Semesta Teknika
Vol. 27, No. 2, 148-158, November 2024
DOI: https://doi.org/10.18196/st.v27i2.21072

Recycled PET Plastics Filament: Characteristic and Cost Opportunity

Ikbal Rizki Putra[1], Muhammad Luqman Bukhori[2], Angger Bagus Prasetiyo[3], Fadzkurisma Robbika[4], Brian Teo Putra[5]

[1]Department of Mechanical Engineering, Sekolah Tinggi Teknologi Kedirgantaraan, Bantul, 551187, Indonesia

[2]Department of Electrical Engineering, Sekolah Tinggi Teknologi Kedirgantaraan, Bantul, 551187, Indonesia

[3]Department of Mechanical Engineering, Institut Teknologi Nasional Yogyakarta, Sleman, 55281

[4]Department of Leather Processing Technology, Politeknik ATK, Bantul, 551187

[5]Department of Aerospace Engineering, Sekolah Tinggi Teknologi Kedirgantaraan, Bantul, 551187, Indonesia

[*] Corresponding author email: ikbal.rizki@sttkd.ac.id

Keywords:
PET Waste; TPST Piyungan; 3D Printer; Filament.

Abstract
Piyungan Integrated Waste Disposal Site (TPST) is a waste disposal site in Yogyakarta province. With an estimated increase in the amount of waste of 8% per year, it is estimated that the TPST will not be able to accommodate waste from the community. One of these wastes is PET bottle. This research aims to develop a new recycling method by converting PET plastic waste into 3D Printer machine filament and investigate the opportunity of this PET filament. This research uses several stage methods: PET filament making, Tensile test, macroscopy photography and opportunity analysis. This study concludes that PET bottle waste can be used as 3D printer filament with a diameter of 1.7 mm. Processing PET bottle waste into 3D printer machine filament can increase the economic value of PET bottle waste. And this can contribute to the potential for processing plastic bottle waste.

INTRODUCTION

The volume of waste in D.I.Yogyakarta province reaches 470 tons per day, with the distribution consisting of 77% organic city waste and 23% inorganic city waste (Sudibyo et al., 2017). Piyungan Integrated Waste Disposal Site (TPST) is a waste disposal site in Yogyakarta province. At TPST, inorganic waste will be recycled and organic waste will be turned into compost. However, with an estimated increase in the amount of waste of 8% per year, it is estimated that the Piyungan TPST will not be able to accommodate waste from the community (Sudibyo et al., 2017). Ideally, the amount of waste entering the Piyungan TPST can be minimized at the source in various ways (Colón et al., 2010; Sarkar et al., 2016). Currently the Piyungan TPST is closed because it has exceeded capacity. TPST closures occurred at the Sarimukti TPST in Bandung and the Rawa Cat TPST in Tangerang due to fire. The closure of TPST resulted in the accumulation of waste in various temporary storage areas because the waste was not processed. Portrait of the TPST conditions is shown in Figure 1.

To overcome the waste problem in the Yogyakarta area, the Yogyakarta City Government issued Regional Regulation (Perda) Number 1 of 2022 concerning Waste Management (Sumadi, 2022). The government urges the public, private sector and/or business entities to manage waste independently in this regulation. This activity can reduce buildup in TPST or Landfill and develop filaments that are sustainable and environmentally friendly (Tadi et al., 2024).

Figure 1. *TPST conditions (a). TPST Piyungan, (b). TPST Sarimukti, (c). TPST Rawa Kucing*

The way to reduce waste generally known by the public is 3R. The 3Rs are Reduce (reducing use), Reuse (reuse), and Recycle (recycle). One of the potentials for recycling plastic waste is to convert plastic waste into Filament for 3D Printer machines. A 3D printer machine is a machine used to convert 3D designs into original objects (Wicaksono et al., 2021). Materials generally used in 3D printing machines are plastic (PLA, ABS and TPU), PP plastic (Pamasaria et al., 2020), resin, ceramic, metal (Amiruddin et al., 2015), bamboo(Khan et al., 2023), olive wood (Fico et al., 2022), crab shell (Palaniyappan & Sivakumar, 2023), Nut (Lohar et al., 2023), coconut (Umerah et al., 2020), feather(Mi et al., 2020) and a mixture sago and polymers (Putra & Tontowi, 2019; Rosid et al., 2019; Tontowi et al., 2017). Application of the 3D Printing method in the field of education is the manufacture of teaching aids for education and medical field (Dyaksa et al., 2021; Szulżyk-Cieplak et al., 2014). The 3D Printer method has also been used in the health sector (Bozkurt & Karayel, 2021), one of which is in making heart rings and implants.

This research potential, apart from supporting the Yogyakarta City Regional Regulation, also supports the 2017-2045 National Research Master Plan program regarding advanced materials in the Material Characterization and Industrial Support Technology sub-section(Kementerian Riset Teknologi dan Pendidikan Tinggi, 2017). This research aims to develop a new recycling method by converting PET plastic waste into 3D Printer machine filament, investigate the mechanical properties of PET plastic waste and analyze this PET filament development from an economic viewpoint.

