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Development of a sustainable bayonet sheath from recycled plastic bottle filament

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ABSTRACT

This study explores the feasibility of converting post-consumer polyethylene terephthalate (PET) beverage bottles into functional filament for additive manufacturing, with a specific focus on producing bayonet sheaths for Indonesian military applications. The primary objective is to determine whether recycled PET can serve as a viable alternative to conventional filaments in terms of mechanical performance and practical applicability. The research employed an experimental approach, processing PET waste into filament via the Fused Filament Fabrication (FFF) method. The material was evaluated for tensile and flexural properties in accordance with ASTM D638 and ASTM D790 standards. Two commercially available filaments, polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS), were used as benchmarks for comparison. PET specimens underwent controlled tensile and bending tests to assess strength, elongation, and deformation behavior. Results showed that recycled PET demonstrated comparable, and in certain metrics superior, performance relative to the benchmark materials, particularly in hardness and load resistance. Although minor inconsistencies were observed, likely to be due to extrusion or printing variations, these did not significantly affect functional performance. A bayonet sheath produced from recycled PET filament met both structural and practical requirements, confirming its suitability for protective gear. This study concludes that recycled PET not only fulfills mechanical requirements for military applications but also contributes to environmental sustainability by reducing plastic waste and supporting circular economy initiatives. The findings highlight the potential for recycled PET to be adopted in broader manufacturing sectors requiring durable, cost-effective, and eco-friendly materials. Further research is recommended to optimize processing techniques, enhance surface characteristics, and evaluate long-term performance under varying operational and environmental conditions to fully validate its industrial viability.

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1. INTRODUCTION

Environmental degradation, encompassing pollution of air, soil, and water, has intensified in recent decades due to the increasing accumulation of waste (Ali & Rahman, 2024; Dijoo & Khurshid, 2022). Among the various types of waste, plastic is one of the most problematic because it does not naturally decompose and can persist in the environment for decades (Dey et al., 2024; Narancic & O'Connor, 2019). In Indonesia, post-consumer polyethylene terephthalate (PET) a material commonly used for beverage bottles has emerged as a major contributor to this issue (Adeloju et al., 2021; Norrrahim et al., 2021). Poor waste management practices have led the country to become the fourth-largest global source of plastic pollution, generating roughly 64 million tons annually, with around 3.2 million tons discharged into the ocean (Ache, 2019; Brooks et al., 2020; Mihai et al., 2024).

To address this challenge, innovative material engineering strategies are required, combining environmental sustainability with functional design. This study is based on the premise that PET waste can be repurposed into robust and practical components through additive manufacturing. The proposed solution processes PET waste into filament using the Fused Filament Fabrication (FFF) technique and applies it to the production of bayonet sheaths for military use (Kantaros et al., 2023; Kumar et al., 2023). This approach integrates waste reduction, eco-friendly manufacturing, and defense equipment innovation within a single framework (Simões, 2024).

For military bayonet sheaths, the material must endure sudden impact without cracking, withstand friction from repeated blade insertion and removal, and resist degradation from exposure to moisture, mud, oils, and cleaning chemicals (Agboola et al., 2019; Al-Samarai & Al-Douri, 2024). PET satisfies these requirements through its toughness, abrasion resistance, chemical stability, and low moisture absorption (Sun et al., 2023; Wang et al., 2019). Its high strength-to-weight ratio ensures that the sheath remains durable while keeping overall equipment weight low. Additionally, 3D printing PET enables ergonomic customization for specific bayonet models and facilitates the inclusion of functional features such as locking systems or attachment points.

To align with military-grade performance expectations, future evaluations may reference standardized testing protocols such as MIL-STD-810H (U.S. Department of Defense, 2019) and MIL-STD-11991A (U.S. Department of Defense, 2016). Incorporating additional analyses, such as outgassing, accelerated aging, or environmental exposure tests, would help assess how closely recycled PET approaches MIL-SPEC tolerances. Even without formal military testing, discussing the current performance of rPET in relation to these standards can significantly strengthen its case for defense applications.

