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PULTRUSION PROCESS OPTIMIZATION IN PET BOTTLE RECYCLING-BASED PRINTER 3D FILAMENT MANUFACTURING: STRIP DIMENSION ANALYSIS AND RESULT QUALITY

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ABSTRACT Waste plastic bottles, especially Polyethylene Terephthalate (PET) bottles, can be recycled into 3D printer filaments. The pultrusion method, which uses PET strips that have been cut to a certain width, can produce filaments continuously. However, differences in the width of used bottle pieces can have an impact on process stability and the quality of the filaments produced. This study investigated how 7 mm, 8 mm, and 9 mm wide PET strips impacted the consistency of filament diameters produced by forming. It starts with cutting the bottles using high-precision knives, then extrusion through Pultrusion molding and then cooling to form filaments. Dimensional precision, surface quality, and mechanical stability of the filament are the main metrics evaluated. The results of the purification show that the pultrusion machine can produce high-quality filaments with smooth surfaces and consistent diameters at temperatures of 210°C to 220°C and rolling speeds of 1.2 to 1.68 rpm. This machine is expected to reduce the impact of waste on the environment while providing alternative raw materials for 3D printing technology with lower production costs. In addition, this research has made a significant contribution to the development of plastic recycling technology and the reduction of environmental pollution.

***Keywords**: Pultrusion machine, 3D Printing Filament, PET plastic waste, Recycling.*

INTRODUCTION

Plastic is a very common material used in daily life, especially as food and beverage containers. One of the most widely used types of plastics is PETG and *polyethylene terephthalate* (PET) (Schneevogt et al., 2021), which is often used as a material for disposable beverage bottles (Ummah, 2019). Despite having various advantages such as lightweight, strong, and easy to produce, PET plastic has properties that are difficult to decompose naturally, making it one of the main causes of environmental pollution. The amount of plastic waste is constantly increasing, with the vast majority of plastic waste not being recycled effectively, causing significant ecosystem damage. Therefore, recycling is the best option for managing plastic waste(Plazonić et al., 2024) and limit the amount of plastic waste disposed of in landfills(Shrivastava, 2018). The integration of recycled plastics in additive manufacturing has attracted attention, with research examining thermal, mechanical, and rheological properties, as well as environmental and economic implications (Ibrahim et al., 2024)(Sanchez et al., 2020).

Because excessive use of plastic has a bad impact on the environment and the nature of natural plastic is not easily decomposed, resulting in the accumulation of plastic waste and becoming the cause of environmental pollution. PET plastic bottles *Polyethylene Terephthalate*, which is often used for beverage packaging(Schyns & Shaver, 2021), can now be converted into filaments for 3D printers

(Luthfianto et al., 2023). This process involves collecting, cleaning, and melting used bottles, which are then extruded into high-quality filaments(de Voorde et al., 2021) (Sebastian & Paul, 2021).

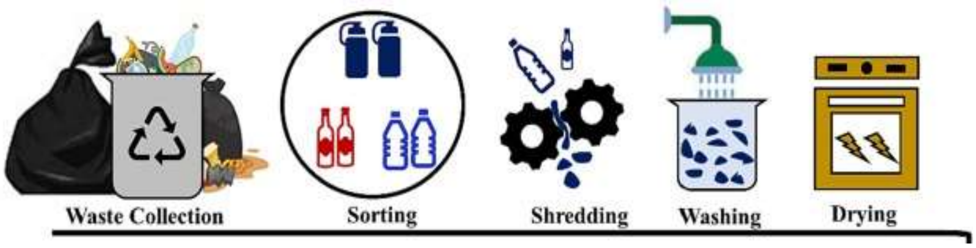

Figure 1. The process of collecting Plastic Bottle Waste for 3D Printer Filament Materials. (https://images.app.goo.gl/cRm7ciq8rYd5RyNM6)

The density of plastic materials is described as the mass per unit volume of a material, generally measured in grams per cubic centimeter (g/cm³) or kilograms per cubic meter (kg/m³). The density of PET plastic is 1.38 g/cm³ (1380 kg/cm3) and 1370 to 1455 kg/m3(Sagar Habib, n.d.).

