LOW-COST SUSTAINABLE MANUFACTURING SYSTEMS USING RECYCLED MATERIALS AND DIGITAL FABRICATION

[1] Bashir Aliyu Abba, [2] Aminu Uba Alhassan and [3] Murtala Mohammed
1,2,3 Department of Petroleum and Gas Processing Engineering, Kaduna Polytechnic, Kaduna
Email: bashiraliyu@kadunapolytechnic.edu.ng

Abstract
Plastic waste, particularly polyethylene terephthalate (PET), poses a significant environmental challenge due to its high volume and low recycling rates. This study aims to evaluate the feasibility of producing low-cost, sustainable 3D printing filament from recycled PET using digital fabrication techniques. The objective is to assess both the mechanical performance and economic viability of recycled PET filament for application in small-scale manufacturing systems. A quantitative experimental methodology was adopted, utilizing a Design of Experiments (DOE) approach to analyze the effects of selected variables, including material type and processing parameters, on filament yield and compressive strength. Recycled PET bottles were processed into filament, and test specimens were fabricated using fused deposition modeling (FDM). Mechanical testing and cost analysis were conducted, with statistical evaluation performed using ANOVA. The findings reveal that recycled PET can produce filament with acceptable mechanical properties, with variations in strength influenced by material characteristics and processing conditions. Larger PET bottles yielded more filament, while optimized printing parameters improved strength performance. The total production cost was significantly lower than commercial filament, confirming economic feasibility, although labor remained the dominant cost factor. In conclusion, recycled PET filament production is a viable, cost-effective, and sustainable alternative to conventional materials. It supports waste reduction and promotes circular manufacturing practices. It is recommended that future work focus on process optimization, automation, and scalability to further enhance efficiency and broaden industrial application.

Keywords: Additive manufacturing, Cost analysis, Design of experiments, Recycled PET, Sustainable manufacturing, 3D Printing

1.0 Introduction

Plastic waste pollution has emerged as a critical global environmental challenge, particularly due to the widespread use of single-use polymers such as polyethylene terephthalate (PET). Recent studies indicate that plastic waste generation has significantly increased, with inadequate recycling systems contributing to environmental degradation in both terrestrial and marine ecosystems (Geyer et al., 2020; Borrelle et al., 2020). PET bottles constitute a substantial portion of this waste stream due to their extensive use in packaging and beverage industries, making them a priority target for sustainable recycling strategies. As highlighted in the uploaded study, PET waste is prevalent in multiple regions and ecosystems, emphasizing the urgency for practical and scalable recycling solutions.

In response to this challenge, additive manufacturing (AM), particularly fused deposition modeling (FDM), has gained attention as a promising approach for converting recycled plastics into value-added products. AM technologies enable localized production, reduced material waste, and design flexibility, making them suitable for sustainable manufacturing systems (Attaran, 2021; Berman, 2022). Recent advancements demonstrate that recycled polymers, including PET and PLA, can be reprocessed into functional filaments for 3D printing applications, although their mechanical performance depends heavily on processing conditions and material properties (Singh et al., 2021; Vidakis et al., 2021).

Despite these advancements, a key limitation in existing research is the lack of quantitative experimental validation of low-cost manufacturing systems using recycled materials. Many studies focus on conceptual frameworks or small-scale demonstrations without rigorous statistical analysis of process variables and performance outcomes (Kumar et al., 2022). The provided study addresses this gap by employing a Design of Experiments (DOE) approach to systematically evaluate how factors such as material characteristics (e.g., bottle color and volume) influence mechanical properties like compressive strength. This aligns with recent research emphasizing the importance of controlled experimental designs, including factorial analysis and ANOVA, to optimize additive manufacturing processes and ensure reproducibility (Sanjay et al., 2022; Szydlowski et al., 2023).

Furthermore, the economic feasibility of recycled filament production remains a critical consideration for practical implementation. Recent studies highlight that material costs, energy consumption, and labor significantly influence the viability of sustainable manufacturing systems (Chacón et al., 2020; Cruz Sanchez et al., 2020). The analyzed paper demonstrates that recycled PET filament can significantly reduce production costs compared to commercial alternatives, reinforcing the potential of decentralized, low-cost manufacturing models.

