



## **Effect of Printing Speed on the Properties of 3D Printed Products Using Recycled PET Filament**

**Deni Fajar Fitriyana<sup>1\*</sup>, Agung Efriyo Hadi<sup>2</sup>, Nugroho Suhodo<sup>1</sup>, Aldias Bahatmaka<sup>1</sup>, Januar Parlaungan Siregar<sup>3,4</sup>, Tezara Cionita<sup>5</sup>, Zuhriyan Ash Shiddieqy Bahlawan<sup>6</sup>, Achmad Yanuar Maulana<sup>7</sup>**

<sup>1</sup>Department of Mechanical Engineering, Faculty of Engineering, Universitas Negeri Semarang, Semarang 50229, Indonesia.

<sup>2</sup>Mechanical Engineering Department, Faculty of Engineering, Malahayati University, Lampung 35153, Indonesia.

<sup>3</sup>Faculty of Mechanical and Automotive Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, 26600, Pekan, Pahang, Malaysia.

<sup>4</sup>Centre for Automotive Engineering, Universiti Malaysia Pahang Al-Sultan Abdullah, 26600 Pekan, Pahang, Malaysia.

<sup>5</sup>Faculty of Engineering, Built Environment & Information Technology, SEGi University, 47810, Selangor, Malaysia.

<sup>6</sup>Department of Chemical Engineering, Faculty of Engineering, Universitas Negeri Semarang, Semarang 50229, Indonesia.

<sup>7</sup>Department of Chemistry, Dong-A University, Busan, 49315, South Korea

\*[deniifa89@mail.unnes.ac.id](mailto:deniifa89@mail.unnes.ac.id)

**Abstract.** Recycled PET has been widely studied for its potential use in 3D printing applications. However, few research has examined how printing speed affects recycled PET filament products' mechanical and physical qualities. This research examines how printing speed influences the physical and mechanical qualities of 3D-printed PET filament goods created from mineral water bottle trash. In this study, filament fabrication is carried out using the homemade pultrusion machine, then the filament is used for 3D printing with variations in printing speed (30, 45, and 60 mm/s). The conducted tests comprise density, tensile, hardness, and compressive testing to examine their physical and mechanical properties. This research found that 45 mm/s printing produced specimens with the maximum density, tensile strength, and hardness. The material reached a density of 0.968 g/cm<sup>3</sup>, tensile strength of 15.752 N/mm<sup>2</sup>, and hardness of 43.50 Shore D under these circumstances.

In contrast, specimens printed at 30 mm/s and 45 mm/s showed the greatest (10.841 N/mm<sup>2</sup>) and lowest (6.510 N/mm<sup>2</sup>) compressive strengths. The density, hardness, and tensile strength of 3D-printed specimens improved as the printing speed increased from 30 to 45 mm/s. Printing rates above 45 mm/s reduced specimen density, hardness, and tensile strength. This work promotes sustainable manufacturing by showing that recycled PET filament may be used for 3D printing and how printing speed affects material qualities, thereby promoting sustainable production practices and reduce dependence on virgin materials.

**Keywords:** fused deposition modeling, recycled PET filament, 3D printing parameters, materials engineering, mechanical properties, sustainable product design.

*(Received 2025-05-31, Revised 2026-03-02, Accepted 2026-03-02, Available Online by 2026-05-24)*

## 1. Introduction

Polyethylene terephthalate (PET) is extensively utilized as the principal material for producing bottled drinking water containers [1]. Nonetheless, the escalating manufacturing and widespread use of PET in many applications have led to a significant rise in plastic waste, consequently increasing worldwide pollution issues [2]. The consumption of PET bottles has been reported to have reached 367 million metric tons to date, which is an approximate 2347% rise over the last thirteen years [3]. PET plastic has several advantages, including high mechanical strength, transparency, and excellent impact and tensile strength properties. In addition, PET is also better in terms of chemical resistance, clarity, processability and thermal stability [4]. However, PET waste that is not managed properly has the potential to pollute the environment because it is difficult to decompose naturally. At present, polyethylene terephthalate (PET) recycling methods are progressing rapidly and diversifying significantly. Products developed from recycled PET have been utilized in several fields, including food and beverage packaging, textiles, automotive manufacturing, electronics, medicine, construction, renewable energy, farming, and a wide array of consumer goods [5].