Because the raw materials for the filament are quite expensive, the solution used is to make a 3D printer filament by recycling plastic bottle waste at the same time to reduce the impact of plastic waste and for the manufacture of the filament, a machine is needed *pultrusion*(Plastik & Pet, 2023)(Hamni & Septira, 2024). Pultruss machine, also referred to as the machine *pultrusion*, can be used to convert used plastic bottles into printer 3D filaments which can then be shaped according to the user's wishes. Combining the words "*pull"* (pull) and *"extrusion"* (extrusion), tensile refers to the withdrawal of plastic from used bottles that have been cut into tape, while extrusion refers to the extrusion process where plastic tape material is molded into filaments with round dimensions through a heating block *nozzle* 3D printing (Batam et al., 2019), which is produced through the FFF deposition process under compressive pressure for sustainable design(Mercado-Colmenero et al., 2023).

Pultrusion is a manufacturing process used to produce long, uniform composite profiles. This process involves drawing the material through a heated mold to form a product with high mechanical properties. In the context of plastic bottle recycling, the pultrusion method is used to convert used plastic materials into filaments with uniform shapes and sizes(Martana et al., 2021b). The working principle is where the material is processed through a series of stages, starting from material preparation, heating, shaping, cooling, to winding. For plastic bottles, the process involves shearing, melting, and extruding the material until it becomes a filament.

a. Machine cut bottle and Pultrussion   b. Cut Bottle   c. Pultrussion

Figure 2. The Process of Making 3D Printing Filament from Waste Plastic Bottles.

3D printing with easy and short equipment has created practical production equipment and made it easier to manufacture a product or object, one example is a 3D printer(Shidiq, Hidayat, et al., 2024). By using a 3D printer or called additive manufacturing(Djonyabe Habiba et al., 2024), the latest print-to-print technology allows users to print 3-dimensional objects with incredible detail. The process begins with specialized software that generates a digital image of the object, which is then sent to a 3D printer, which then converts the printed material into an actual object. In industry, 3D printing is used to speed up production times and prototype new products. It is also used in various industries, such as medical equipment, toys, and even large-scale home manufacturing. 3D printers do not use ink as a raw material because the print is not just an image on paper anymore, but uses plastic materials. There are several types of 3D printer machines, including *Fused Deposition Modeling* (FDM), *Stereolithograpy* (SLA), *Selective Laser Sintering* (SLS).

A long cylinder of a certain diameter made of a wide variety of polymers is known as a 3D filament. The standard filament diameter size is 1.75 mm which involves heating the nozzle to 190 °C (Shidiq, Sidiq, et al., 2024)(Martana et al., 2021a). There are many types of materials used in 3D printers, depending on the type of 3D printer machine to be used. The filament materials used in 3D printers are *thermoplastic* which has strong properties and is easy to form. In general, there are 4 types of filaments, namely PLA (*polylactic acid*), ABS (*acrylonitrile bsutadiene styrene*), TPE (*thermoplastic elastomers*), and PC (*polycarbonate*) (Joshi, 2012).

PET (*polyethylene terephthalate*) is a thermoplastic resin derived from the polyester group. PET is widely produced in the chemical industry and is used in synthetic fibers, beverage bottles and food containers, and in engineering resins combined with glass fibers. The filament of PET bottles is the result of recycled plastic that is formed into long materials, such as threads, and used for 3D printing.

The heater in this filament forming tool is a 3D printer heater because it has the same purpose and similar shape, allowing the plastic to be heated and produced like a filament in an efficient and consistent manner. Heat is transferred through conduction using this heater. Conduction heat transfer is a mechanism for transferring heat from a high-temperature location to a lower-temperature location through a solid object without being followed by particle transfer. The nozzle temperature parameters used are 240ºC, 250ºC and 260ºC (Batam et al., 2019).

METHOD

The procedure carried out in the study was to design a printer 3D filament pultrusion machine on plastic bottle incision variations to study how the heating temperature and the rpm of the roller affect the power generated from each plastic bottle incision. In the design stage, the researcher designed a machine with a cutting, heating, and winding system. *The nozzle* used has a diameter of 1.75mm to meet the standard specifications of 3D *printing* filaments.