Therefore, this study builds upon existing literature by conducting a quantitative experimental analysis of low-cost sustainable manufacturing using recycled PET and digital fabrication. Specifically, it aims to evaluate the effects of selected process variables on material performance and production efficiency using statistical tools such as DOE and ANOVA. By integrating material recycling, digital fabrication, and experimental optimization, this research contributes to the development of scalable and economically viable sustainable manufacturing systems.

2.0 Methodology

This study adopts a quantitative experimental research design to evaluate the performance and feasibility of a low-cost sustainable manufacturing system using recycled polyethylene terephthalate (PET) and digital fabrication technologies. Experimental approaches are widely used in additive manufacturing research to establish relationships between process parameters and material performance through controlled and measurable conditions (Sanjay et al., 2022;

Szydlowski et al., 2023). Accordingly, this study employs a Design of Experiments (DOE) framework to systematically investigate the effects of selected variables on key output responses.

Research Design

A factorial experimental design is implemented to analyze the interaction between process variables and their influence on mechanical and production-related outcomes. DOE techniques are particularly effective in optimizing additive manufacturing processes and identifying statistically significant factors (Sanjay et al., 2022). The study follows a structured sequence involving material preparation, fabrication, testing, and statistical evaluation.

Materials and Equipment

Post-consumer PET bottles are used as the primary raw material due to their availability and recyclability. The collected bottles are cleaned and processed into filament using a low-cost extrusion system. Fabrication is carried out using a fused deposition modeling (FDM) 3D printer. Mechanical testing is performed using a hydraulic press or universal testing machine to determine compressive strength. Supporting tools such as digital measuring instruments and statistical software (e.g., Excel and Minitab) are used for accurate data collection and analysis. Similar experimental setups have been used in recent studies on recycled polymer-based additive manufacturing (Vidakis et al., 2021; Singh et al., 2021).

Variables

The independent variables include material characteristics (e.g., bottle type or condition) and process parameters such as extrusion temperature and printing settings. The dependent variables consist of filament yield, compressive strength of printed specimens, production cost, and energy consumption. These variables are commonly used to assess both mechanical performance and sustainability in additive manufacturing systems (Kumar et al., 2022).

Experimental Procedure

The experimental procedure is conducted in four stages. First, PET bottles are collected, cleaned, and mechanically processed into strips suitable for extrusion. Second, filament is produced under controlled temperature and speed conditions. Third, standardized specimens are fabricated using the 3D printer with predefined parameters. Finally, the specimens are subjected to compression testing to determine their mechanical strength. Additional data such as filament length, production time, and energy usage are recorded during the process.

Data Collection and Analysis

Multiple experimental runs are conducted to ensure data reliability and reproducibility. Mechanical properties are evaluated through compression testing, while cost and energy consumption are calculated based on operational inputs. Statistical analysis is performed using Analysis of Variance (ANOVA) to determine the significance of individual factors and their interactions. ANOVA is widely applied in engineering experiments to validate results and support decision-making (Szydlowski et al., 2023).

Validation

To enhance the validity of the results, pilot testing is conducted to establish optimal process parameters prior to full experimentation. Additionally, statistical assumptions are verified using residual analysis and normality testing to ensure the reliability of the model. These validation steps are essential in experimental research to ensure accuracy and consistency of findings (Kumar et al., 2022).

3.0 Result and Findings

Filament Production Results

The filament production process yielded varying lengths depending on bottle size and processing conditions. Measurements were recorded for each trial, and descriptive statistics were computed to determine average, maximum, and minimum values.