Numerous studies have indicated that recycled PET possesses significant promise as a filament feedstock for additive manufacturing, especially in 3D printing [6]–[8]. This versatility is substantiated by its material properties, including a comparatively high melting point, an advantageous melt flow index, a glass transition temperature, a coefficient of thermal expansion, tensile strength, and cost efficiency. In addition to its technological benefits, the utilization of recycled PET promotes ecological sustainability and circular-economy principles, rendering it an attractive choice for 3D-printing filament applications [6]–[8]. Recently, various studies have investigated the utilization of recycled PET from waste bottles to produce filaments and 3D-printed objects, owing to its excellent flowability and superior mechanical qualities, predominantly tensile and flexural modulus and strength [6]. Several 3D printing techniques, including Fused Deposition Modelling (FDM) and Fused Filament Fabrication (FFF), have been utilized to manufacture products with recycled PET filament [6]–[8]. In FDM technology, critical process variables including nozzle temperature, material flow rate, and printing speed significantly influence print quality, mechanical characteristics, and overall part performance. The interplay of these parameters affects interlayer adhesion, structural integrity, and the surface aesthetics of the manufactured components [9]. Budiono et al. [10] showed that printing speed greatly affects the dimensional durability of recycled PET bottle 3D-printed specimens. When generated at 40 mm/s, specimens had dimensions closest to a reference geometry [10]. Yousaf et al. [11] reported that recycled PET often exhibits variability stemming from differences in material sources and prior service conditions, which can negatively affect print quality and mechanical performance. Recycling operations may diminish material strength and durability while increasing moisture content, which could lead to printing-related complications.

Conversely, virgin PET typically exhibits greater consistency, hence enhancing the optimization of printing parameters. Nonetheless, recycled PET offers significant environmental advantages, rendering it a crucial area of research for advancing recycling methodologies and material compositions to optimize its efficacy. However, few research has examined how printing speed affects recycled PET filament products' mechanical and physical qualities. This research examines how printing speed affects the physical and mechanical qualities of 3D-printed items using PET filament from mineral water bottle trash. This research supports UN Sustainable Development Goal 12: Responsible Consumption and Production by promoting recycled materials and sustainable production.

## 2. Methods

### 2.1. *Materials and Specimen Fabrications*

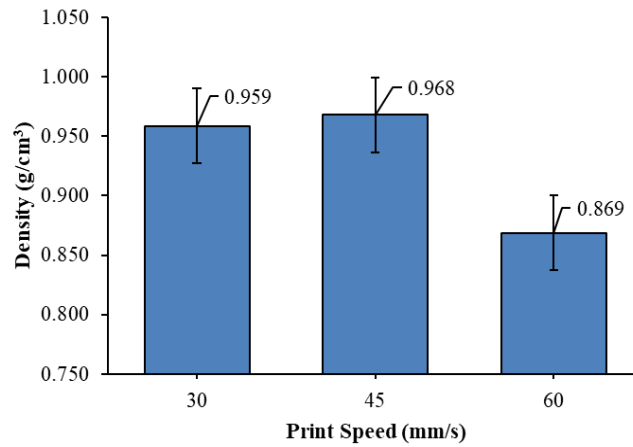
This research employed PET bottle garbage from Gunung Pati, Semarang, Indonesia. Drinking water is often packaged in PET bottles. PET has a melting temperature of 255–265°C and a glass transition temperature of 67–140°C. Tensile modulus is 2.7–4.1 GPa, whereas tensile strength is 58.6–72.4 MPa. Flexural modulus is 2.4–3.1 GPa, and flexural strength is 96.5–124.1 MPa. Its impact strength is 34.68 J/m, indicating its durability and strength [12].

The research method applied in this study refers to the approach used in the previous research by Fitriyana et al. [13]. Waste PET bottles were initially cut into 7 mm wide sheets, which were then converted into filament using a specialized pultrusion device. The resulting filament had a diameter of 1.75 mm. In this study, 3D-printed specimens were produced according to ASTM standards for each test. Autodesk Inventor was used to generate the designs, which were then exported in .stl format. Ideamaker software was then used to configure the 3D printing settings by importing these design files. The model files were saved as .gcode and uploaded to an SD card, which could be plugged into a 3D printer (Ender 3 Pro, Creality 3D, Shenzhen, China) after the parameters were configured. The printer parameters were adjusted after the filament was loaded into the extruder. The 3D printing process commenced by selecting the "Print from SD" option. The nozzle temperature was set to 225°C, while the bed temperature was maintained at 60°C. The printing speed was adjusted to 30, 45, and 60 mm/s utilizing a linear infill pattern. The initial layer height was set to 0.12 mm, and the subsequent layers to 0.10 mm, with a nozzle diameter of 0.4 mm. The flow rate was increased to 105% from the initial to the fourth layer and thereafter decreased to 100% for the fifth layer onward. Specimens were fabricated with no voids, achieving 100% filling density [13], [14].