At this stage, the researcher designed to find a solution to the existing problem by using modeling approaches such as flowchart systems and designing a *pultrusion* machine using Autodesk Fusion 360. In this study, there are several variables that are analyzed. The free variables used include the width of the PET bottle cut, the heating temperature, and the winding speed. The observed bound variables are the diameter, density, and quality of the resulting filament.

RESULTS AND DISCUSSION

The process begins with cutting the bottle using a high-precision knife (as shown in figure 2 part2) followed by extrusion through a pultrusion mold, as well as cooling to form the filament. The main parameters analyzed include dimensional precision, surface quality, and mechanical stability of the filament(For et al., 2014). The results show that the designed *pultrusion* machine can produce filaments with smooth surfaces and consistent diameters. The results of the study show that:

1. Heat Required to Form Filaments

Heat is the heat energy required to change the temperature of an object, in this case a filament, until it reaches a certain temperature. To calculate the amount of calories needed, the equation is used:

$$Q = M.C.\Delta T$$

So the calculation of each 7mm, 8mm, 9mm incision experiment is the same because the ΔT value is the same, namely,

- $Q = 13.3g \times 1250J/g\ K \times 462°K = 7680750\ J$
- $Q = 13.3g \times 1250J/g\ K \times 467°K = 7763875\ J$
- $Q = 13.3g \times 1250J/g\ K \times 472°K = 7847000\ J$

From the analysis through the equation above, data in the form of Q values in 3 experiments with estimated time in the following table is obtained:

$$P = \frac{Q}{t}$$

Table 1. Power against time

No	Q1(J)	Q2(J)	Q3(J)	Q(J)	t	P (Watt)
1	7680750	7763875	7847000	7763875	300	25879.6
2	7680750	7763875	7847000	7763875	400	19409.7
3	7680750	7763875	7847000	7763875	500	15527.8
4	7680750	7763875	7847000	7763875	600	12939.8
5	7680750	7763875	7847000	7763875	700	11091.3
6	7680750	7763875	7847000	7763875	800	9704.8
7	7680750	7763875	7847000	7763875	900	8626.5

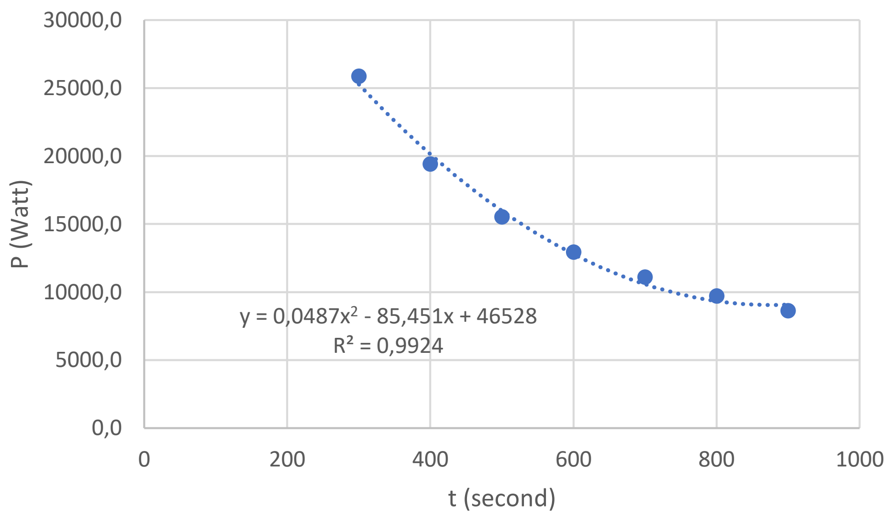

Figure 3. Power graph against time

The equation y = 0.0487x2 - 85.451x + 46528 and R^2 = 0.9924, signifies an excellent match. The minimum power of 9044.05Watt occurs in 877.3 seconds, which is calculated from the first derivative of the equation.

2. Filament Formation Data

The use of used plastic bottles as raw materials for 3D filaments is an innovative solution in recycling plastic waste. In this process, PET bottles are cut into sheets with a width of 7 mm, 8 mm, and 9 mm before being further processed using a pultrusion machine. The analysis of the results of these pieces is important to determine the quality and suitability of the pieces as a filament material.