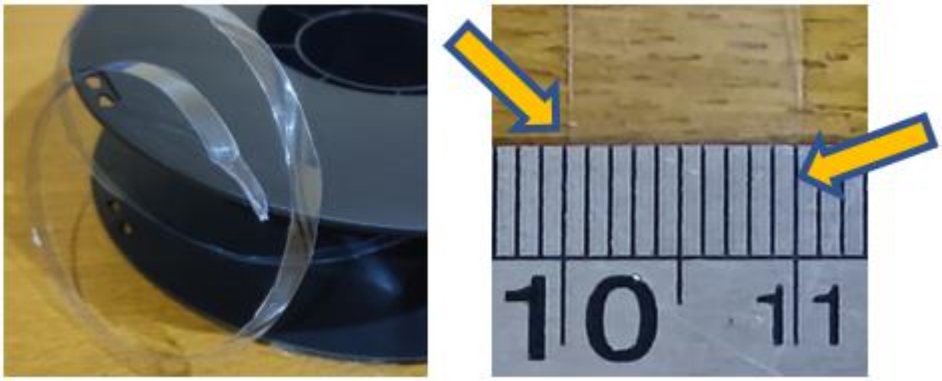
RESEARCH METHODS

Plastic is categorized into 2 types, namely thermoplastic and thermoset. This research uses PET plastic which is included in the thermoplastic category. Polyethylene terephthalate (PET) is the most common and the cheapest plastic(Bardoquillo et al., 2023; Brivio et al., 2024; Pintos et al., 2023). This plastic waste was chosen because it is easy to obtain. Plastic waste sources come from household, environmental, and industrial waste. Table 1. shows the mechanical properties of the PET plastic(Farah et al., 2016; Nisticò, 2020).

Table 1. *Mechanical Properties of PET Plastic*

Mechanical Propertis of PET Plastic		
No	**Mechanical Properties**	**Values**
1	Modulus Young's (E)	2800-3100 MPa
2	Tensile Strength	55-75 MPa
3	Elastic Limitation	2-5%
4	Melting Temperature	255 °C

The first step is to cut plastic bottle waste into sheets 10 mm wide. The purpose of cutting plastic into sheets is to simplify the process of extruding sheets into filaments. The cutting results can be seen in Figure 2. Plastic strip are cut with a specially designed plastic cutting tool. This cutting tool is shown in Figure 3. This tool is used to maintain consistent strip size. This consistency supports easy feeding of the extrusion nozzle.



(a) (b)

Figure 2. *(a) Cutting Strip Result and (b) strip with 10 mm width*

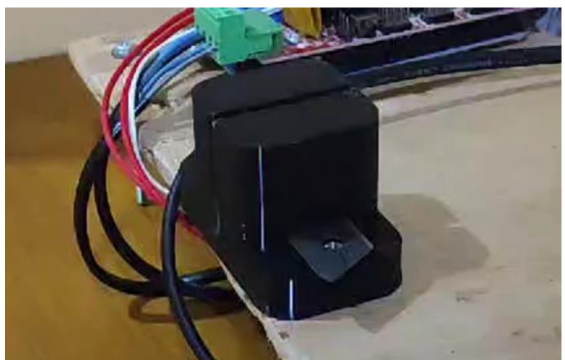


Figure 3. *Cutting Device*

The next stage is to pull the plastic strip through a heater to form a filament with a diameter of 1.7 mm. This pulling process is carried out at a temperature of 220-235 °C. An automatic spool assists the pulling process with a speed of 12 rpm. Constant temperature and spool speed settings aim to produce a filament that has a homogeneous size and reduce bubbles in the drawn filament. Figure 4 shows the drawing process and Figure 5 shows the design of the cutting tool and heating tool.