### 2.2. *Specimen Testing*

This research will evaluate 3D-printed specimens' density, tensile strength, hardness, and compressive strength. Construction density testing measures material compactness and internal voids or porosity [13], [14]. This study used ASTM D792 density tests on 10 x 10 x 10 mm specimens. DME 220 series electronic density meters from Vibra Canada Inc. (Mississauga, ON, USA) were used for the test. Tensile testing measures material strength under tensile stresses [13]. This research used ASTM D638 tensile testing [15], [16]. The Hung Ta Instrument Co., Ltd. (Sammutprakarn, Thailand) HT-2402 Computer Servo Control Material Testing Machine was used for the tests. Hardness testing is a material testing process by measuring the hardness value of the material using a durometer [13]. The hardness testing in this study utilized an HT-6600D Shore D Durometer Hardness Tester, produced by Huatec Group Corporation (Beijing, China). The test specimens were fabricated with dimensions of 10 mm in length, 10 mm in width, and 6 mm in thickness, in compliance with ASTM D2240. Compressive testing is a mechanical test that is useful for measuring and knowing the strength of objects against compressive forces [13]. The compression testing approach in this study adhered to the ASTM D695 standard. The test specimens produced for this investigation measured 25.4 mm x 12.7 mm x 12.7 mm. The assessments were conducted utilizing the HT-2402 Computer Servo Control Material Testing Machine, produced by Hung Ta Instrument Co., Ltd. (Sammutprakarn, Thailand). Each test in this study was conducted in triplicate, and the mean value for each set of measurements was subsequently calculated.

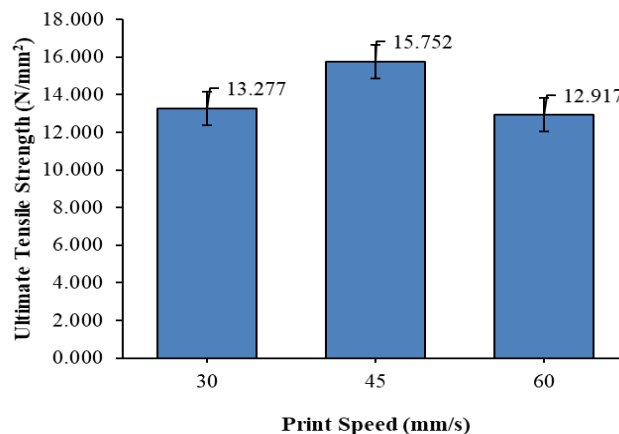
### 3. Results and Discussion



**Figure 1.** Effect of printing speed on the density of specimens

Figure 1 illustrates the correlation between printing speed and specimen density. The best density test findings in this study were achieved at a print speed of 45 mm/s, yielding a density value of 0.968 g/cm<sup>3</sup>, followed by 30 mm/s at 0.959 g/cm<sup>3</sup> and 60 mm/s at 0.869 g/cm<sup>3</sup>. The density of the specimen increased with elevated print speed. This effect is clearly demonstrated in specimens exhibiting printing speeds between 30 mm/s and 45 mm/s. However, as the print speed reaches 45 mm/s, the density of the specimens decreases. Elevated printing speeds (>45 mm/s) might exceed the extruder's ability to provide material consistently, leading to irregular filament flow. Furthermore, material extruded too rapidly lacks sufficient time to adhere to the preceding layer. These conditions could decrease interlayer bond strength and elevate porosity, leading to reduced density. This study's results reveal that the best printing speed is 45 mm/s.

Chen et al. (2022) found that layer height impacts object density together with printing speed [17]. This study matches Ismail et al. [9]. Their results suggest that 3D printer speed may affect product density. As printing speed increased from 20 to 40 mm/s, specimen density increased. The interference screw specimens' density dropped as the printing speed reached 60 mm/s. The higher printing speed may not allow the material to settle or mix effectively, resulting in holes or spaces in the printed structure and reducing density [9].