Plastic bottle pieces with a width of 7 mm, 8 mm, and 9 mm will affect the Pultrusion process because the size of the strip will determine:

- The volume of material that goes into the Pultrusion mold.
- The consistency of the diameter of the resulting filament.
- Pulling and cooling efficiency during the production process

Figure 4. Bottle strips that have been cut at a thickness of 7, 8 and 9 mm.

From several experiments, research will be carried out with a predetermined rolling speed, namely rpm 1.20, 1.44, 1.68 and the temperature for melting is 210°C, 215°C, 220°C from each incision width of 7mm, 8mm, 9mm as follows.

Table 2. Data of PET bottle cut width 7mm

NO	Roller Rotation Speed (rpm)	Temperature Difference (°C) $\Delta T = T_2 - T_1$			Filament Length (cm)	Filament weight (kg)	Time (minutes)	Diameter filamen (mm)
		T_2 (°C)	T_1 (°C)	ΔT (°C)				
1.	1.20	210	21	189	317	0.008	14:08	1.75
2.	1.44	215	21	194	451	0.011	19:39	1.75
3.	1.68	220	21	199	428	0.012	16:20	1.75

Figure 5. Filament results at an incision width of 7 mm

Pieces with this width tend to produce filaments with small diameters. Although cooling is faster, there is a risk that the filament will become brittle and break easily if the withdrawal process is unstable. Pieces with a width of 7 mm tend to be easier to shape and produce a smoother surface compared to wider cuts.

Table 3. Data of PET bottle width cut 8mm

NO	Roller Rotation Speed (rpm)	Temperature Difference (°C) $\Delta T = T_2 - T_1$			Filament Length (cm)	Filament weight (kg)	Time (minutes)	Diameter filamen (mm)
		T_2 (°C)	T_1 (°C)	ΔT (°C)				
1.	1.20	210	21	189	329	0.008	16:00	1.75
2.	1.44	215	21	194	407	0.010	17:55	1.75
3.	1.68	220	21	199	338	0.007	15:36	1.75

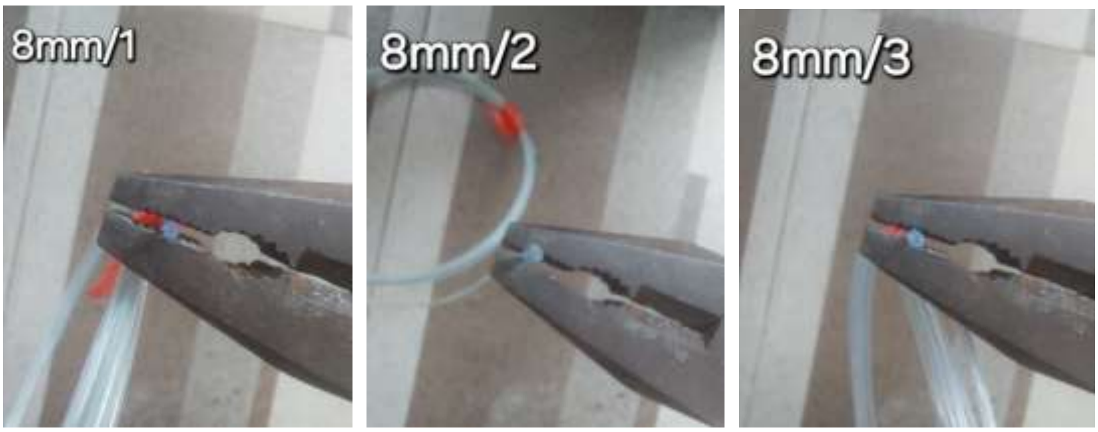

Figure 6. Filament results at an incision width of 8 mm

Demonstrates optimal results with a balance between filament strength and flexibility. The resulting filament diameter is more consistent, in accordance with the standards required for 3D printing.