It is anticipated that the study will show recycled PET performing on par with, or surpassing, conventional filaments like PLA and ABS in certain performance aspects. Beyond demonstrating technical feasibility, the research is expected to support environmental goals by reducing plastic waste and fostering a circular economy. The outcomes may provide advantages for both the manufacturing and defense industries, delivering a sustainable and effective alternative to traditional materials.

The novelty of this research lies in the use of post-consumer PET waste as 3D printing filament (FFF) for the manufacture of military bayonet holsters, integrating environmental sustainability with defense equipment requirements. Unlike previous studies that only emphasized plastic recycling for civilian applications, this research offers an innovative approach by directing rPET to military-standard products that require resistance to impact, friction, moisture, and chemical exposure. By linking rPET performance to military testing standards such as MIL-STD-810H and MIL-STD-11991A, this research presents a new perspective that recycled materials are not only environmentally friendly but also have the potential to meet military-grade performance criteria. This makes the research unique as it presents a circular economy-based solution that is both applicable and strategic for the defense sector.

2. RESEARCH METHOD

This study utilized a quantitative experimental approach to determine the potential of recycled polyethylene terephthalate (rPET) as a sustainable filament for fabricating military bayonet sheaths via 3D printing. The methodological framework was adapted from recent studies in polymer recycling and additive manufacturing technologies.

2.1 Reference Materials

For comparative analysis, two widely used thermoplastics, acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA), were selected due to their proven performance in additive manufacturing.

2.2 Material Preparation

Discarded 1.5-liter PET beverage bottles were sourced from community waste collection points in Indonesia. Each bottle underwent a thorough cleaning process to remove labels, adhesive residues, and surface contaminants. The clean bottles were shredded into small flakes, then dried to minimize moisture content, in line with best practices for rPET processing [18], [10]. These flakes were subsequently fed into a desktop extrusion unit to produce continuous filament optimized for the Fused Filament Fabrication (FFF) process.

2.3 Design and Fabrication

The bayonet sheath model was created in Computer-Aided Design (CAD) software, exported as an STL file, and processed with slicing software to generate G-code instructions for printing. For each filament type, printing parameters such as nozzle and bed temperatures, layer height, and print speed were fine-tuned to achieve optimal surface quality and dimensional accuracy [10], [20]. Printing was performed on an FFF 3D printer in a controlled environment to ensure consistent results.

The entire experimental workflow is illustrated in the research flow diagram (Figure 1), covering all stages from raw material collection to final mechanical testing and analysis. This methodology was designed to ensure that the proposed PET filament could be rigorously evaluated and benchmarked against existing commercial filaments in practical 3D printing applications.