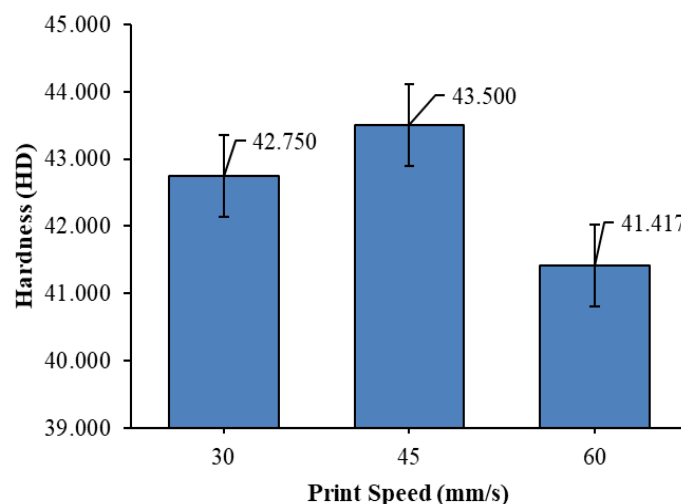
**Figure 2.** Effect of printing speed on the tensile strength of specimens

Figure 2 shows how printing speed affects 3D-printed tensile strength. The greatest tensile strength observed in this study was 15.752 N/mm<sup>2</sup> at a printing speed of 45 mm/s. The specimen printed at 30 mm/s had a tensile strength of 13.277 N/mm<sup>2</sup>, whereas the specimen produced at 60 mm/s had 12.917 N/mm<sup>2</sup>. As printing speed increased, notably from 30 to 45 mm/s, specimen tensile strength improved.

Increased printing speed improves material melting, increasing strength. Melting improves interlayer bonding by increasing material adherence to the previous layer. Stronger interlayer connections boost mechanical strength, notably tensile strength. As printing speed exceeds 45 mm/s, specimen tensile strength drops. Excessively high printing speeds can impede effective material melting, leading to a reduction in strength. At speeds exceeding 45 mm/s, the material may lack adequate time to melt and integrate with the preceding layer uniformly. Consequently, inconsistencies in layer adhesion may occur, leading to imperfections in the material's microstructure and decreasing tensile strength. Moreover, increased printing rates may cause significant heat accumulation in the nozzle, leading to reduced material viscosity and the risk of flaws like warping or delamination.

Research conducted by Kumar et al., (2020) on understanding the relationship between structure, properties, and processes in 3D printing using PETG materials with the FDM method [18]. The results showed that changes in FDM process parameters can affect the mechanical properties of 3D models printed using PETG materials. It was found that the tensile and flexural strength increased from 40 mm/s along with the printing speed until it reached a maximum and stabilized at 60 mm/s printing speed and reached a minimum limit at 80 mm/s before breaking. In addition to printing speed, several aspects impact PET specimens from mineral water bottles' Ultimate Tensile Strength [19]. Speed may also alter 3D printing density, resulting in varying tensile strengths [20]. Sahoo et al. (2023) used FDM to manufacture PLA specimens by altering layer thickness, infill percentage, and printing speed. The speed settings were 40, 50, and 60 mm/s. For maximal roughness, 60 mm/s was best [21]. Printing speed and layer thickness affect tensile characteristics [22]. The mechanical properties of printing parts are highly dependent on the molding parameters [23].

An increase in density leads to a corresponding increase in tensile strength, and vice versa. Increased density indicates reduced pores or voids within the material, facilitating more robust and cohesive connections among molecules or across layers. This improves the specimen's mechanical strength, encompassing its tensile strength. If the specimen's density is low, it contains more pores or voids within the substance. The presence of these pores can lead to microstructural abnormalities in the material, which diminishes tensile strength because specific locations become more vulnerable to damage under tensile pressures. This study's findings align with Solechan et al.'s [24] research, which shows that increased biocomposite density correlates with enhanced ultimate tensile strength. The analysis revealed that the maximum tensile strength of 30.68 MPa was recorded in specimens exhibiting the highest density of 1.39 g/cm<sup>3</sup>.

