

Improving the Hardness of 3D Printable ABS Filament Through Thermal and Cooling Process Control

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Article Information	ABSTRACT
Article History Received : August 10, 2025 Revised : August 25, 2025 Published : October 02, 2025	The properties of filament are widely recognized as critical factors influencing the performance of fused filament fabrication (FFF) in 3D printing. Acrylonitrile Butadiene Styrene (ABS) is frequently utilized in this process due to its high strength, durability, and availability. Nevertheless, the characteristics of the filament are highly dependent on processing parameters, particularly extrusion temperature and cooling method, which directly affect its mechanical behavior and dimensional stability. The objective of this study was to evaluate the effect of extrusion temperature and cooling medium on the hardness of ABS filaments produced using a single-screw plastic extruder. Experimental procedures were performed at three extrusion temperatures, namely 180 °C, 200 °C, and 220 °C, with cooling applied by water immersion and by air using a blower. The results demonstrated that air cooling produced superior hardness values and more consistent dimensional stability compared to water cooling. The optimum condition was observed at an extrusion temperature of 180 °C under air cooling, which resulted in the highest hardness values along the filament length (95.63HA average). These findings suggest that careful optimization of extrusion parameters, particularly the selection of an appropriate cooling method, is essential to improve filament quality for additive manufacturing applications.
Keywords: <i>ABS filament; Extrusion temperature; Cooling method; Filament hardness</i>	

INTRODUCTION

Additive manufacturing through fused deposition modeling (FDM) has transformed the production of functional prototypes and end-use components by offering design flexibility, reduced cost, and shorter lead times. The final quality of FDM parts depends strongly on the properties and consistency of the filament feedstock. Acrylonitrile Butadiene Styrene (ABS) is a commonly used thermoplastic for FDM because of its favorable mechanical strength, impact resistance, and thermal stability (Rankouhi et al., 2016; Tian et al., 2025); its standardized filament diameters of 1.75 mm and 2.85 mm also support broad compatibility with commercial printers and reproducible printing outcomes (Pratama et al., 2025; Rijekki et al., 2024). Reviews of ABS in fused filament fabrication highlight the central role of processing–structure–property relationships in determining printed part performance and emphasize the need for tight production control of filament properties. (Divakaran et al., 2024; Peterson, 2019; R et al., 2021)

ABS filaments are typically produced by single-screw extrusion in which polymer pellets are melted, forced through a die, and cooled before winding. The extrusion temperature and the

cooling medium are two critical process variables that influence melt viscosity, extrusion rate, solidification behavior, and final filament dimensions (Abbott et al., 2018). Process studies and single-screw extrusion overviews indicate that barrel and nozzle temperatures together with screw speed determine the melt homogeneity and throughput, while cooling strategy governs heat extraction and dimensional locking of the extruded strand (Abeykoon, 2016; Ranjan et al., 2024; Shahrubudin et al., 2019).

Experimental and modeling studies have shown that extrusion conditions and post-extrusion cooling affect microstructure, residual stresses, and ultimately mechanical properties of extruded polymeric products. Finite-difference and thermal models of filament extrusion link heat transfer, polymer healing and diffusion, and stress evolution to resulting filament and interlayer bond quality, indicating that both thermal history in the hot end and the cooling path after exit are decisive for filament stability. Empirical investigations have likewise demonstrated that extrusion parameters influence filament diameter control and printed part dimensional accuracy, while forced-air cooling and other cooling regimes produce different trade-offs between geometric fidelity and mechanical strength. (Gilmer et al., 2021; Kattinger et al., 2023; Lee & Liu, 2019; Mishra et al., 2022)

Previous studies have shown that extrusion parameters, particularly temperature and screw speed, significantly influence filament diameter and surface quality, which are critical for ensuring feed consistency in FDM printing (R et al., 2021). Investigations into ABS filament production indicate that adjusting processing conditions can improve mechanical strength and reduce diameter variability (Curmi & Rochman, 2025). Cooling methods also play a crucial role which is forced-air cooling can enhance dimensional accuracy, whereas water cooling offers faster heat removal but may affect internal residual stresses (Lee & Liu, 2019).