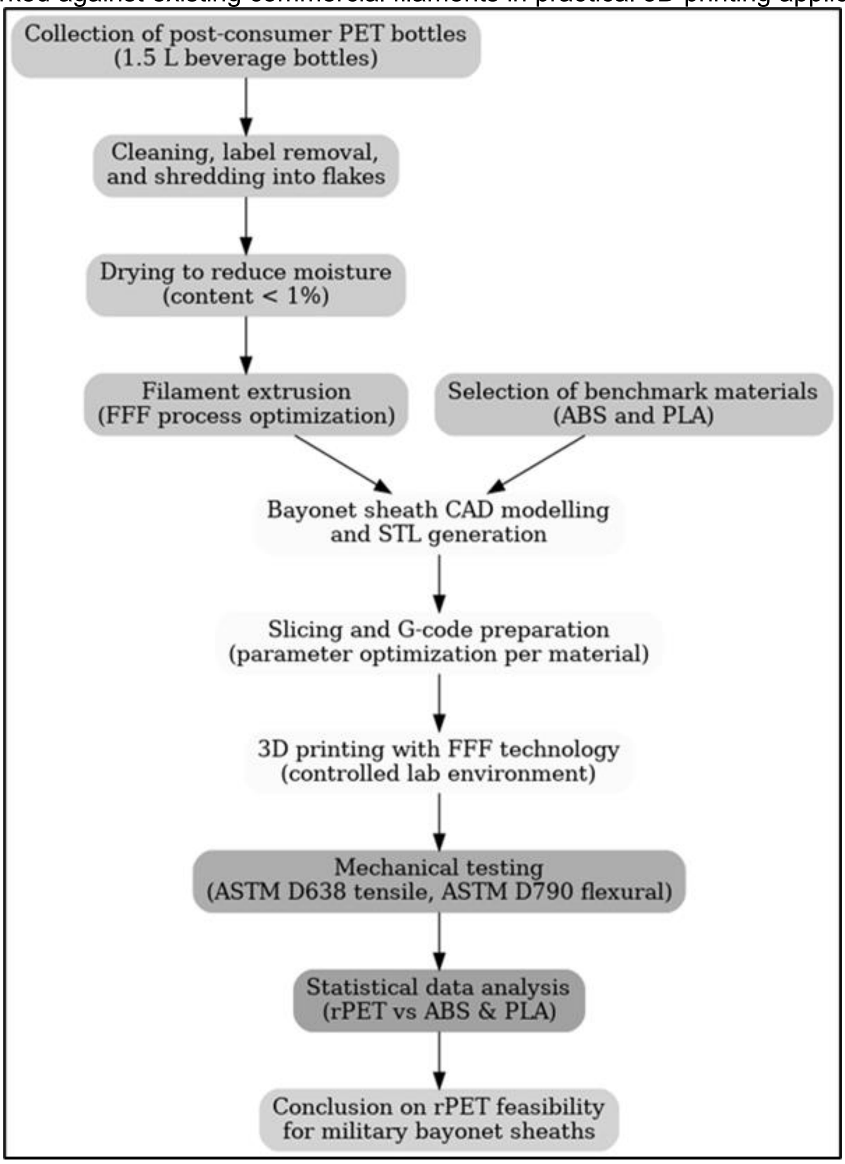


Figure 1. Research flow diagram

2.4 Mechanical Evaluation

The printed specimens were subjected to tensile and flexural tests to measure their mechanical capabilities. Tensile testing followed ASTM D638-14 at 21.1 °C with a crosshead speed of 5 mm/min, recording tensile strength, elongation at break, and modulus of elasticity. Flexural testing was carried out in accordance with ASTM D790-17 under identical temperature conditions and a crosshead speed of 1.398 mm/min, determining flexural strength and modulus. Three specimens per material type were tested to ensure accuracy and reproducibility.

2.5 Data Processing

Results from the PET samples were statistically compared with those of ABS and PLA. The analysis focused on percentage differences in tensile and flexural properties to determine whether PET fulfilled the mechanical and functional requirements for bayonet sheath applications.

Figure 2. Tensile Testing Setup

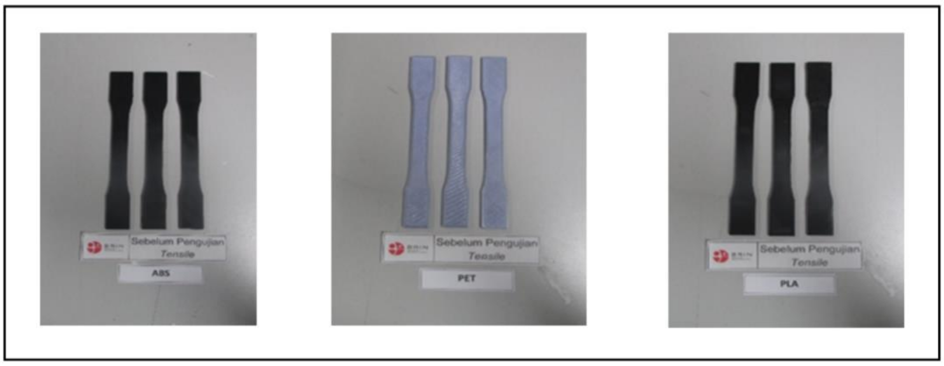
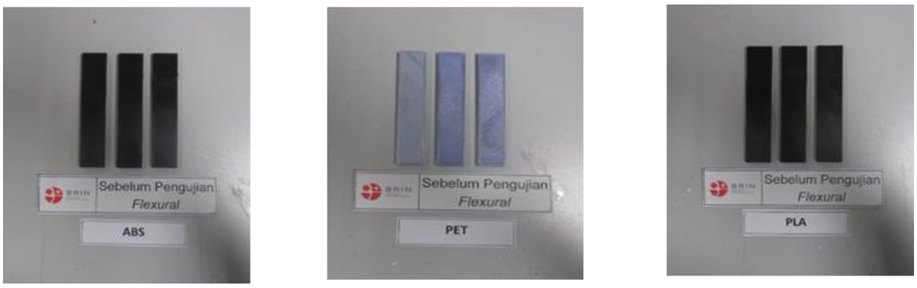