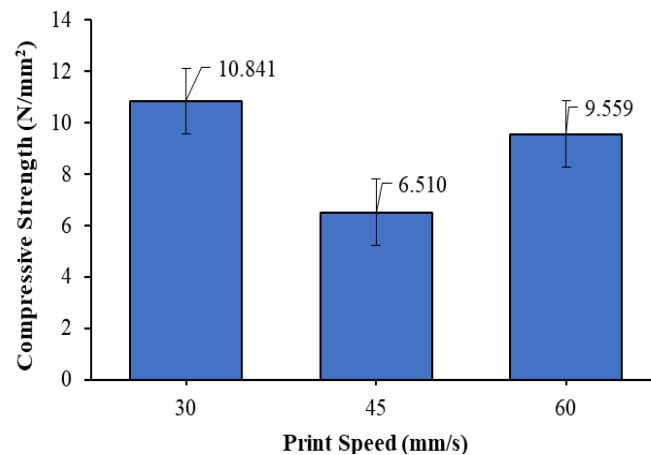


**Figure 3.** Effect of printing speed on the hardness of specimens

Figure 3 shows how printing speed affects 3D-printed specimen hardness. Best hardness was 43.50 Shore D at 45 mm/s printing speed. Hardness was 42.750 Shore D for 30 mm/s prints. In comparison, 60 mm/s samples were 41.417 Shore D hardness. With faster printing speeds, notably 30–45 mm/s, specimens were harder. The 3D-printed specimens became less hard as the printing speed exceeded 45 mm/s.

This investigation established a correlation between the hardness of the specimens and their densities, indicating that the trend in hardness matched that of density. A greater density value correlates with the increased hardness of the produced specimens and vice versa [25], [26]. The increase in density may decrease porosity, enhance particle adhesion, elevate load transmission, and render the material more resilient to deformation. Consequently, the hardness of the composite specimens improved.

Figure 4 shows how printing speed affects 3D-printed specimen compressive strength. At 30 mm/s, 45 mm/s, and 60 mm/s printing rates, compressive strengths (N/mm<sup>2</sup>) were 10.841, 6.510, and 9.559, respectively. This study demonstrates the relationship between compressive strength and specimen density, suggesting that the trend in compressive strength is inversely proportional to the trend in density (Figure 4). Increased density values are associated with a reduction in the compressive strength of the specimens generated, and vice versa. The results of this investigation align with the findings documented by Othman et al. [27]. Their findings demonstrate a rise in density, succeeded by a reduction in compressive strength, especially in FC and PFC1 specimens.



**Figure 4.** Effect of printing speed on the compressive strength of specimens

#### 4. Conclusion

This research examines how printing speed affects recycled PET filament 3D-printed objects' physical and mechanical qualities. Testing shows that printing speed significantly impacts specimen density, tensile strength, hardness, and compressive strength. When printing speed increases from 30 to 45 mm/s, density, hardness, and tensile strength improve. However, printing speeds exceeding 45 mm/s degrade these qualities. Insufficient time for solidification and interlayer adhesion may cause internal cavities in the printed structure. Thus, increasing porosity lowers density and mechanical qualities of printed components. Highest density, tensile strength, and hardness were achieved at 45 mm/s printing speed, with 0.968 g/cm<sup>3</sup> density, 15.752 N/mm<sup>2</sup> tensile strength, and 43.50 Shore D hardness. We found an inverse relationship between density and compressive strength. As density increases, specimen compressive strength decreases, and vice versa. The specimen with the maximum density and produced at 45 mm/s had the lowest compressive strength, 6.510 N/mm<sup>2</sup>. However, this study did not account for heat-induced degradation of PET during printing, which could affect the specimens' mechanical properties. Furthermore, long-term stability evaluations and empirical prototype assessments are necessary to yield comprehensive insights into the functionality of recycled PET. Additionally, examining the impact of alternative printing settings, such as layer height and infill %, could enhance the optimization of recycled PET for industrial use.

#### Declaration of AI and AI assisted technologies in the writing process

The author(s) declare that no artificial intelligence (AI) or AI-assisted technologies were used in the preparation, writing, or editing of this manuscript. All aspects of the work were conducted and written solely by the author(s).

#### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### Acknowledgements

The authors would like to thank the Faculty of Engineering, Universitas Negeri Semarang, Indonesia, for supporting this research through the Kolaborasi Antar Lembaga Research Grant in 2026 with contract number 89.4.5/UN37/PPK.05/2026.