Although prior work has addressed many individual factors, important gaps remain. Reviews and recent optimization studies point out that while overall temperature windows and cooling categories are known, the specific interaction between extrusion temperature and cooling medium and their combined effect on mechanical indicators such as hardness and dimensional stability of ABS filaments produced by single-screw extrusion are not comprehensively characterized. Additionally, studies on process capability and advanced extrusion optimization emphasize the need for integrated experiments that couple filament diameter control, thermal histories, and mechanical characterization to generate actionable manufacturing guidelines (Husain et al., 2023; Tikhani & Hubert, 2025).

Therefore, the main objective of this research is to systematically investigate the combined influence of extrusion temperature and cooling medium on the hardness and dimensional stability of ABS filaments produced by single-screw extrusion, with the aim of developing practical recommendations to enhance filament quality and ensure more consistent 3D printing outcomes.

RESEARCH METHODS

The raw material used in this study was Acrylonitrile Butadiene Styrene (ABS) pellets, a commercial thermoplastic polymer obtained from a local supplier in Indonesia. The material exhibits typical properties of ABS, including a glass transition temperature of approximately 105 °C, density of 1.04 g/cm³, melt flow index of 18–23 g/10 min, and elongation at break of 23–25% (Sabah et al., 2019).

Equipment Description

The primary equipment utilized in this study was a single-screw extruder machine, which was custom-fabricated by the researcher (figure1). The extruder consisted of a hopper, a heated barrel with multiple temperature-controlled zones, a rotating screw, and a die for shaping the molten polymer into filament strands. The machine was designed to allow precise control of barrel temperature and screw speed to ensure stable extrusion conditions. The die produced a continuous filament with a nominal diameter of 1.75 mm, which is the standard dimension for fused deposition modeling (FDM) applications.



Figure 1. Single Screw Extruder Machine

A Shore A durometer hardness tester (ASTM D2240 compliant) was employed to evaluate the surface hardness of the extruded filaments. The instrument measures resistance to indentation by applying a calibrated spring force to a standardized indenter pressed onto the specimen's surface. The hardness tester was selected for its high accuracy and repeatability, making it suitable for assessing relative mechanical performance under varying processing conditions.

Additionally, supporting tools included a water bath maintained at ambient temperature for rapid cooling and a forced air blower to provide slower cooling conditions. Both cooling systems were integrated into the extrusion line to investigate their influence on the physical and mechanical properties of the ABS filament.

Experimental Procedure

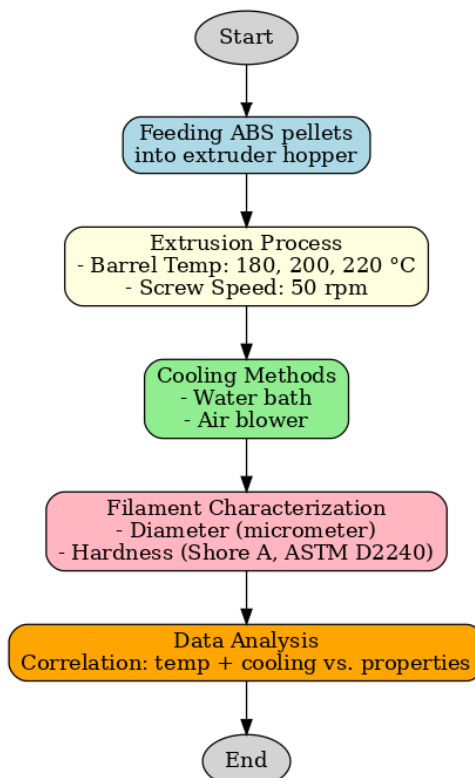


Figure 2. Flow diagram

The procedure can be seen in the process flow diagram presented in Figure 2. The experimental procedure began with the preparation stage, which included gathering all necessary equipment and materials. Acrylonitrile Butadiene Styrene (ABS) pellets were first washed thoroughly and air-dried to remove any surface impurities and contaminants, ensuring clean material input for extrusion. After this cleaning process, the pellets were fed into the hopper of the single-screw extruder.

During extrusion, the pellets were gradually melted in the heated barrel, which was divided into three temperature zones set at 180 °C, 200 °C, and 220 °C for experimental variation. The screw rotation speed was maintained at a constant 50 revolutions per minute to ensure steady material transport and mixing. The molten polymer was forced through the die to form a continuous filament strand with a target diameter of 1.75 mm.