Figure 3. Tensile Test Specimens: (a) ABS, (b) PET, (c) PLA

Figure 4. Bending Test Setup



(a) **(b)** **(c)**

Figure 5. Bending Test Specimens: (a) ABS, (b) PET, (c) PLA

3. RESULTS AND DISCUSSIONS

This section presents the experimental results and analysis of mechanical tests conducted on three types of 3D printing filaments: ABS, PET, and PLA. The discussion covers tensile and bending performance comparisons, followed by the evaluation of a printed functional product.

3.1. Tensile Test Results

Tensile testing (ASTM D638) revealed that PLA achieved the highest tensile strength (26.27 N/mm²) and elongation at break (4.39%), indicating superior fracture resistance due to its high degree of crystallinity and strong interlayer adhesion typical of polylactide-based filaments. PET followed with 25.23 N/mm² and 3.92%, while ABS recorded the lowest values (22.84 N/mm²; 3.55%). The minimal variation in ABS (±0.05 N/mm²) reflects stable interlayer fusion, whereas the greater scatter in PET results (±2.44 N/mm²) is likely due to void formation and inconsistent melt flow during FFF extrusion a known challenge in semi-crystalline polymers with higher glass transition temperatures. PLA's combination of high performance and low variability (±0.22 N/mm²) confirms its predictable mechanical behavior, consistent with recent studies highlighting its homogeneous molecular orientation under controlled print parameters. Overall, PLA remains the most reliable for tensile loading, PET offers competitive strength with potential for optimization, and ABS, while weaker, provides exceptional reproducibility as an asset for applications prioritizing manufacturing consistency.

The tensile performance trends in this study corroborate established findings on FFF thermoplastics. PLA's superior tensile strength compared to ABS [25] is attributed to its higher crystallinity and restricted chain mobility, whereas ABS maintains better impact resistance at the expense of stiffness. Consistent with [20], recycled PET achieved tensile strength comparable to virgin PET when processed under optimized drying and extrusion, although property scatter remains linked to void formation and molecular orientation inconsistencies. Reference [10] further associated PET's semi-crystalline nature with sensitivity to thermal gradients during printing, explaining the variability observed in our results. This study confirms these relationships while highlighting that rPET, despite intermediate strength between PLA and ABS, presents a viable alternative with performance optimizable via controlled thermal processing and print parameter refinement. The exceptional reproducibility of ABS tensile data mirrors the manufacturing stability reported in [7], reinforcing the reliability–variability trade-off across these materials.

While previous studies have examined the tensile behavior of PLA, ABS, and virgin or recycled PET individually, this research provides a direct, controlled comparison of recycled PET filament against commercial PLA and ABS under identical FFF printing and ASTM D638 testing conditions for a specific defense-related application, namely a military bayonet sheath. The novelty lies in demonstrating that recycled PET, despite higher variability, achieves tensile strengths approaching PLA while surpassing ABS, and that its performance aligns with theoretical expectations from polymer science regarding crystallinity, glass transition behavior, and interlayer bonding. Additionally, this work is among the first to contextualize rPET's mechanical performance within the framework of potential military-grade material requirements, such as MIL-STD-810H and MIL-STD-11991A, thereby bridging sustainable materials engineering with defense manufacturing needs.