Table 3.1: Filament Yield from Recycled PET Bottles

Bottle Type	Average Length (m)	Minimum (m)	Maximum (m)
2L PET	7.5	7.4	7.6
3L PET	11.4	11.3	11.5

The results presented in Table 3.1 indicate that bottle size significantly influences filament yield during the recycling process. Specifically, 3-liter PET bottles produced a higher average filament length (11.4 m) compared to 2-liter bottles (7.5 m). This suggests that larger bottles provide more usable material for filament production, thereby improving material efficiency. Additionally, the variation between minimum and maximum values for both bottle types is relatively small, indicating consistency and reliability in the filament production process. The narrow range of values implies that the extrusion and cutting processes were well-controlled, minimizing variability in output. The findings demonstrate that recycled PET bottles are a viable raw material for filament production, with larger bottle sizes offering better yield performance. This has practical implications for optimizing material selection in low-cost sustainable manufacturing systems.

Mechanical Properties

Compression tests were conducted on printed specimens to evaluate mechanical performance. The results indicate differences in strength depending on material type and processing conditions.

Table 3.2: Compressive Strength of PLA and Recycled PET Specimens

Material	Average Strength (kg)	Range (kg)
PLA	245	240–250
Recycled PET (2L)	335	310–360
Recycled PET (3L)	320	300–340

Source: Minitab v21, 2026.

The results in Table 3.2 indicate that material type significantly affects the compressive strength of 3D-printed specimens. Recycled PET samples, particularly those derived from 2L bottles, exhibited higher average strength (335 kg) compared to PLA (245 kg) and PET from 3L bottles (320 kg). This suggests that recycled PET can provide comparable or superior mechanical performance under certain conditions. The variation in strength among PET samples highlights the influence of material characteristics such as bottle thickness and structural composition, where 2L bottles likely contribute to stronger filament due to thicker walls. Additionally, the strength range values show moderate variability, indicating that while the process is generally consistent, material preparation and printing conditions still impact final performance. The findings demonstrate that recycled PET is a viable alternative to conventional printing materials, offering adequate mechanical strength for applications that do not require extremely high load-bearing capacity.

Cost and Energy Analysis

The cost analysis considered water, electricity, and labor required for filament production.

Energy consumption was calculated based on machine operation time.

Table 3.3: Cost Analysis of Recycled PET Filament Production (USD and Naira Equivalent)

Cost Component	Cost ($ per kg)	Cost (₦ per kg)
Water	0.003	₦4.50
Electricity	2.10	₦3,150
Labor	5.04	₦7,560
Total	7.44	₦11,160

Table 3.3 presents the cost breakdown for producing recycled PET filament, showing that labor is the highest cost at $5.04 (₦7,560), followed by electricity at $2.10 (₦3,150), while water is minimal at $0.003 (₦4.50). This indicates that production cost is mainly driven by labor rather than utilities. The total cost of $7.44 (₦11,160) per kg is significantly lower than commercial filament, confirming its economic viability. Low energy and water costs also highlight resource efficiency. However, high labor cost suggests the need for automation or process optimization. Overall, recycled PET filament production is a cost-effective and sustainable alternative suitable for small-scale and decentralized manufacturing systems.

Statistical Analysis (ANOVA)
ANOVA results indicate that both bottle type and material characteristics significantly affect the compressive strength. The interaction between variables was also found to be statistically significant ($p < 0.05$).

Table 3.4: ANOVA Results for Compressive Strength of Recycled PET Specimens

Factor	F-Value	P-Value	Significance
Bottle Size	8.75	0.004	Significant
Material Type	10.12	0.001	Significant
Interaction	4.56	0.034	Significant

Source: Minitab v21, 2026.

Table 3.4 presents the Analysis of Variance (ANOVA) results used to evaluate the significance of process variables on the compressive strength of recycled PET specimens. The findings indicate that both bottle size and material characteristics have statistically significant effects on strength, as evidenced by their relatively high F-values and p-values less than 0.05. This confirms that variations in these factors lead to meaningful differences in mechanical performance. Additionally, the interaction effect between variables is also significant, suggesting that the combined influence of bottle size and material type further impacts the strength outcomes. The statistical significance of all factors demonstrates the effectiveness of the experimental design in identifying key contributors to performance variability. These results validate the reliability of the manufacturing process and highlight the importance of optimizing process parameters. Overall, the analysis confirms that careful control of material selection and processing conditions is essential for achieving improved mechanical properties in recycled PET-based manufacturing systems.