Immediately after exiting the die, the filament was subjected to two different cooling methods. In the first method, the filament was submerged in a water bath at room temperature to achieve rapid cooling. In the second method, cooling was performed using a forced air blower to induce slower solidification. Both methods were applied to examine how cooling rate influenced dimensional stability and mechanical performance of the extruded filament.

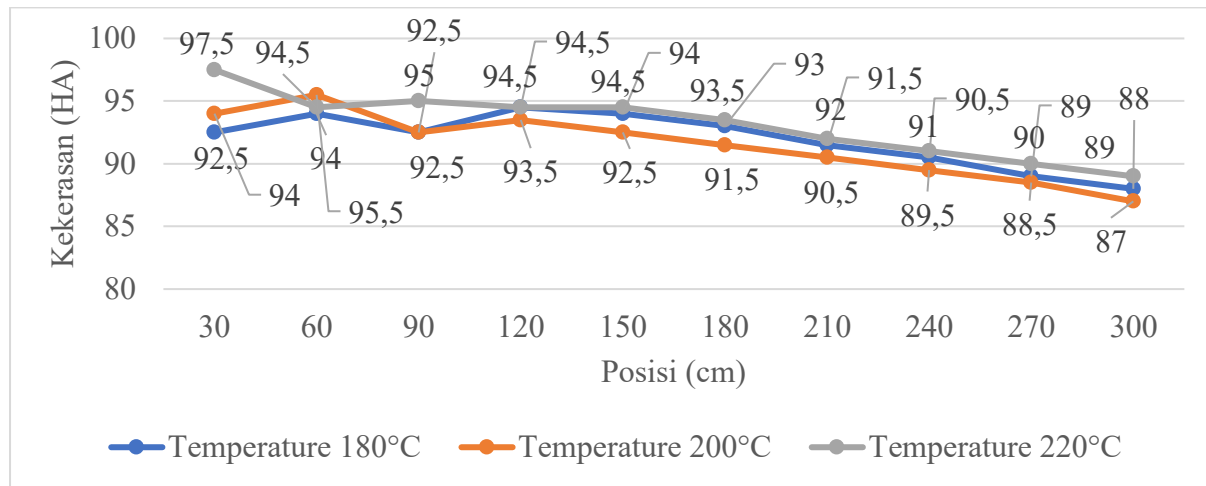
Following extrusion, filament characterization was carried out. Filament diameter was measured at ten evenly spaced points along each sample using a precision digital micrometer to assess dimensional uniformity. Surface hardness was then evaluated using a Shore A durometer, following the ASTM D2240 procedure. Three readings were taken for each sample, and the average value was recorded. These data sets were subsequently analyzed to identify correlations between extrusion temperature, cooling method, and the resulting filament properties.



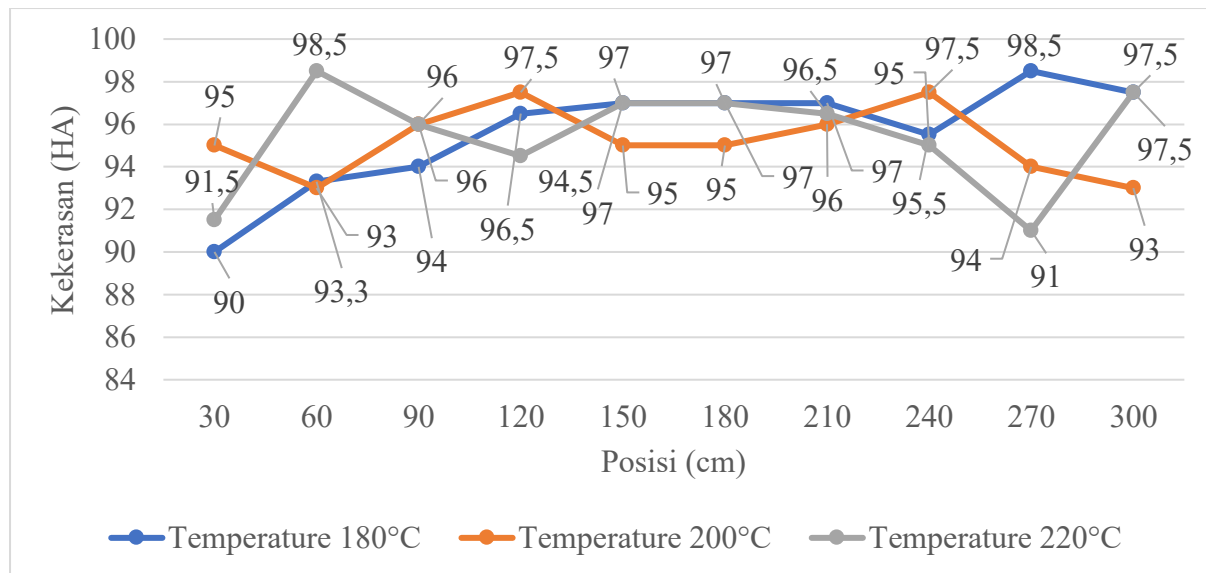
Figure 3. Filament manufacturing process