Tabel 1. Tensile Test Specimens

Material	Thickness (mm)	Width (mm)	Gauge Length (mm)	Max Force (N)	Elastic Modulus (N/mm²)	Tensile Strength (N/mm²)	Break Strain (%)	Std. Dev. (Tensile Strength)
ABS	3.287	13.083	115	982.14	1209.89	22.84	3.55	0.05
PET	3.230	13.347	115	1087.19	1018.31	25.23	3.92	2.44
PLA	3.287	12.950	115	1117.92	1386.46	26.27	4.39	0.22

As illustrated in Figure 6, the tensile graph for ABS showed consistent values across all three specimens, indicating good reliability with low standard deviation. PET, on the other hand, showed significant variation in maximum force and elongation particularly in specimen 2 which suggests inconsistencies likely caused by printing defects. Despite this, the stress and strain at break were relatively stable, showing that PET maintains a reasonable load-bearing capacity. PLA exhibited stable tensile behavior similar to ABS, with minimal variation among specimens.

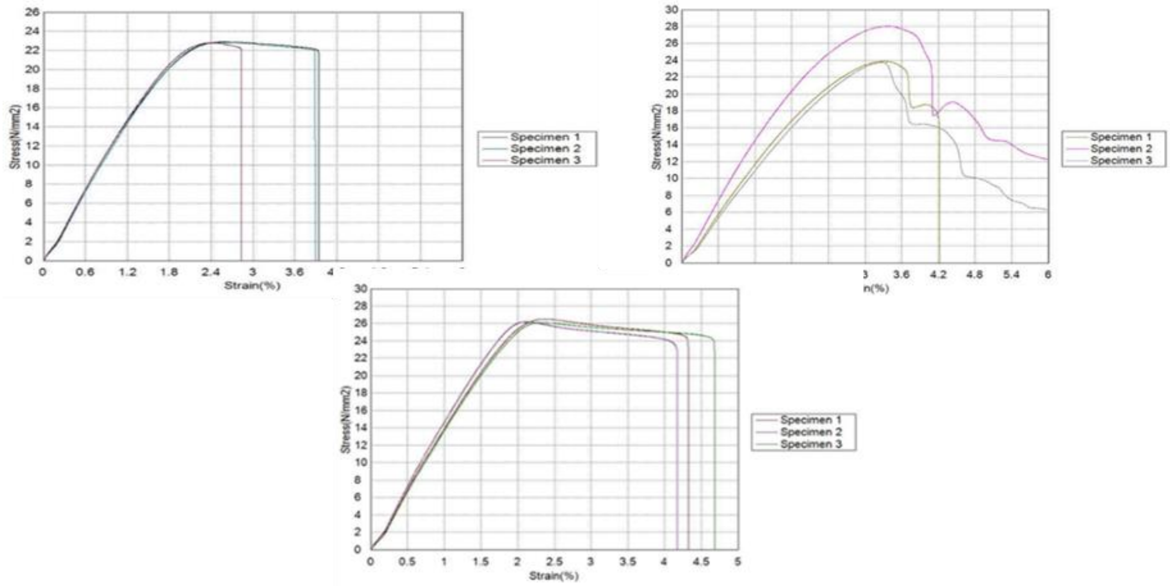


Figure 6. Tensile test results: (a) ABS, (b) PET, (c) PLA

3.2. Bending Test Results

Flexural testing (ASTM D790) was performed on ABS, PET, and PLA specimens at 21.1 °C with a crosshead speed of 1.398 mm/min. PLA achieved the highest flexural strength (48.75 N/mm²) and maximum force (105.91 N), followed by PET (42.69 N/mm²; 93.73 N) and ABS (34.65 N/mm²; 74.87 N). PLA's low standard deviation in flexural strength (±0.96 N/mm²) and strain (±0.14%) indicates stable mechanical performance and strong interlayer adhesion under bending loads. ABS also showed good consistency (±0.90 N/mm²), reflecting its isotropic behavior in FFF printing despite lower stiffness compared to PLA.