### References

- [1] C. Lee, Y.-C. Jang, K. Choi, B. Kim, H. Song, and Y. Kwon, "Recycling, Material Flow, and Recycled Content Demands of Polyethylene Terephthalate (PET) Bottles towards a Circular Economy in Korea," *Environments*, vol. 11, no. 2, pp. 1–14, 2024. doi: <https://doi.org/10.3390/environments11020025>.
- [2] M. Zulhusni, C. A. Sari, and E. H. Rachmawanto, "Implementation of DenseNet121 Architecture for Waste Type Classification," *Adv. Sustain. Sci. Eng. Technol.*, vol. 6, no. 3, pp. 1–9, 2024.
- [3] T. Massoud and J. Dsilva, "Closing the PET plastic recycling loop: A sustainable transformation from plastic to fiber," *Next Sustain.*, vol. 6, pp. 1–9, 2025, doi: <https://doi.org/10.1016/j.nxsust.2024.100095>.
- [4] H. Kieserling *et al.*, "Towards understanding particle-protein complexes: Physicochemical, structural, and cellbiological characterization of  $\beta$ -lactoglobulin interactions with silica, polylactic acid, and polyethylene terephthalate nanoparticles," *Colloids Surfaces B Biointerfaces*, 2025, doi: <https://doi.org/10.1016/j.colsurfb.2025.114702>
- [5] S. Ahmed, D. Shan, and W. Zhou, "Advances in Recycling and Resource Recovery of Post-Consumer Polyethylene Terephthalate ( PET ) Waste for Sustainable Waste Management and Circular Economy," *ENERGY Environ. Econ.*, vol. 2025, pp. 1–18, 2025.
- [6] L. Toth, E. Slezák, K. Bocz, and F. Ronkay, "Progress in 3D printing of recycled PET," *Mater. Today Sustain.*, vol. 26, pp. 1–13, 2024, doi: <https://doi.org/10.1016/j.mtsust.2024.100757>.
- [7] A. Toghan, O. K. Alduaij, M. M. S. Sanad, and N. A. Elessawy, "Scalable Engineering of 3D Printing Filaments Derived from Recycling of Plastic Drinking Water Bottle and Glass Waste.," *Polymers (Basel)*, vol. 16, no. 22, pp. 1–11, Nov. 2024, doi: <https://doi.org/10.3390/polym16223195>
- [8] C. K. Ror, S. Negi, and V. Mishra, "Development and characterization of sustainable 3D printing filaments using post-consumer recycled PET: processing and characterization," *J. Polym. Res.*, vol. 30, no. 9, pp. 1–11, 2023, doi: <https://doi.org/10.1007/s10965-023-03742-2>.
- [9] R. Ismail, D. F. Fitriyana, F. W. Nugraha, A. P. Bayuseno, and M. I. Ammarullah, "Investigation of the influence of 3D printing parameters on the properties of interference screws made of PLA/PCL/HA biocomposite filaments," *Mater. Technol.*, vol. 40, no. 1, pp. 1–19, 2025, doi: <https://doi.org/10.1080/10667857.2024.2443598>
- [10] H. Santosa Budiono, F. Hilmy, and I. Taufik, "The Effect of Printing Speed Variations on Dimensional Stability of 3D Printing Results Made from Waste Bottle Filament," *J. E-Komtek*, vol. 7, no. 1, pp. 187–194, 2023, doi: <https://doi.org/10.37339/e-komtek.v7i1.1114>.
- [11] A. Yousaf, A. Al Rashid, R. Polat, and M. Koç, "Potential and challenges of recycled polymer plastics and natural waste materials for additive manufacturing," *Sustain. Mater. Technol.*, vol. 41, pp. 1–23, 2024, doi: <https://doi.org/10.1016/j.susmat.2024.e01103>.
- [12] A. Kumar, R. Bedi, and B. Singh, "Composite materials based on recycled polyethylene terephthalate and their properties – A comprehensive review," *Compos. Part B*, vol. 219, no. January, p. 108928, 2021, doi: <https://doi.org/10.1016/j.compositesb.2021.108928>.
- [13] D. Fajar, F. Teguh, S. Rudianzah, S. Palanisamy, and H. Noviyanto, "Investigation of the effect of nozzle temperature on the properties of 3D printed pet ( polyethylene terephthalate ) filament from plastic bottle waste," *Int. J. Adv. Manuf. Technol.*, vol. 142, pp. 4073–4085, 2026.
- [14] J. Jamari, D. F. Fitriyana, P. S. Ramadhan, S. Nugroho, R. Ismail, and A. P. Bayuseno,