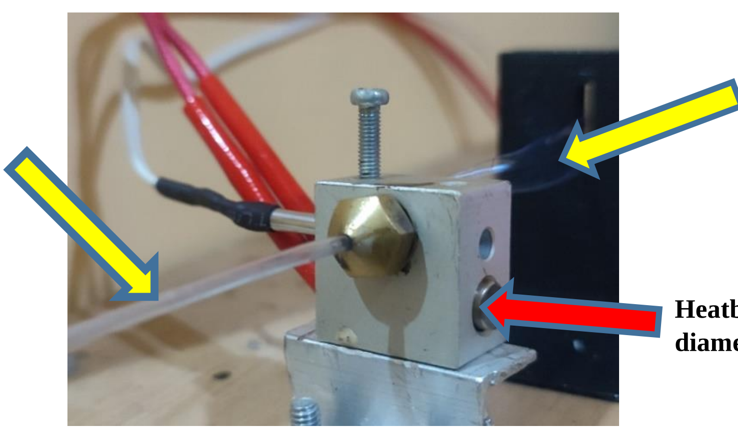


Figure 4. *Filament Pulling Process*

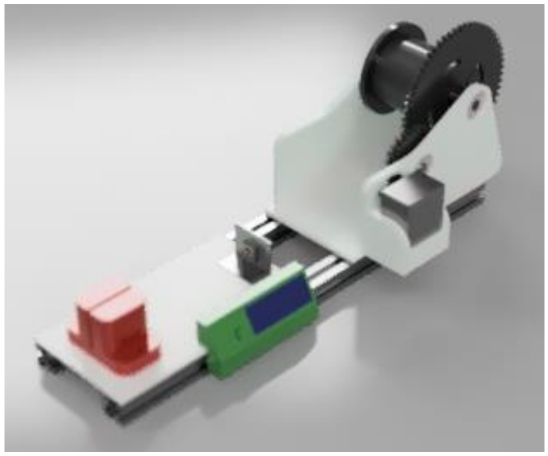


Figure 5. *Design of Filament Cutter and Spool*

This research used tensile testing to determine the tensile strength of plastic bottle waste filaments. The standard used in this test is ASTM D-3379. For specimen sizes, see Figure 6. This test uses Universal Testing Maching (UTM) with a 1-50 kN size range. For this test method, the specimen gage length shall be between 20 and 30 mm, and 30 specimens will be used as a testing sample. Testing was carried out at the Akademik Teknologi Kulit Yogyakarta. The testing process can be seen in Figure 7. This test produces load and stroke graphs, which will be used to obtain stress and strain graphs and determine the tensile strength of PET bottle waste filaments.

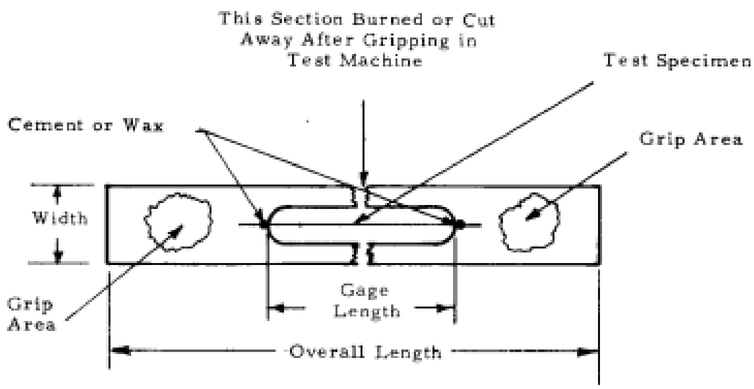


Figure 6. *Testing Speciment (ASTM D-3379)*

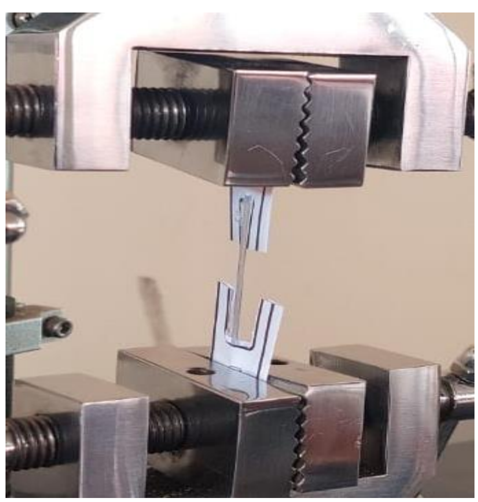


Figure 7. *Testing Process*

Apart from tensile testing, other tests carried out are macroscopic photos and cost analysis. Macro photos were taken to determine the shape of the pulled filament and void location at the pulled filament. Macro photos were taken at the UGM engineering materials laboratory. The macro photo process can be seen in Figure 8. Next, a cost analysis was carried out to investigate the chance of PET bottle waste being used as an alternative material for 3D printer machines.

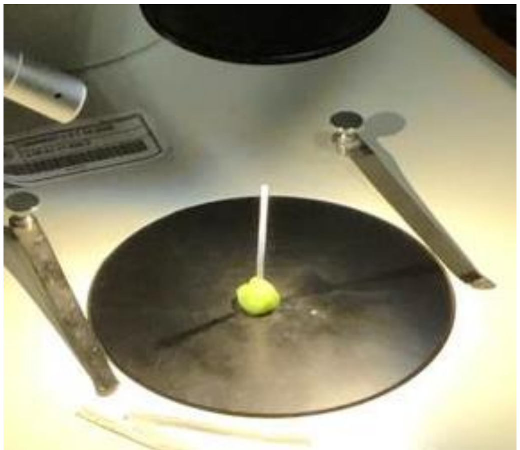


Figure 8. *Macroscopic Photography*

RESULTS AND DISCUSSION

The produced 3D-printed Recycled PET specimens were tested on a Universal Testing Machine which applied external force, and breaking points were observed for analysis purposes. Testing results were divided into 3 charts of 30 samples. Each chart consists of 10 samples to ensure detailed analysis comparison between samples. Figure 9 to Figure 12 shows the behaviour of PET waste filament after tensile testing. It was found that the maximum load that this filament could withstand was 30.2 N in Sample 21 and the lowest load it could withstand was 13.64 N in Sample 6 and Sample 16. From these graphs, it is found that the tensile strength value of this Sample 21 filament is 13.36 MPa with a strain of 115%. This low tensile strength value is caused by the final shape of the PET waste filament, which is not perfectly round but has a gap in the middle, as shown in Figure 12. A perfectly round shape has better mechanical bonds than a perfectly round shape (Hwang, 2019). The results of taking macroscopic photos in Figure 12 show that there is no porosity and void, but there is a gap in the middle of the filament, which makes the shape not perfectly round. This gap also increases the crack propagation speed, which results in low tensile strength.