In contrast, PET exhibited the highest variability in flexural strength (±10.39 N/mm²) and maximum force (±21.69 N), which can be attributed to incomplete polymer chain fusion and void formation during cooling—typical challenges in processing semi-crystalline thermoplastics. Despite this, PET's mean flexural strength exceeded that of ABS, demonstrating its potential for structural applications if processing parameters are optimized.

Overall, PLA outperformed both PET and ABS in flexural properties, combining high stiffness with consistent results. PET occupied an intermediate position, offering competitive strength but requiring improved thermal and extrusion control to reduce variability. ABS, while mechanically weaker in bending, remains advantageous for applications requiring predictable and repeatable performance.

The flexural behavior observed in this study is consistent with earlier reports on FFF-printed thermoplastics. References [25] and [10] noted that PLA generally exhibits superior flexural modules and strength compared to ABS, largely due to its higher degree of crystallinity and lower ductility, which enhance stiffness under bending loads. Similarly, [20] highlighted that recycled PET can match or exceed ABS in flexural strength when processed with optimal drying and controlled cooling but may present high variability due to semi-crystalline morphology and residual internal stresses. The elevated scatter in PET’s flexural results here reflects these known challenges, reinforcing the importance of precise extrusion control and post-processing techniques. ABS’s consistent but lower flexural strength aligns with findings from [7], confirming its reliability despite reduced stiffness.

While prior studies have assessed the bending properties of PLA, ABS, and virgin PET separately, this work delivers a direct comparative evaluation under identical ASTM D790 test conditions, specifically targeting the applicability of recycled PET in military bayonet sheath production. The novelty lies in demonstrating that rPET’s flexural strength surpasses ABS and approaches PLA, despite higher variability, and in linking these findings to polymer structure theory specifically the influence of crystallinity, glass transition temperature, and interlayer adhesion on bending performance. Furthermore, by situating the results within the context of potential compliance with military-grade durability standards, the study provides a practical bridge between sustainable polymer recycling and high-performance defense applications.

Table 2. Bending Test Specimens

Material	Thickness (mm)	Width (mm)	Lower Support Span (mm)	Max Stress (N/mm²)	Max Strain (%)	Max Force (N)	Std. Dev. (Max Stress)	Std. Dev. (Max Strain)	Std. Dev. (Max Force)
ABS	3.247	15.970	51.95	34.65	4.053	74.87	0.90	0.31	2.81
PET	3.233	16.330	51.73	42.69	3.816	93.73	10.39	0.33	21.69
PLA	3.277	15.923	52.43	48.75	3.577	105.91	0.96	0.14	0.95