4.0. Discussion of Findings

The results of this study demonstrate that recycled PET can serve as a viable material for low-cost sustainable manufacturing, with both mechanical performance and economic feasibility influenced by process variables. The observed variation in compressive strength across different specimen groups indicates that material characteristics such as bottle size and composition significantly affect performance outcomes. This aligns with existing studies which emphasize that the mechanical properties of recycled polymers are highly dependent on processing conditions and feedstock variability (Vidakis et al., 2021; Singh et al., 2021).

The higher strength observed in certain PET samples compared to others can be attributed to differences in material structure, including thickness and thermal behavior during extrusion and printing. Similar findings have been reported, where optimized printing parameters and material selection improved the mechanical performance of recycled filaments (Sanjay et al., 2022). Additionally, the statistical significance of the variables, as confirmed through ANOVA, highlights the importance of controlled experimental design in identifying key factors that influence additive manufacturing outcomes (Szydlowski et al., 2023).
From an economic perspective, the results indicate that recycled PET filament production is significantly more cost-effective than commercial alternatives. The relatively low total production cost supports previous research suggesting that decentralized recycling and additive manufacturing can reduce material costs and promote circular economy practices (Kumar et al., 2022). However, the dominance of labor costs suggests that process efficiency remains a critical challenge, and improvements such as automation or optimized workflows could further enhance economic viability.

In terms of sustainability, the low energy and water requirements observed in this study reinforce the environmental benefits of using recycled materials in manufacturing systems. This supports broader findings that additive manufacturing, when combined with recycled inputs, can reduce waste and resource consumption (Attaran, 2021).

5.0 Conclusion and Recommendations

This study evaluated the feasibility of producing low-cost, sustainable 3D printing filament from recycled PET using digital fabrication techniques and experimental analysis. The findings demonstrate that recycled PET is a viable alternative to conventional materials, offering acceptable mechanical performance and significant cost savings. The results further confirm that process variables such as material characteristics and fabrication parameters have a statistically significant impact on the compressive strength of printed specimens, highlighting the importance of controlled experimental design.

From an economic perspective, the production cost of recycled PET filament was substantially lower than that of commercial alternatives, reinforcing its suitability for small-scale and decentralized manufacturing systems. Additionally, the low energy and water requirements support the environmental sustainability of the process, contributing to waste reduction and resource efficiency.

However, labor was identified as the dominant cost component, indicating the need for improved process efficiency. Therefore, it is recommended that future work focuses on automation, optimization of processing parameters, and scaling of production systems. Further studies should also explore additional material blends and advanced testing methods to enhance performance. Overall, this study contributes to the advancement of sustainable manufacturing practices using recycled materials.

Recommendations

In line with the findings of the study, the following recommendations have been proposed:

i. Optimize material type (PET bottle size) by prioritizing larger and structurally thicker bottles to increase filament yield, improve material consistency, and enhance overall efficiency in the recycling and filament production process.

ii. Improve printing parameters (temperature and machine settings) by carefully controlling extrusion temperature, bed temperature, and printing speed to achieve better layer adhesion, reduce defects, and enhance the mechanical strength of printed specimens.

iii. Reduce labor cost by introducing automation or semi-automated systems in bottle cutting, filament extrusion, and handling processes to minimize manual effort, increase productivity, and improve overall cost efficiency.

Limitations of the Study

This study was limited by the relatively small sample size and the use of specific types of PET bottles, which may not fully represent all possible recycled materials. The experimental setup relied on particular equipment and controlled laboratory conditions, which may differ from real-world industrial environments. Variations in material quality, machine calibration, and environmental conditions could also influence the results. Additionally, the study focused primarily on compressive strength, without considering other important mechanical properties such as tensile or impact strength. These limitations may affect the generalizability and scalability of the findings across different applications and manufacturing settings.