The diameter of the filament was measured with a vernier calliper and with ImageJ software to ensure the results were right. The measured filament diameter is 1.7 mm in diameter. Previous research found that using a non-standard filament diameter does not cause any compatibility issues as long as the diameter remains below 1.75 mm (Nikam et al., 2023). This study found that as long as the diameter is perfectly round, Non-standard filament will work fine.

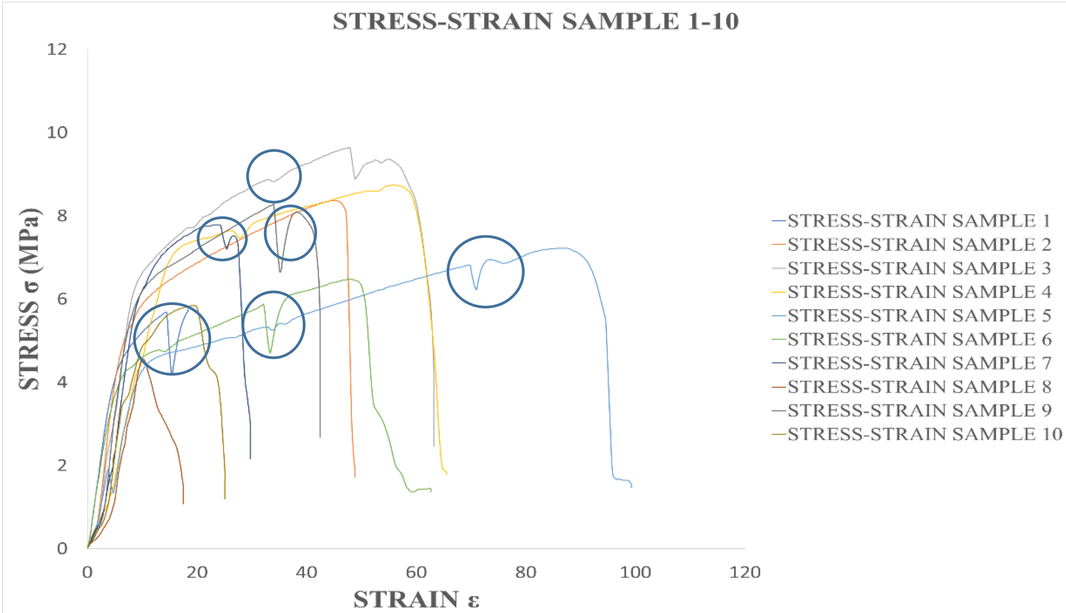


Figure 9. *Stress-Strain Graph Sample 1-10*

Figure 9 shows the behavior and stress vs strain relation of Sample 1 to Sample 10. Meanwhile, Sample 5 has the most extended strain value, with a value of 100%, but the sample with the most significant value of stress is Sample 3, with a value of 9.65 MPa. Also, Samples 1 and 10 show the same behavior. They experience the same stress fluctuations before reaching their ultimate tensile stress. This behaviour is marked with a blue circle in Figure 9.

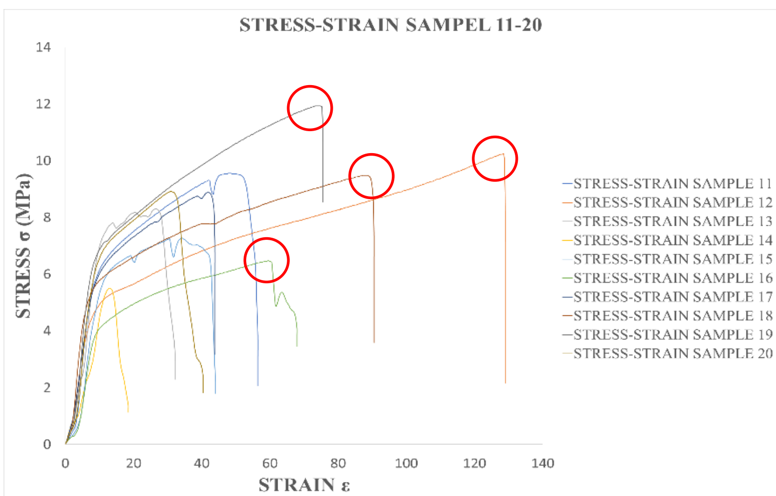


Figure 10. *Stress-Strain Graph Sample 11-20*

Figure 10 shows the behaviour and stress vs strain relation of Sample 11 to Sample 20. Meanwhile, Sample 12 has the most extended strain value, with a value of 128%, but the sample with the most significant value of stress is Sample 19, with a value of 11.93 MPa. The behavior of Sample 11 to Sample 20 is slightly different from Sampel 1 to Sample 10. Not all samples from Sample 11 to Sample 20 experience the fluctuation of stress. Samples 12, 16, 18 and 19 did not experience this fluctuation. This difference in behaviour is marked with a red circle in Figure 10.