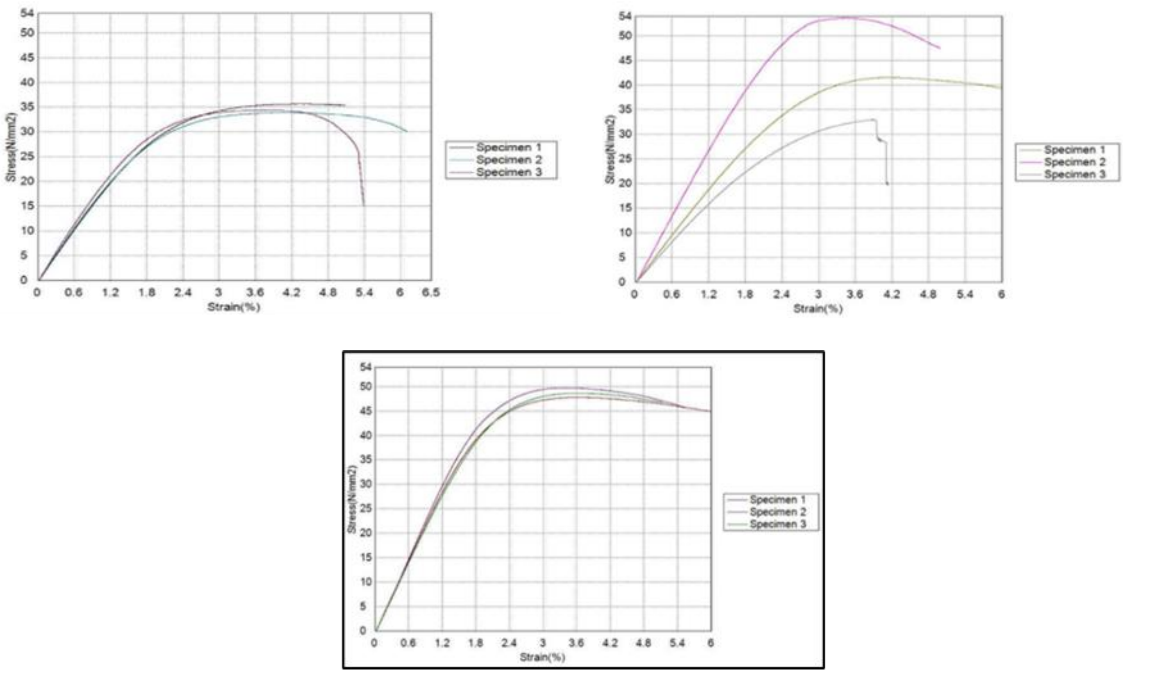


Figure 7. Bending test results: (a) ABS, (b) PET, (c) PLA

3.3. Printed Bayonet Sheath

As a final validation of rPET's applicability, a military bayonet sheath was modeled in CAD, fabricated via FFF printing, and evaluated for practical handling. The successful production of the sheath (Figure 4) demonstrates that rPET can be processed into geometrically accurate, dimensionally stable, and mechanically functional components. The mechanical performance observed in tensile and flexural testing directly supports its use in this application: the tensile strength (25.23 N/mm²) ensures resistance to pulling forces during repeated blade insertion and removal, while the flexural strength (42.69 N/mm²) provides adequate rigidity to protect the blade from lateral impacts or compressive loads during field use.

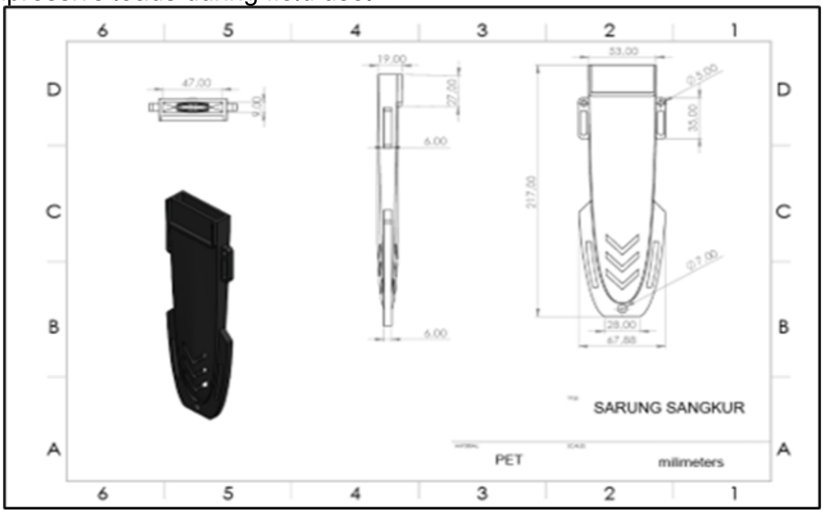


Figure 8. Bayonet sheath modeled in CAD

Moreover, rPET's inherent toughness, abrasion resistance, and low moisture absorption are advantageous in military environments where equipment is exposed to moisture, mud, and oils. While minor variability in mechanical results suggests that optimized extrusion and printing parameters are needed for consistent large-scale production, the functional sheath prototype confirms the material's operational feasibility. When considered alongside potential compliance with military environmental durability standards such as MIL-STD-810H and material stability standards like MIL-STD-11991A, this functional validation bridges laboratory performance data with real-world defense applications, reinforcing the role of rPET as both a sustainable and high-performance alternative to conventional filaments.