RESULTS AND DISCUSSION

Hardness Stability Along the Filament Length



(a)



(b)

Figure 4. Hardness along filament with (a) water cooling system (b) air blower cooling system

The experimental results revealed notable differences in hardness distribution along the filament length between the water cooling and air cooling methods, as shown in Figure 4. In the water cooling condition, hardness values exhibited relatively large variations with a clear decreasing trend from the initial position at 30 cm to the end of the filament at 300 cm. This indicates that water cooling induces non-uniform heat transfer rates along the filament, leading to variations in microstructural development and residual stress distribution. The high thermal gradient generated by direct contact with water promotes localized differences in polymer crystallization rates, which in turn reduces hardness in the latter sections of the filament (Sood et al., 2010).

In contrast, the air cooling method demonstrated smaller fluctuations and generally stable hardness values along the filament length, with only minor variations observed at certain points. Air convection enables gradual and more uniform heat removal, thereby minimizing microstructural heterogeneity along the material (N. Turner et al., 2014). This more consistent cooling process contributes to uniform hardness distribution and reduces the risk of deformation or dimensional defects commonly observed in thermoplastic polymers such as ABS when cooled too rapidly (Sousa et al., 2021).

Overall, these findings are consistent with previous studies reporting that slower and more controlled cooling enhances dimensional accuracy, mechanical strength, and thermal stability in ABS-based products (Rankouhi et al., 2016). Therefore, the cooling method should be considered a critical factor in filament manufacturing to ensure consistent quality along the product length.