Table 4. Data of PET bottle 9mm cut width

NO	**Roller Rotation Speed (rpm)**	**Temperature Difference (°C) $\Delta T = T_2 - T_1$**			**Filament Length (cm)**	**Filament weight (kg)**	**Time (minutes)**	**Diameter filamen (mm)**
		T_2 (°C)	T_1 (°C)	ΔT (°C)				
1.	1.20	210	21	189	320	0.006	13:41	1.75
2.	1.44	215	21	194	300	0.005	12:20	1.75
3.	1.68	220	21	199	285	0.005	9:40	1.75

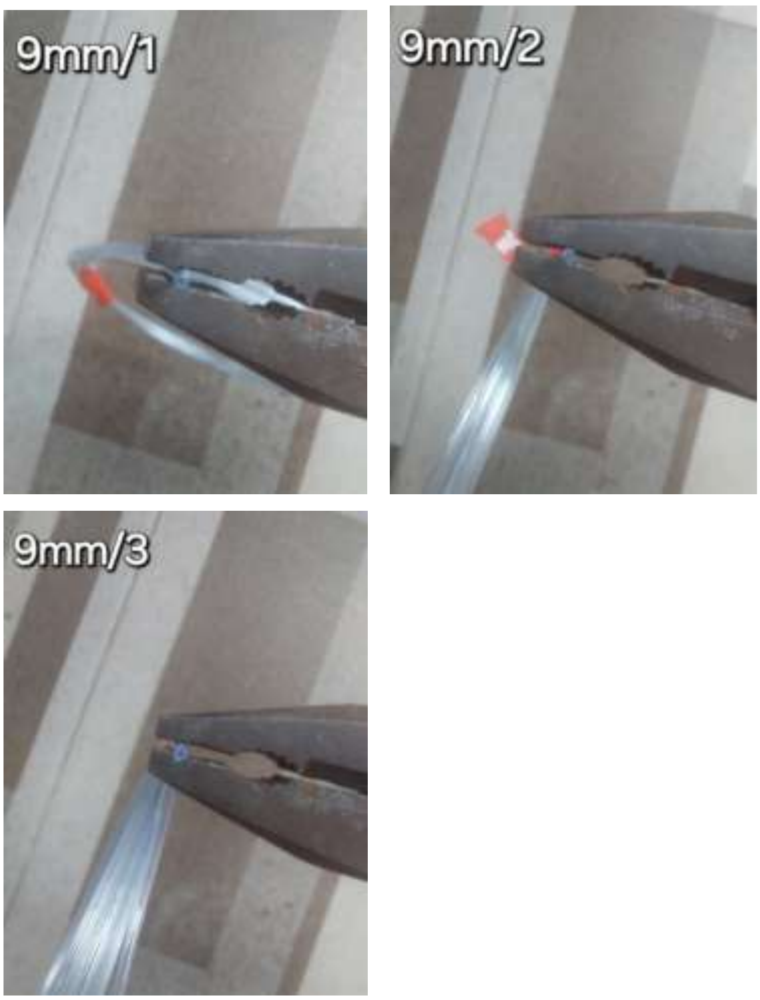

Figure 7. Filament results at 9 mm incision width

This wider cut results in a filament with a stable diameter, although there is a small cavity in the center that may require heating temperature adjustment to prevent clumping occur. In addition, slower cooling can lead to irregularities in the filament surface.

Inconsistent width of the bottle cut can cause variations in the diameter of the resulting filament. This shows that pieces with smaller widths tend to produce better filaments because they melt more evenly.

