Applied Chemical Engineering (2024) Volume 7 Issue 3
doi: 10.59429/ace.v7i3.5537

ORIGINAL RESEARCH ARTICLE

Energy-efficient FDM printing of sustainable polymers: Optimization strategies for material and process performance

Subramani Raja[1,*], Rusho Maher Ali[2,*], S. Karthikeyan[3], Raviteja Surakasi[4], R. Anand[5], Neelamegam Devarasu[6], Sathish T.[7]

[1] *Centre for Sustainable Materials and Surface Metamorphosis, Chennai Institute of Technology, Chennai, Tamilnadu, 600069, India*

[2] *Lockheed Martin Engineering Management, University of Colorado, Boulder, Colorado, 80308, United States*

[3] *Department of Mechanical Engineering, Erode Sengunthar Engineering College, Erode, Tamilnadu, 638057, India*

[4] *Department of Mechanical Engineering, Lendi Institute of Engineering and Technology, Jonnada, Vizianagaram, Andhra Pradesh,535005, India*

[5] *Department of Aeronoutical Engineering, Nehru Institute of Technology, Coimbatore, Tamilnadu, 641008, India*

[6] *Department of Electronics and Communication Engineering, Vel Tech Rangarajan Dr. Sagunthala R&D Institute of Science and Technology, 400 feet Outer Ring Road, Avadi, Chennai, 600062, Tamilnadu, India*

[7] *Department of Mechanical Engineering, Vel Tech Multi Tech Dr.Rangarajan Dr.Sakunthala Engineering College,Chennai, Tamilnadu, 600062, India*

***Corresponding author:** Subramani Raja, sraja@citchennai.net; Rusho Maher Ali, maru4732@colorado.edu

ARTICLE INFO

Received: 23 August 2024
Accepted: 8 October 2024
Available online: 15 October 2024

ABSTRACT

The integration of sustainable polymers in fused deposition modeling (FDM) 3D printing offers a promising pathway toward reducing the environmental impact of additive manufacturing. However, the energy-intensive nature of FDM processes presents a significant challenge to the overall sustainability of this technology. In this study, we explore the use of bio-based and recycled polymers in FDM printing and develop optimization strategies to reduce energy consumption without compromising material and print performance. Our results demonstrate that by systematically optimizing key printing parameters such as extrusion temperature, print speed, and layer height it is possible to achieve up to 20% energy savings. Additionally, we find that novel material formulations and advanced thermal management techniques enhance the mechanical properties of printed objects by up to 15%, all while minimizing energy use. This research not only advances the field of sustainable 3D printing but also provides a framework for the development of next-generation materials and processes that align with the principles of a circular economy.

Keywords: additive manufacturing; sustainable polymers; energy-efficient fused deposition modeling (FDM); circular economy; energy consumption; mechanical properties; optimization; polymer performance; eco-friendly materials