Average Hardness

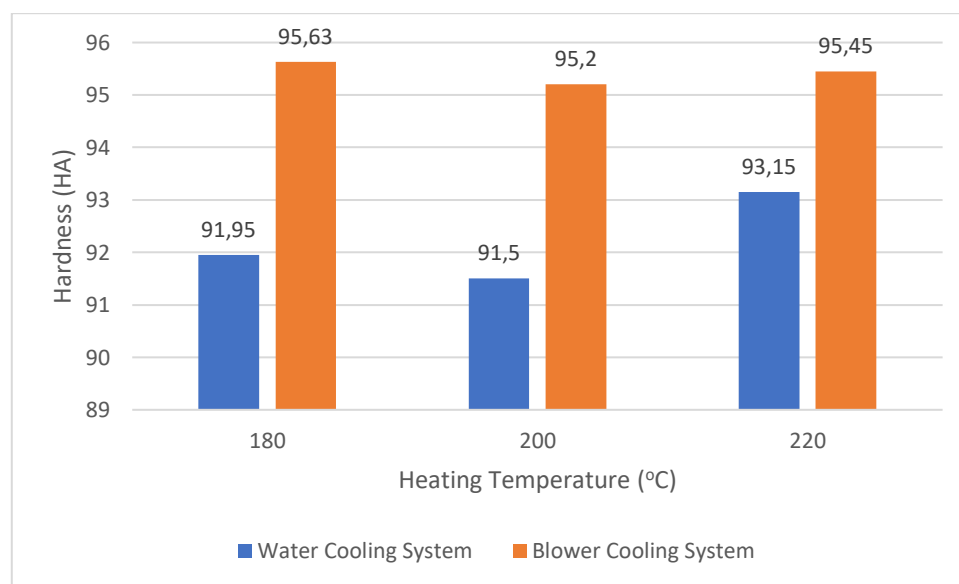


Figure 5. Average Hardness of ABS filament

The results of the hardness tests, expressed in Shore A values in Figure 5, indicate that the cooling method has a substantial influence on the mechanical performance of the produced ABS filament. For water cooling, the average hardness values obtained were 91.95 at 180 °C, 91.50 at 200 °C, and 93.15 at 220 °C. In comparison, air cooling produced higher average hardness values at all tested extrusion temperatures, namely 95.63 at 180 °C, 95.20 at 200 °C, and 95.45 at 220 °C. This consistent improvement in hardness under air cooling suggests that slower, more uniform cooling promotes a more homogeneous microstructure and reduces the formation of internal defects, such as voids or microcracks, which can weaken the polymer matrix (N. Turner et al., 2014).

The superior performance of air cooling can be attributed to its gradual heat dissipation through convective transfer, which allows more controlled polymer chain relaxation and crystallization. In contrast, the rapid quenching effect in water cooling introduces steep thermal gradients and higher residual stresses, potentially leading to slight reductions in hardness (Tymrak et al., 2014). Previous studies have reported that excessive cooling rates in thermoplastic processing can adversely affect interlayer adhesion and increase brittleness in the final product, while controlled cooling enhances both dimensional accuracy and mechanical properties (Rankouhi et al., 2016).

These findings imply that, within the tested extrusion temperature range, the choice of cooling method plays a more decisive role in determining final hardness than temperature variations alone. Therefore, optimizing the cooling strategy is critical to ensuring consistent mechanical quality in ABS filament manufacturing.

The heating conditions during extrusion play a significant role in determining the hardness of the produced ABS filaments. In this study, higher extrusion temperatures (200–220 °C) generally resulted in a slight reduction in measured surface hardness compared to lower temperatures (180 °C). This phenomenon can be attributed to the increased chain mobility at elevated processing temperatures, which may reduce packing density upon solidification. Conversely, at lower extrusion temperatures, the polymer chains experience less thermal relaxation, producing filaments with slightly higher surface hardness. This observation is consistent with general polymer processing behavior, where mechanical properties are highly sensitive to the thermal history of the material.

Tabel 1. Table Hardness from other reference

Material Type	Hardness Shore D
PLA	80
ABS	75
PTEG	72
ASA	75
My Research	87-97

(Sedlak et al., 2023)

Literature data indicate that PLA typically exhibits a Shore D hardness of approximately 80, making it the stiffest among commonly used 3D printing thermoplastics. ABS and ASA generally present lower hardness values around 75, while PETG is slightly softer at around 72, which correlates with its higher ductility and toughness. In contrast, the ABS filament produced in this research demonstrated a significantly higher hardness, ranging from 87 to 97 HA Shore D. This value exceeds the typical range reported in literature for ABS and even surpasses PLA. The increase in hardness may be attributed to differences in processing parameters, cooling conditions, and microstructural morphology formed during extrusion. The finding suggests that extrusion conditions can substantially enhance surface resistance to indentation, resulting in improved durability and potential performance advantages in 3D printing applications.

Industrial Applicability of the Findings

The results of this research, particularly the significantly higher hardness values (87–97 Shore D) achieved in ABS filaments, highlight promising implications for industrial-scale applications. In many manufacturing sectors, such as automotive, consumer electronics, and functional prototyping, materials with enhanced hardness are preferred due to their improved wear resistance and dimensional stability. The extrusion method employed in this study, though developed at a laboratory scale, replicates key stages of industrial filament production, including pellet feeding, controlled heating, extrusion, and cooling.

If scaled up, the process parameters identified, such as extrusion temperature and cooling methods, could be optimized within larger, continuous extrusion systems to achieve consistent filament quality. Furthermore, the water-cooling route demonstrated in this research, which resulted in more uniform hardness, is already widely implemented in industrial polymer processing, suggesting that the transition from laboratory to industrial scale would be technically feasible.

However, industrial implementation would require additional considerations, including process automation, quality control at high throughput rates, and long-term performance testing of the filaments in actual 3D printing environments. Despite these challenges, the superior hardness

values obtained in this study provide a strong indication that with proper scale-up, the methodology can contribute to the production of higher-performance ABS feedstock for industrial additive manufacturing applications.