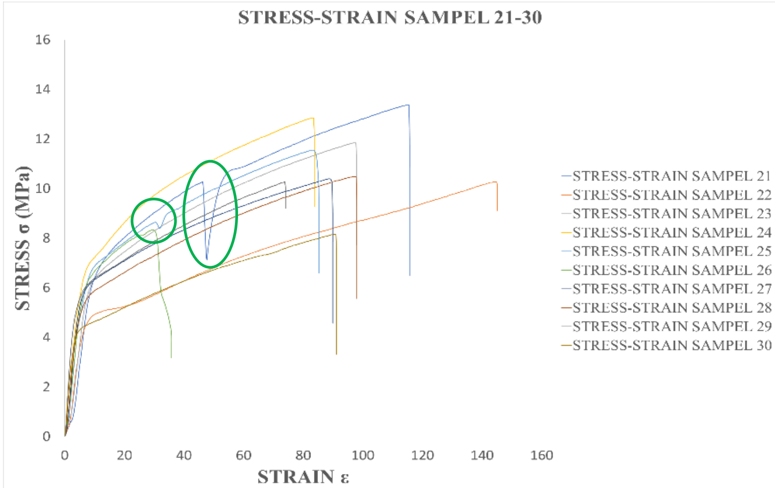


Figure 11. *Stress-Strain Graph Sample 21-30*

Figure 11 shows the behaviour and stress vs strain relation of Sample 21 to Sample 30. Meanwhile, Sample 22 has the most extended strain value, with a value of 145%, but the sample with the most significant value of stress is Sample 21, with a value of 13.36 MPa. The behaviour of Sample 21 to Sample 30 is slightly different from Sampel 1 to Sample 10 in Figure 9 and Sample 11 to Sample 20 in Figure 10. Only Sample 21 and Sample 25 experience the fluctuation of stress. This fluctuation of stress is marked with a green circle in Figure 11.

This study carried out focuses on making filaments from recycled plastic bottles. As said above, non-standard filament will work well if the diameter is perfectly round. Macroscopy photos were taken to determine the final shape of the PET waste filament and check whether there were porosity and air bubbles in the filament or not. Figure 12 shows that at 5X zoom magnification, there is a Gap in the middle of the filament, and at 11.5X zoom magnification, there is no porosity and void or air bubbles. The absence of porosity and voids or air bubbles is an indicator that the filament produced can be used.

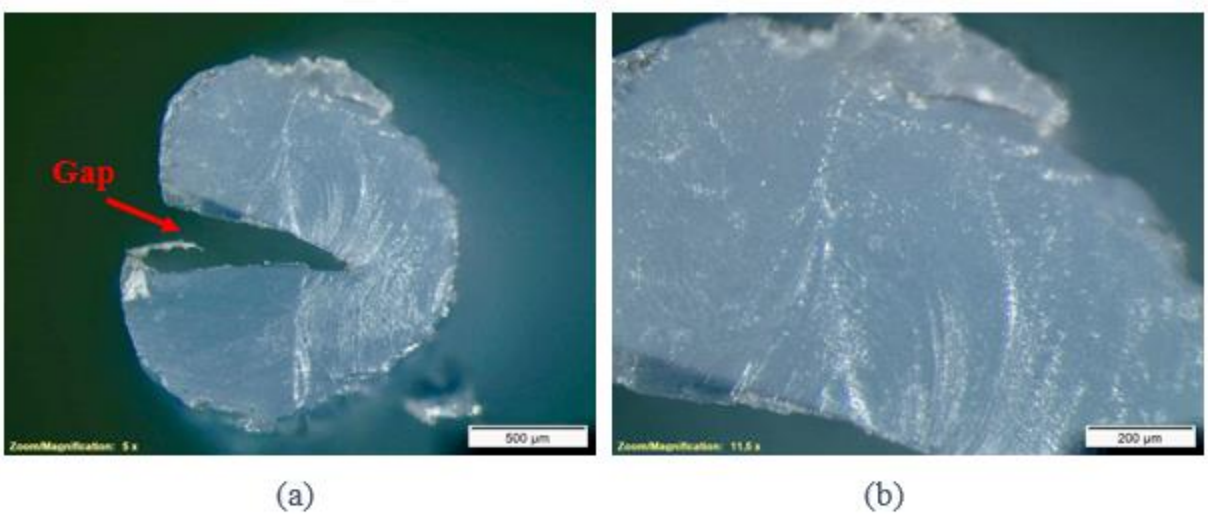


Figure 12. *Macroscopy Photo (a) 5x Magnification (b) 11,5 Magnification*

However, the presence of a gap in the middle of the filament results in low tensile strength of the filament and affect the printing capabilities of the filament. As well as, it affects the printing ability of the filament. This gap is caused by the very short tip distance of the nozzle, so that the short time lag and the cross-section of the nozzle result in the plastic strip not being completely formed into a solid filament. Figure 13 shows a cross-section of the nozzle and hotend. Shown in the red circle, the distance at the nozzle tip is so short that the plastic strip cannot solidify to form the filament. This short distance causes gaps to appear in the filament. To prevent this gap from happening, the distance of the tip of the nozzle needs to be increased. The longer the tip, the more heating time the filament will have before exiting the nozzle.