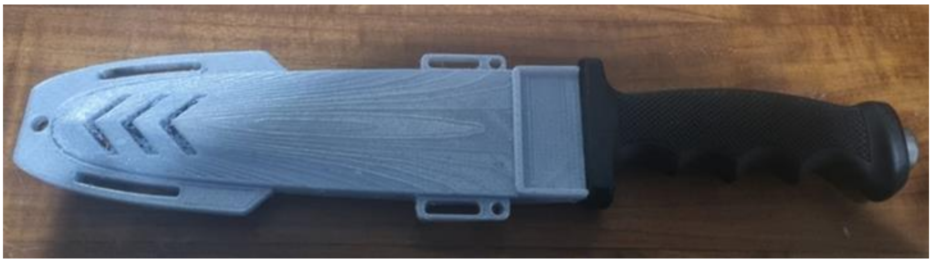


Figure 9. Bayonet sheath printed using recycled PET filament

4. CONCLUSION

This study comprehensively evaluated the mechanical performance of recycled polyethylene terephthalate (rPET) filament in comparison with two widely used commercial thermoplastics, PLA and ABS, for additive manufacturing of military bayonet sheaths. Testing under standardized conditions (ASTM D638 for tensile and ASTM D790 for flexural) revealed that PLA exhibited the highest tensile (26.27 N/mm²) and flexural strength (48.75 N/mm²), followed closely by rPET (25.23 N/mm²; 42.69 N/mm²) and ABS (22.84 N/mm²; 34.65 N/mm²). While rPET displayed competitive mechanical properties, higher variability—particularly in flexural tests—was observed, likely due to void formation, inconsistent molecular orientation, and thermal gradients during printing. When analyzed in the context of polymer structure–property relationships, PLA's superior strength is attributable to its higher crystallinity and strong interlayer adhesion, whereas ABS's lower strength but excellent reproducibility reflects its amorphous structure and stable processing behavior. rPET's intermediate performance is consistent with literature on semi-crystalline PET, where properties are highly sensitive to drying, extrusion parameters, and cooling rates. Nonetheless, the present study demonstrates that, even when derived from post-consumer waste, rPET can achieve tensile and flexural strengths approaching those of PLA and exceeding ABS, provided appropriate process optimization is applied. The functional validation—printing a full-scale bayonet sheath—confirmed that rPET not only meets the mechanical requirements for such protective gear but also offers advantages in abrasion resistance, chemical stability, and low moisture absorption. These attributes align with the durability demands of field-deployed military equipment and indicate potential compatibility with military performance standards such as MIL-STD-810H (environmental durability) and MIL-STD-11991A (material stability). This positions rPET as a sustainable, high-performance alternative to virgin polymers in defense manufacturing, with the added benefit of contributing to waste reduction and circular economy initiatives. The novelty of this work lies in directly comparing rPET, PLA, and ABS under identical manufacturing and testing conditions for a defense-specific application, integrating mechanical property analysis with practical prototype validation, and contextualizing results within potential military-grade requirements. Beyond military uses, these findings hold relevance for other sectors—such as automotive, marine, and outdoor equipment manufacturing—where lightweight, durable, and corrosion-resistant components are essential. Future research should focus on refining extrusion and printing parameters to minimize property variability, conducting extended durability testing under accelerated aging and environmental cycling, and exploring surface treatments or composite reinforcement to further enhance rPET's structural performance. By bridging sustainable materials science with high-demand engineering applications, this study demonstrates a viable pathway for transforming PET waste into functional, defense-ready products. Future research should focus on optimizing extrusion and printing parameters to minimize the variability of rPET's mechanical properties and explore composite reinforcement or surface treatments to improve structural performance. In addition, long-term durability testing using accelerated aging and environmental cycling methods is needed to further validate the reliability of rPET against military standards and high-intensity industrial applications.

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