CONCLUSION

The findings of this study demonstrate that the cooling method has a more significant influence on the hardness of ABS filament compared to variations in extrusion temperature within the tested range. Air cooling consistently produced higher average Shore A hardness values, with results of 95.63 HA at 180 °C, 95.20 HA at 200 °C, and 95.45 HA at 220 °C. In comparison, water cooling yielded average hardness values of 91.95 HA at 180 °C, 91.50 HA at 200 °C, and 93.15 HA at 220 °C. The superior performance of air cooling is attributed to its gradual and uniform heat dissipation, which promotes more homogeneous microstructural development and minimizes residual stresses. In contrast, the rapid quenching effect of water cooling generates steeper thermal gradients, resulting in greater variability and slightly lower hardness values.

The cooling method is the dominant factor influencing hardness, while temperature variation within the tested range did not produce statistically significant differences. These results highlight the importance of optimizing cooling strategies in filament manufacturing to achieve consistent mechanical performance.

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REFERENCES

- Abbott, A. C., Tandon, G. P., Bradford, R. L., Koerner, H., & Baur, J. W. (2018). Process-structure-property effects on ABS bond strength in fused filament fabrication. *Additive Manufacturing*, 19, 29–38. <https://doi.org/10.1016/j.addma.2017.11.002>
- Abeykoon, C. (2016). Single screw extrusion control: A comprehensive review and directions for improvements. *Control Engineering Practice*, 51, 69–80. <https://doi.org/10.1016/j.conengprac.2016.03.008>
- Curmi, A., & Rochman, A. (2025). Screw extrusion fused granulate Fabrication: Trends, materials, extruder classification and future development. *Polymer*, 330(April), 128459. <https://doi.org/10.1016/j.polymer.2025.128459>
- Divakaran, N., Y, A., Mohapatra, A., & Mohanty, S. (2024). Material extrusion-based 3D printed capacitor optimization: Enhancing performance with ZnO and Cu-CNT reinforced ABS composites. *Applied Materials Today*, 40(July), 102363. <https://doi.org/10.1016/j.apmt.2024.102363>
- Gilmer, E. L., Anderegg, D., Gardner, J. M., Sauti, G., Siochi, E. J., McKnight, S. H., Dillard, D. A., McIlroy, C., & Bortner, M. J. (2021). Temperature, diffusion, and stress modeling in filament extrusion additive manufacturing of polyetherimide: An examination of the influence of processing parameters and importance of modeling assumptions. *Additive Manufacturing*, 48(PA), 102412. <https://doi.org/10.1016/j.addma.2021.102412>
- Husain, M., Singh, R., & Pabla, B. (2023). On process capability of single screw extruder for fabricating PVDF composite matrix. *Materials Today: Proceedings*, November, 1–7. <https://doi.org/10.1016/j.matpr.2023.11.009>
- Kattinger, J., Kornely, M., Ehrler, J., Bonten, C., & Kreutzbruck, M. (2023). Analysis of melting