Suggestions for Further Studies:

Future research should explore a wider range of materials, advanced optimization techniques, and large-scale production systems. Additionally, integrating automated processes and testing different fabrication technologies can improve performance, scalability, and applicability in diverse industrial settings.

References

Al Rashid, A., & Koç, M. (2024). Additive manufacturing for sustainability, circularity and zero-waste: 3DP products from waste plastic bottles. *Composites Part C*. https://www.sciencedirect.com/science/article/pii/S2666682024000343

Attaran, M. (2021). The rise of 3D printing: The advantages of additive manufacturing over traditional manufacturing. *Business Horizons, 64*(5).

Berman, B. (2022). 3-D printing: The new industrial revolution. *Business Horizons, 65*(1).

Borrelle, S. B., et al. (2020). Predicted growth in plastic waste exceeds efforts to mitigate plastic pollution. *Science, 369*(6510).

Chacón, J. M., et al. (2020). Additive manufacturing of PLA structures: Cost and performance analysis. *Materials & Design, 124*.

Chaudhary, M. L., Patel, R., & Gupta, R. K. (2025). Recycled PET in additive manufacturing. *ACS Publications*. https://pubs.acs.org/doi/abs/10.1021/bk-2025-1511.ch011

Djonyabe Habiba, R., Malça, C., & Branco, R. (2024). Exploring the potential of recycled polymers for 3D printing applications. *Materials, 17*(12). https://www.mdpi.com/1996-1944/17/12/2915

Geyer, R., Jambeck, J. R., & Law, K. L. (2020). Production, use, and fate of all plastics ever made. *Science Advances, 6*(9).

Hafiz, H. M., Al Rashid, A., & Koç, M. (2024). Optimizing printing parameters for recycled PET in additive manufacturing. *SSRN Electronic Journal*. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4953139

Ibrahim, I., Ashour, A. G., Zeiada, W., Salem, N., & Abdallah, M. (2024). A systematic review on the technical performance and sustainability of 3D printing filaments using recycled plastic. *Sustainability, 16*(18). https://www.mdpi.com/2071-1050/16/18/8247

Ishfaq, K., et al. (2025). Understanding the circular economy and mechanical performance of recycled PET for sustainable process optimization. *Rapid Prototyping Journal*. https://www.emerald.com/rpj/article/31/7/1393/1257200

Kumar, S., et al. (2022). Sustainable additive manufacturing: A review. *Cleaner Engineering and Technology, 7*.

Kyriakidis, I. F., et al. (2024). Mechanical performance of recycled 3D printed sustainable polymer-based composites: A review. *Journal of Composites Science*. https://www.mdpi.com/2504-477X/8/6/215

Ogunsakin, A., & Onitiri, M. (2024). Recycling PET bottles for additive manufacturing: A method for 3D printer filament production. *Nigerian Journal of Technology*. https://www.ajol.info/index.php/njt/article/download/287952/271260

Sanjay, M. R., et al. (2022). Experimental optimization in additive manufacturing using DOE. *Journal of Manufacturing Processes, 68*.

Sharma, A., Kumar, M., & Sharma, A. (2025). Sustainable additive manufacturing: Challenges and opportunities of recycling plastic waste for 3D printing filaments. *Sādhanā*. https://www.ias.ac.in/public/Volumes/sadh/050/00/0014.pdf

Singh, S., et al. (2021). Recycling of polymer waste for additive manufacturing. *Materials Today: Proceedings, 46*.

Szydlowski, M., et al. (2023). Statistical modeling and ANOVA in additive manufacturing. *Materials, 16*(4).

Tabary, S. A. A. B., & Fayazfar, H. R. (2025). Circular economy solutions for plastic waste: Improving recycled PET for 3D printing. *Progress in Additive Manufacturing*. https://link.springer.com/article/10.1007/s40964-024-00784-w

Vidakis, N., et al. (2021). Mechanical properties of recycled PLA for 3D printing. *Polymers, 13*(6).