3. Filament volume and density

$$V = \pi(\frac{d}{2})^2 \times s$$

$$\rho = \frac{m}{V}$$

- 7mm wide PET plastic bottle filament volume

$$V = \pi(\frac{d}{2})^2 \times s$$

$$V = 3.14 \times (\frac{0.00175}{2})^2 \times 3.98$$

$$V = 0.0000095682\ m^3$$

$$\rho = \frac{m}{V}$$

$$\rho = \frac{0.011}{0.0000095682}$$

$$\rho = 1149.64\ kg/m^3$$

- 8mm wide PET plastic bottle filament volume

$$V = \pi(\frac{d}{2})^2 \times s$$

$$V = 3.14 \times (\frac{0.00175}{2})^2 \times 3.58$$

$$V = 0.0000086065\ m^3$$

$$\rho = \frac{m}{V}$$

$$\rho = \frac{0.008}{0.0000086065}$$

$$\rho = 929.53\ kg/m^3$$

- 9mm wide PET plastic bottle filament volume

$$V = \pi(\frac{d}{2})^2 \times s$$

$$V = 3.14 \times (\frac{0.00175}{2})^2 \times 3.01$$

$$V = 0.0000072362\ m^3$$

$$\rho = \frac{m}{V}$$

$$\rho = \frac{0.005}{0.0000072362}$$

$$\rho = 690.97\ kg/m^3$$

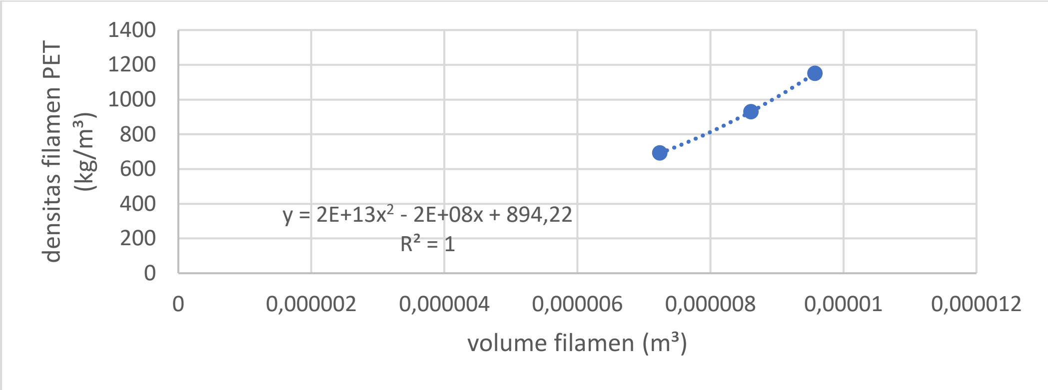

Figure 8. Volume to density graph

From the results that have been obtained from several experiments that have been carried out using this filament-making pultrusion machine, a graph of the results will be made.