- and flow in the hot-end of a material extrusion 3D printer using X-ray computed tomography. *Additive Manufacturing*, 76(August), 103762. <https://doi.org/10.1016/j.addma.2023.103762>
- Lee, C. Y., & Liu, C. Y. (2019). The influence of forced-air cooling on a 3D printed PLA part manufactured by fused filament fabrication. *Additive Manufacturing*, 25(November 2018), 196–203. <https://doi.org/10.1016/j.addma.2018.11.012>
- Mishra, R., Bu Aamiri, O., Satyavolu, J., & Kate, K. (2022). Effect of process conditions on the filament diameter in single screw extrusion of natural fiber composite. *Manufacturing Letters*, 32, 15–18. <https://doi.org/10.1016/j.mfglet.2022.01.003>
- N. Turner, B., Strong, R., & A. Gold, S. (2014). A review of melt extrusion additive manufacturing processes: I. Process design and modeling. *Rapid Prototyping Journal*, 20(3), 192–204. <https://doi.org/10.1108/RPJ-01-2013-0012>
- Peterson, A. M. (2019). Review of acrylonitrile butadiene styrene in fused filament fabrication: A plastics engineering-focused perspective. *Additive Manufacturing*, 27(March), 363–371. <https://doi.org/10.1016/j.addma.2019.03.030>
- Pratama, S. B. Y., Sari, N. P., Wicaksono, H., & Faizin, A. (2025). THE INFLUENCE OF TEMPERATURE AND SCREW ROTATION SPEED ON DIAMETER IRREGULARITY IN PLASTIC EXTRUSION USING RECYCLED PLA. *The Journal Applied of Mechanical Engineering Technology and Innovation*, 1(1), 21–29. <https://doi.org/https://doi.org/10.52158/jameti.v1i1.1314>
- R, R. M., R, V., & S, R. (2021). Experimental analysis on density, micro-hardness, surface roughness and processing time of Acrylonitrile Butadiene Styrene (ABS) through Fused Deposition Modeling (FDM) using Box Behnken Design (BBD). *Materials Today Communications*, 27(February). <https://doi.org/10.1016/j.mtcomm.2021.102353>
- Ranjan, N., Kumar, R., & Singh, R. (2024). 1.33 - Single screw extrusion for recycling of biomedical scaffolds (S. B. T.-C. M. P. (Second E. Hashmi (Ed.); pp. 307–313). Elsevier. <https://doi.org/https://doi.org/10.1016/B978-0-323-96020-5.00114-X>
- Rankouhi, B., Javadpour, S., Delfanian, F., & Letcher, T. (2016). Failure Analysis and Mechanical Characterization of 3D Printed ABS With Respect to Layer Thickness and Orientation. *Journal of Failure Analysis and Prevention*, 16(3), 467–481. <https://doi.org/10.1007/s11668-016-0113-2>
- Rijekki, N. F., Sari, N. P., Faizin, A., Duratun, S., & Rosady, N. (2024). The effect of heating temperature on 3D print filament diameter consistency produced by HDPE and LDPE plastic extrusion machine. 5(2), 104–117.
- Sabah, F., Wahid, A., Abdelkarim, K., Hamid, C., & Mohamed, El. (2019). Failure Analysis of Acrylonitrile Butadiene Styrene (ABS) Materials and Damage Modeling by Fracture. *International Journal of Performability Engineering*, 15, 2285. <https://doi.org/10.23940/ijpe.19.09.p1.22852293>
- Sedlak, J., Joska, Z., Jansky, J., Zouhar, J., Kolomy, S., Slany, M., Svasta, A., & Jirousek, J. (2023). Analysis of the Mechanical Properties of 3D-Printed Plastic Samples Subjected to Selected Degradation Effects. *Materials*, 16(8). <https://doi.org/10.3390/ma16083268>
- Shahrubudin, N., Te Chuan, L., & Ramlan, R. (2019). An Overview on 3D Printing Technology: Technological, Materials, and Applications. 35, 1286–1296. <https://doi.org/10.1016/j.promfg.2019.06.089>
- Sood, A. K., Ohdar, R. K., & Mahapatra, S. S. (2010). Parametric appraisal of mechanical property of fused deposition modelling processed parts. *Materials and Design*, 31(1), 287–295. <https://doi.org/10.1016/j.matdes.2009.06.016>

- Sousa, A. M., Pinho, A. C., & Piedade, A. P. (2021). Mechanical properties of 3D printed mouthguards: Influence of layer height and device thickness. *Materials and Design*, 203. <https://doi.org/10.1016/j.matdes.2021.109624>
- Tian, Y., Zheng, B., Khan, M., & He, F. (2025). Influence of sliding direction relative to layer orientation on tribological performance, noise, and stability in 3D-printed ABS components. *Tribology International*, 210(April), 110762. <https://doi.org/10.1016/j.triboint.2025.110762>
- Tikhani, F., & Hubert, P. (2025). Extrusion optimization and advanced mechanical characterization of fibre-reinforced polycarbonate filaments: Improving performance for fused filament fabrication. *Composites Part A: Applied Science and Manufacturing*, 191(November 2024), 108752. <https://doi.org/10.1016/j.compositesa.2025.108752>
- Tymrak, B. M., Kreiger, M., & Pearce, J. M. (2014). Mechanical properties of components fabricated with open-source 3-D printers under realistic environmental conditions. *Materials and Design*, 58, 242–246. <https://doi.org/10.1016/j.matdes.2014.02.038>