- “Interference screws 3D printed with polymer-based biocomposites (HA/PLA/PCL),” *Mater. Manuf. Process.*, 2022, doi: <https://doi.org/10.1080/10426914.2022.2157428>.
- [15] E. H. Wijayanto, A. I. Imran, and J. P. Siregar, “Mechanical Properties of Epoxy Composite Reinforced with Spent Coffee Ground and Coffee Husk,” *Adv. Sustain. Sci. Eng. Technol.*, vol. 7, no. 4, pp. 1–8, 2025.
- [16] A. I. Imran, J. P. Siregar, T. Cionita, and D. Fajar, “Mechanical Performance of Epoxy Composite Reinforced with Wood Dust and Crumb Rubber Waste,” *Adv. Sustain. Sci. Eng. Technol.*, vol. 7, no. 4, pp. 0250408-01–08, 2025, doi: <https://doi.org/10.26877/kkjsz792>.
- [17] R. Chen *et al.*, “Additive manufacturing of complexly shaped SiC with high density via extrusion-based technique – Effects of slurry thixotropic behavior and 3D printing parameters,” *Ceram. Int.*, vol. 48, no. 19, pp. 28444–28454, 2022, doi: <https://doi.org/10.1016/j.ceramint.2022.06.158>.
- [18] M. A. Kumar, M. S. Khan, and S. B. Mishra, “Effect of machine parameters on strength and hardness of FDM printed carbon fiber reinforced PETG thermoplastics,” *Mater. Today Proc.*, vol. 27, pp. 975–983, 2020, doi: <https://doi.org/10.1016/j.matpr.2020.01.291>.
- [19] C. Tang, J. Liu, Y. Yang, Y. Liu, S. Jiang, and W. Hao, “Effect of process parameters on mechanical properties of 3D printed PLA lattice structures,” *Compos. Part C Open Access*, vol. 3, pp. 1–15, 2020, doi: <https://doi.org/10.1016/j.jcomc.2020.100076>.
- [20] R. Srinivasan, W. Ruban, A. Deepanraj, R. Bhuvanesh, and T. Bhuvanesh, “Effect on infill density on mechanical properties of PETG part fabricated by fused deposition modelling,” *Mater. Today Proc.*, vol. 27, pp. 1838–1842, 2020, doi: <https://doi.org/10.1016/j.matpr.2020.03.797>.
- [21] S. Sahoo, H. Sutar, P. Senapati, B. Shankar Mohanto, P. Ranjan Dhal, and S. Kumar Baral, “Experimental investigation and optimization of the FDM process using PLA,” *Mater. Today Proc.*, vol. 74, pp. 843–847, 2023, doi: <https://doi.org/10.1016/j.matpr.2022.11.208>.
- [22] A. Bist, R. Dobriyal, M. Gwalwanshi, and S. Avikal, “Influence of Layer Height and Print Speed on the Mechanical Properties of 3D-Printed ABS,” *AIP Conf. Proc.*, vol. 2481, no. April 2017, 2022, doi: <https://doi.org/10.1063/5.0107304>.
- [23] M. Ouhsti, B. El Haddadi, and S. Belhouideg, “Effect of printing parameters on the mechanical properties of parts fabricated with open-source 3D printers in PLA by fused deposition modeling,” *Mech. Mech. Eng.*, vol. 22, no. 4, pp. 895–907, 2018, doi: <https://doi.org/10.2478/mme-2018-0070>.
- [24] S. Solechan *et al.*, “Characterization of PLA/PCL/Nano-Hydroxyapatite (nHA) Biocomposites Prepared via Cold Isostatic Pressing,” *Polymers (Basel)*, vol. 15, no. 3, pp. 1–17, 2023, doi: <https://doi.org/10.3390/polym15030559>.
- [25] M. Riza and D. Efendi, “Effect of Infill Density on Mechanical Properties of 3D,” vol. 070025, 2023.
- [26] J. Manalu *et al.*, “Effect of Natural Fiber Stacking Sequence on the Properties of Hybrid Composites for Drone Frame Applications,” *Adv. Sustain. Sci. Eng. Technol.*, vol. 7, no. 4, pp. 1–11, 2025.
- [27] R. Othman *et al.*, “Relation between density and compressive strength of foamed concrete,” *Materials (Basel)*, vol. 14, no. 11, pp. 1–22, 2021, doi: <https://doi.org/10.3390/ma14112967>.