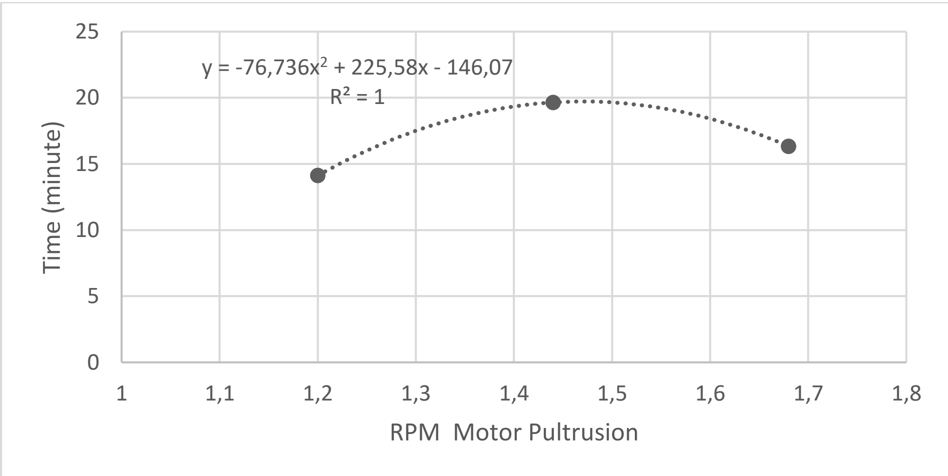

Figure 9. Rpm graph affects time at 7mm incision

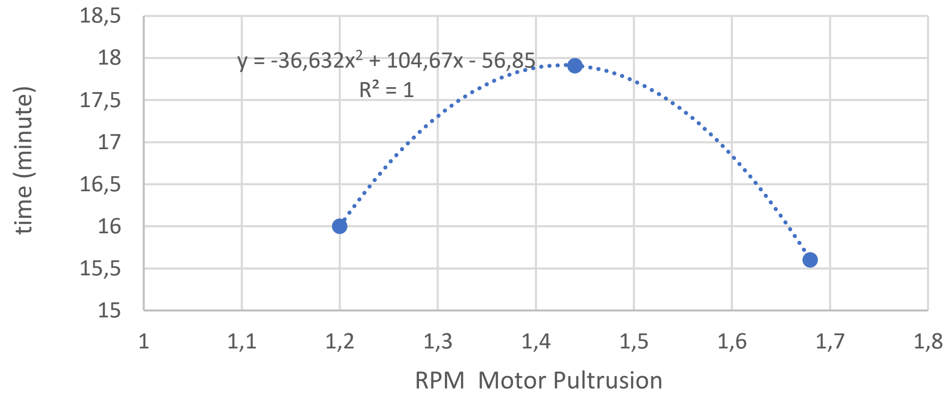

Figure 10. Rpm graph affects time on 8mm incision

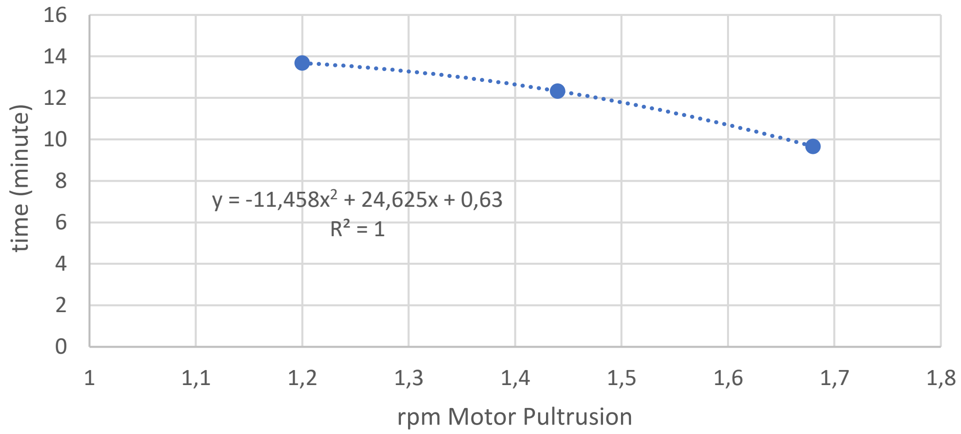

Figure 11. rpm graph affects time at 9mm incision

The results of the experiment showed that PET strips with a width of 8 mm produced filaments with a more stable diameter, had a tolerance of ±0.05 mm against the standard size of 1.75 mm, and showed a balance between strength and flexibility. 7 mm strips produce thinner filaments and are at risk of breaking during 3D printing, while 9 mm strips tend to suffer from irregularities in cooling, leading to imperfections in the diameter of the filament.

The symmetrical and consistent cut in width helps maintain a stable flow of material through the extruder nozzle. Unevenness of the cut may result in fluctuations in the output diameter

Table 5. Potential Impact of Strip Width on Filaments

Strip Width	Potential Impact on Filaments
7 mm	Filaments tend to be thinner, cooling faster, but the risk of breaking is higher if the pull is unstable.

8 mm	Optimal width to maintain a balance between filament strength and flexibility.
9 mm	The filament is thicker, but there is a hole in the middle because of air bubbles in the filament. This may require adjusting the heating temperature so that it does not clump.

CONCLUSION

Based on the results of research that has been carried out regarding the design of a pultrusion machine to produce 3D printing filaments from PET plastic bottles, the following can be concluded:

1. The designed pultrusion machine is able to process PET plastic bottle waste into 3D printing filament with filament results that have a consistent diameter and smooth surface. The machine integrates an efficient cutting, heating and winding system.
2. The designed machine successfully converts PET plastic bottles into 3D filaments with power optimization for the time obtained P = $9044.05\ Watt$ in time t = 877.3 seconds = 0.24 hours. At the 8mm rpm incision observed from the tool obtained a time value t = 1.53 minutes = 91.8 seconds.
3. The temperature equation to rpm from the design of this tool is in the form of a linear equation, from the results of this study obtained with a temperature speed to rpm of 20.8°C/rpm.
4. for the formation of filaments with a diameter of 1.75mm was found at 215 °C with a roll speed of 1.44 rpm, the length obtained was 4.07m with a time of 17:55 minutes. The results of the analysis showed that the size of the incision width affected the length of the resulting filament, with the best results at a width of 8 mm.
5. The use of PET plastic bottle waste as an alternative raw material in the manufacture of 3D printing filaments has been proven to reduce the amount of plastic waste that pollutes the environment. This process also provides added value by producing value-added products, thereby supporting efforts to manage plastic waste in a sustainable manner.

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