycled PET bottles demonstrated the system's capability in producing usable filament. Figure 11 shows the final output results of PET filament evaluated for diameter consistency.

Table 2: Optimal filament temperature result at each tested speed

Speed (RPM)	Temp (°C)	Resulting Diameter (mm)
1	200	1.7
2	200	1.7
3	210	1.7
4	210	1.6

Based on the 3D Vase tests, filaments extruded at 2 RPM and 200°C (with a nozzle temp of 245°C) produced optimal results. Filaments at 3 RPM and 210°C were also satisfactory. These combinations were selected for benchmark printing, confirming their performance in real-world applications.

Figure 11: Filament result from recycled PET testing at various speed/temperature settings.

Energy-wise, recycled PET filament production consumes less energy than virgin PLA. For example, 1 kg of virgin PLA emits 2.5 kg of CO_2, while 1 kg of recycled PET emits only 1.2 kg. Economically, our device uses about 114W, compared to 150W for competing devices with shredders, showing greater efficiency and environmental friendliness.

V. Conclusion

Plastics resist natural biodegradation, leading to environmental challenges. Traditional recycling methods via large centralized plants often produce low-value products. This research presents a low-cost, portable filament-making device that recycles PET bottles into 3D printable filament.

The device features a compact ergonomic design and smartphone integration, allowing real-time monitoring and control. Testing showed consistent filament diameters, around 1.7 mm for most speeds and 1.6 mm at 4 RPM. The best printing results were achieved using filament produced at 2 RPM/200°C and 3 RPM/210°C.

While PLA showed superior print quality, recycled PET offers greater environmental sustainability, producing less CO_2 and requiring less energy. Cost savings are significant—our device costs around \$112 (Rp 1.7 million), compared to a typical \$217 commercial unit. This price difference makes 3D printing more accessible, especially in underserved regions, and promotes innovation while reducing plastic waste.

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