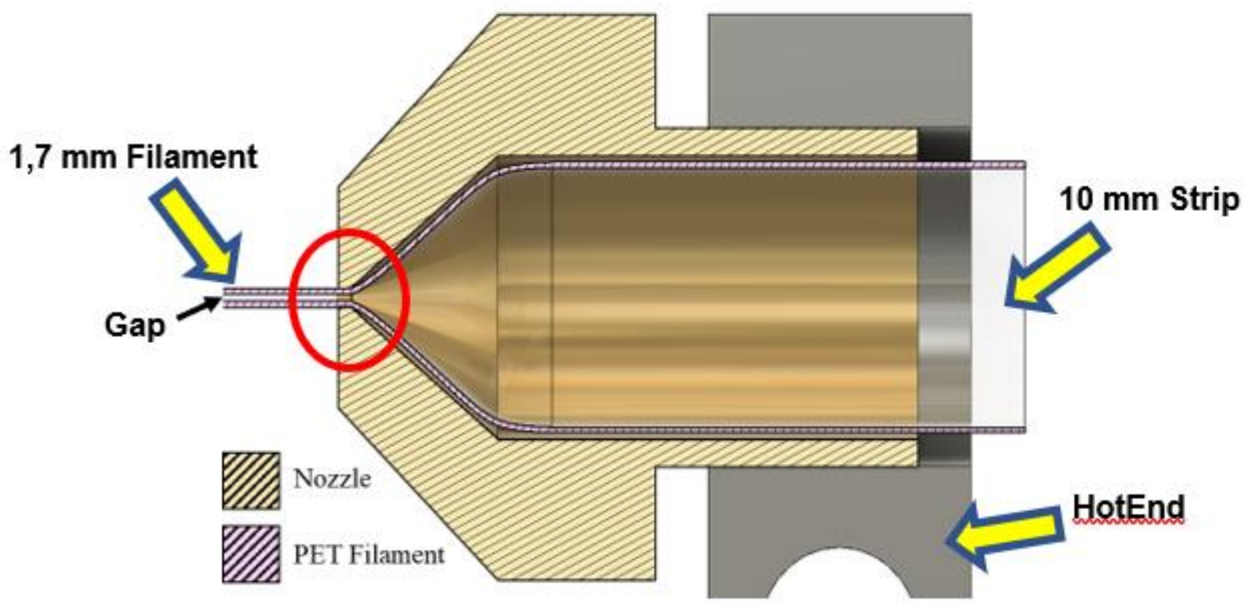


Figure 13. *Section Analysis of Hotend*

This gap also affects the printing ability of the filament. It can be seen in Figure 14 that in the preheat process with a printing temperature of 260°C the filament coming out of the nozzle is not smooth and intermittent. This will result in a printing process that is not smooth because the output from the nozzle is inconsistent. This study suggests that the cross-section of the nozzle tip should be made longer so that the plastic strip can have a lag time to solidify into a filament.

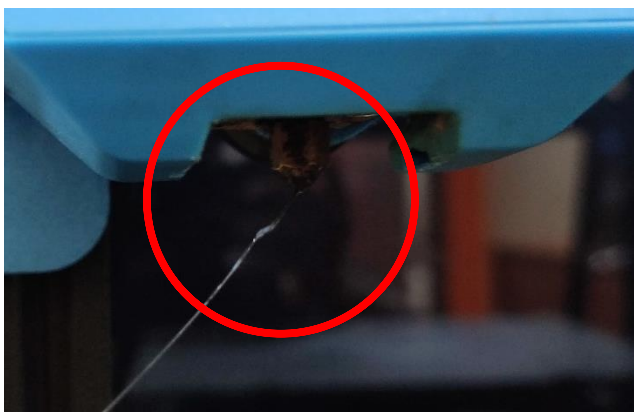


Figure 14. *Printing Capabilities of PET Waste Filament*

In terms of price, commercial filaments already on the market are priced at IDR. 230.000 to IDR. 250.000 for 1 kg of filament (Table 2). This price is certainly not cheap for some 3D printer machine users. Meanwhile, the price of plastic bottle waste at waste collectors is IDR. 3.000. The considerable price difference makes developing alternative materials from PET bottle waste very feasible.

Table 2. *Price Comparison Between Bottle Waste and Fabricated Filament*

Price Comparison	
Bottle Waste Price (Per Kg)	**Fabricated Filament Price (Per Kg)**
Rp3.000	Rp230.000 - Rp250.000

Apart from the price comparison in table 2. An analysis was also carried out regarding the amount of plastic bottle waste needed to make 1kg of filament. The weight of 1 PET bottle is 14.55 grams. 1 PET bottle produces filament weighing 9.07 grams or a weight reduction of 38%. Table 3 shows the comparison of the weight of the filament produced with the weight of 1 PET bottle. Because 1 PET bottle produces 9.07 grams of filament. So, to produce 1000 grams or 1 kg of filament requires 111 waste PET bottles.

Table 3. *Price Comparison Between Bottle Waste and Fabricated Filament*

Filament (Number of Bottle - Result Filament) Comparison		
Bottle Weight (Gram)	**Number of Bottles**	**Resulting Filament (Gram)**
14,55	1	9,07
	110,25	1000

In 1 kg of PET bottle waste, there are 69 PET bottles. Because to produce 1kg of filament requires 111 bottles. So, a minimum of 2kg of PET bottle waste is needed. If a price comparison is made, 2kg of bottle waste is priced at IDR. 6,000 and the price of commercial filament is Rp. 250,000. This difference is a development opportunity that is worth continuing.

CONCLUSION

This study concludes that PET bottle waste can be used as a 3D printer filament with a diameter of 1.7 mm. In addition, the PET bottle waste converter needs to be upgraded in the nozzle section to improve the quality of the plastic bottle waste filament, its mechanical properties, and the printing ability of the filament. These results highlight the potential to reduce plastic waste and turn it into a valuable material for 3D printing. The presence of gaps in the filament will cause faster crack propagation. This results in a lower tensile strength value.

From an economic perspective, processing PET bottle waste into 3D printer machine filament can increase the financial value of PET bottle waste. And this can contribute to the potential for processing plastic bottle waste. In addition, this activity can reduce buildup in TPST or Landfill and develop sustainable and environmentally friendly filaments.

ACKNOWLEDGEMENT

This research was funded by Grant [Penelitian Dosen Pemula] of Kemendikbudristek (Indonesia Ministry of Education) in 2023.

REFERENCES

Amiruddin, M., Harjanto, I., Setyoadi, Y., & Carsoni. (2015). Perancangan Dan Manufaktur Printer 3 Dimensi Tipe Fused DeposFition Modeling (Fdm). *Seminarnasionalhasilpenelitian(Snhp-V)*, *November*, 547–551.

Bardoquillo, E. I. M., Firman, J. M. B., Montecastro, D. B., & Basilio, A. M. (2023). Chemical recycling of waste polyethylene terephthalate (PET) bottles via recovery and polymerization of terephthalic acid (TPA) and ethylene glycol (EG). *Materials Today: Proceedings*, *xxxx*. https://doi.org/10.1016/j.matpr.2023.04.160

Bozkurt, Y., & Karayel, E. (2021). 3D printing technology; methods, biomedical applications, future opportunities and trends. *Journal of Materials Research and Technology*, *14*, 1430–1450. https://doi.org/10.1016/j.jmrt.2021.07.050

Brivio, L., Meini, S., Sponchioni, M., & Moscatelli, D. (2024). Chemical recycling of polyethylene terephthalate (PET) to monomers: Mathematical modeling of the transesterification reaction of bis(2-hydroxyethyl) terephthalate to dimethyl terephthalate. *Chemical Engineering Science*, *284*(November 2023). https://doi.org/10.1016/j.ces.2023.119466

Colón, J., Martínez-Blanco, J., Gabarrell, X., Artola, A., Sánchez, A., Rieradevall, J., & Font, X. (2010). Environmental assessment of home composting. *Resources, Conservation and Recycling*, *54*(11), 893–904. https://doi.org/10.1016/j.resconrec.2010.01.008

Dyaksa, G. A., Arfian, N. U. R., & Choridah, L. (2021). *DEVELOPMENT OF CRANIUM 3DIMENSION-PUZZLE PRODUCTS USING 3D PRINTING*. *1*, 23–30.

Farah, S., Anderson, D. G., & Langer, R. (2016). Physical and mechanical properties of PLA, and their functions in widespread applications — A comprehensive review. *Advanced Drug Delivery Reviews*, *107*, 367–392. https://doi.org/10.1016/j.addr.2016.06.012

Fico, D., Rizzo, D., De Carolis, V., Montagna, F., Palumbo, E., & Corcione, C. E. (2022). Development and characterization of sustainable PLA/Olive wood waste composites for rehabilitation applications using Fused Filament Fabrication (FFF). *Journal of Building Engineering*, *56*(May), 104673. https://doi.org/10.1016/j.jobe.2022.104673

Hwang, J. K. (2019). Effects of diameter and preparation of round shaped tensile specimen on mechanical properties. *Materials Science and Engineering: A*, *763*(May), 138119. https://doi.org/10.1016/j.msea.2019.138119

Kementerian Riset Teknologi dan Pendidikan Tinggi. (2017). *RENCANA INDUK RISET NASIONAL TAHUN 2017-2045*. *28*. https://doi.org/10.1201/9781482277098-12

Khan, A., Sapuan, S. M., Yusuf, J., Siddiqui, V. U., Zainudin, E. S., Zuhri, M. Y. M., Tuah Baharuddin, B. T. H., Ansari, M. A., & Rahman, A. A. A. (2023). An examination of cutting-edge developments in Bamboo-PLA composite research: A comprehensive review. *Renewable and Sustainable Energy Reviews*, *188*(June), 113832. https://doi.org/10.1016/j.rser.2023.113832

Lohar, D. V., Nikalje, A. M., & Damle, P. G. (2023). Synthesis and characterization of PLA hybrid composites using bio waste fillers. *Materials Today: Proceedings*, *72*, 2155–2162. https://doi.org/10.1016/j.matpr.2022.08.276

Mi, X., Li, W., Xu, H., Mu, B., Chang, Y., & Yang, Y. (2020). Transferring feather wastes to ductile keratin filaments towards a sustainable poultry industry. *Waste Management*, *115*, 65–73. https://doi.org/10.1016/j.wasman.2020.07.022

Nisticò, R. (2020). Polyethylene terephthalate (PET) in the packaging industry. *Polymer Testing*, *90*(June). https://doi.org/10.1016/j.polymertesting.2020.106707

Palaniyappan, S., & Sivakumar, N. kumar. (2023). Development of crab shell particle reinforced polylactic acid filaments for 3D printing application. *Materials Letters*, *341*(March), 134257. https://doi.org/10.1016/j.matlet.2023.134257

Pamasaria, H. A., Saputra, T. H., Hutama, A. S., & Budiyantoro, C. (2020). Optimasi Keakuratan Dimensi Produk Cetak 3D Printing berbahan Plastik PP Daur Ulang dengan Menggunakan Metode Taguchi. *JMPM (Jurnal Material Dan Proses Manufaktur)*, *4*(1), 12–19. https://doi.org/10.18196/jmpm.4148

Pintos, P. B., León, A. S. De, & Molina, I. (2023). u rn a l P re. *Additive Manufacturing*, 103908. https://doi.org/10.1016/j.addma.2023.103908

Putra, I. R., & Tontowi, A. E. (2019). Properti Mekanik Material [Sagu / PMMA] " 3D -Printable ." *Seminar Nasional Inovasi Dan Aplikasi Teknologi Di Industri*, 320–323.

Rosid, I. A., Putra, I. R., & Tontowi, A. E. (2019). Mechanical Properties Of Tensile And Bending Strength Analysis In Biocomposite [SAGOO/PMMA] Material. *Conference SENATIK STT Adisutjipto Yogyakarta*, *5*, 507–514. https://doi.org/10.28989/senatik.v5i0.371

Sarkar, S., Pal, S., & Chanda, S. (2016). Optimization of a Vegetable Waste Composting Process with a Significant Thermophilic Phase. *Procedia Environmental Sciences*, *35*, 435–440. https://doi.org/10.1016/j.proenv.2016.07.026

Sudibyo, H., Majid, A. I., Pradana, Y. S., Budhijanto, W., Deendarlianto, & Budiman, A. (2017). Technological Evaluation of Municipal Solid Waste Management System in Indonesia. *Energy Procedia*, *105*, 263–269. https://doi.org/10.1016/j.egypro.2017.03.312

Sudibyo, H., Pradana, Y. S., Budiman, A., & Budhijanto, W. (2017). Municipal Solid Waste Management in Indonesia - A Study about Selection of Proper Solid Waste Reduction Method in D.I. Yogyakarta Province. *Energy Procedia*, *143*, 494–499. https://doi.org/10.1016/j.egypro.2017.12.716

Sumadi. (2022). *Peraturan Daerah (PERDA) Nomor 1 Tahun 2022 tentang Perubahan atas Peraturan Daerah Kota Yogyakarta Nomor 10 Tahun 2012 Tentang Pengelolaan Sampah*. *2*(8.5.2017), 2003–2005.

Szulżyk-Cieplak, J., Duda, A., & Sidor, B. (2014). 3D Printers – New Possibilities in Education. *Advances in Science and Technology Research Journal*, *8*(24), 96–101. https://doi.org/10.12913/22998624/575

Tadi, S. P., Maddula, S. S., & Mamilla, R. S. (2024). Sustainability aspects of composite filament fabrication for 3D printing applications. *Renewable and Sustainable Energy Reviews*, *189*(PA), 113961. https://doi.org/10.1016/j.rser.2023.113961

Tontowi, A. E., Raharjo, K. P., Sihaloho, R. I., & Baroroh, D. K. (2017). Comparison of design method for making composite of (PMMA/HA/Sericin). *Materials Science Forum*, *901 MSF*, 85–90. https://doi.org/10.4028/www.scientific.net/MSF.901.85

Umerah, C. O., Kodali, D., Head, S., Jeelani, S., & Rangari, V. K. (2020). Synthesis of carbon from waste coconutshell and their application as filler in bioplast polymer filaments for 3D printing. *Composites Part B: Engineering*, *202*(September), 108428. https://doi.org/10.1016/j.compositesb.2020.108428

Wicaksono, R. A., Kurniawan, E., Syafrianto, M. K., Suratman, R. F., & Sofyandi, M. R. (2021). Rancang Bangun dan Simulasi 3D Printer Model Cartesian Berbasis Fused Deposition Modelling. *Jurnal Engine: Energi, Manufaktur, Dan Material*, *5*(2), 53. https://doi.org/10.30588/jeemm.v5i2.895