1. Introduction

Fused deposition modeling (FDM) has emerged as one of the most popular additive manufacturing techniques due to its ability to fabricate complex geometries using thermoplastic materials at relatively low costs[1-3]. This method's broad adoption spans industries ranging from automotive to healthcare, where rapid prototyping and custom part production are essential[4-6]. However, the environmental implications of FDM, particularly regarding its energy consumption and dependence on petroleum-based polymers, have raised concerns among researchers and practitioners aiming to promote sustainable manufacturing practices. FDM offers several advantages over other additive manufacturing techniques, making it one of the most widely adopted methods for 3D printing. First, FDM is highly cost-effective, particularly for prototyping and low-volume production, due to the relatively low cost of both equipment and materials. This stands in contrast to techniques such as selective laser sintering (SLS), which requires higher initial investments in machinery and material costs. Moreover, FDM is highly compatible with a wide range of materials, including bio-based and recycled polymers, making it a preferred choice for sustainability-focused applications. Unlike stereolithography (SLA), which primarily uses photopolymers, FDM can print with more environmentally friendly materials, such as PLA and PETG, contributing to a reduced environmental footprint.Another critical advantage of FDM lies in its energy consumption. While SLS and SLA both require higher energy input due to the use of lasers and UV light, respectively, FDM operates at lower temperatures and without high-energy light sources, making it a more energy-efficient option. This study specifically builds on these advantages by optimizing the FDM process to further reduce energy consumption, demonstrating its potential to be both an environmentally and economically viable solution for sustainable manufacturing[7-9]. The polymers selected for this study bio-based PLA (Polylactic Acid) and recycled PETG (Polyethylene Terephthalate Glycol) are increasingly used in FDM 3D printing due to their favorable balance between mechanical performance and environmental impact. PLA, a biodegradable polymer derived from renewable resources such as cornstarch or sugarcane, is widely used in industries like packaging, medical devices, and consumer products. Its mechanical properties, such as high tensile strength and stiffness, combined with its low environmental footprint, make it a strong candidate for future engineering applications where sustainability is a priority. Recycled PETG, known for its impact resistance and thermal stability, is another polymer gaining popularity in fields like automotive and aerospace engineering. Its ability to be recycled and reused multiple times without significant degradation in performance makes it ideal for applications where both material longevity and environmental considerations are critical. These polymers not only address the current demand for eco-friendly materials but also hold promise for a future where engineering and manufacturing industries will increasingly prioritize sustainable and circular economy principles.The selection of these polymers in this study is thus motivated by their proven performance in existing applications and their potential to serve as robust, sustainable alternatives in next-generation engineering designs[10-12]. Studies have demonstrated that these materials can achieve mechanical properties comparable to their conventional counterparts, making them suitable for various FDM applications. However, the thermal stability and printability of these sustainable polymers remain a challenge, requiring further optimization to match the performance of traditional materials like acrylonitrile butadiene styrene (ABS) and nylon. Parallel to material innovations, the energy efficiency of FDM processes has become a critical area of research. The energy consumption of FDM is influenced by various parameters, including extrusion temperature, print speed, layer height, and cooling rates. Recent studies have employed experimental and computational approaches to optimize these parameters, with the goal of minimizing energy use while maintaining or improving print quality[13-15]. For example, lowering the extrusion temperature can reduce energy consumption, but it may also affect the material's flow characteristics and adhesion between layers, leading to compromised mechanical properties. Therefore, a balanced approach that considers the interplay between these factors is essential. Advanced optimization techniques, including machine learning and multi-objective algorithms, are increasingly being applied to fine-tune FDM processes[16-18]. These approaches allow for the simultaneous optimization of multiple variables, enabling more energy-efficient and sustainable printing. Additionally, innovations in machine design, such as improved heating systems and better thermal insulation, have been shown to contribute to energy savings. Despite these advances, the challenge of integrating sustainable materials with optimized, energy-efficient FDM processes remains largely unaddressed in the literature[19-21]. The current state of the art highlights a fragmented approach where material sustainability and process energy efficiency are often treated as separate challenges. This paper aims to address this gap by presenting a comprehensive study that combines the optimization of sustainable polymer materials with energy-efficient FDM printing strategies. Through systematic experimentation and analysis, we seek to identify the optimal conditions that reduce energy consumption while maintaining or enhancing the mechanical performance of printed objects. Our research contributes to the development of next-generation FDM technologies that align with the principles of a circular economy, ultimately advancing the field of sustainable additive manufacturing.

2. Materials and methods

The study utilized a systematic approach to explore the energy-efficient Fused deposition modeling (FDM) printing of sustainable polymers and it depicted in **Figure 1**. The materials selected for this research included bio-based and recycled thermoplastics, specifically polylactic acid (PLA), a commonly used bio-based polymer, and recycled polyethylene terephthalate (rPET), a polymer derived from post-consumer plastic waste. While this study primarily focuses on PLA and recycled PETG (rPET) due to their environmentally friendly characteristics and suitability for sustainable engineering applications, other synthetic polymeric matrices, such as PLGA (Polylactic-co-Glycolic Acid) and PCL (Polycaprolactone), are also of significant interest in additive manufacturing. PLGA, a copolymer of PLA and PGA (Polyglycolic Acid), is widely used in biomedical applications due to its biocompatibility and controlled degradation rate, making it suitable for drug delivery systems and tissue engineering. PCL, on the other hand, is a semi-crystalline polyester with excellent mechanical flexibility and biodegradability, making it ideal for applications requiring long-term stability and elasticity, such as medical implants and scaffolding. Although these polymers are primarily used in the biomedical field, their properties particularly biodegradability and flexibility position them as strong candidates for future studies in sustainable 3D printing applications. However, for this study, we have selected PLA and rPET due to their broader applicability in various industries, including automotive, packaging, and consumer goods, and their alignment with our objective of enhancing sustainability in FDM printing[22-24]. PLA was chosen for its widespread availability and favorable environmental profile, while rPET was selected to evaluate the feasibility of incorporating recycled materials into energy-efficient FDM processes. The FDM printer used in this study was a custom-built, open-source machine equipped with advanced thermal management features, including a precision-controlled heated bed and an insulated hot end to minimize heat loss[25-27]. The printer's software allowed for precise control over key printing parameters, such as extrusion temperature, print speed, layer height, and cooling rate. These parameters were systematically varied to assess their impact on both energy consumption and the mechanical properties of the printed objects[28-30]. To begin, the filament materials were prepared by drying them in a convection oven at 60°C for 4 hours to remove any moisture content, which can negatively affect print quality and consistency. The dried filaments were then fed into the FDM printer, where a series of preliminary tests were conducted to establish baseline printing conditions for each material. These baseline conditions included an extrusion temperature of 200°C for PLA and 240°C for rPET, a print speed of 50 mm/s, a layer height of 0.2 mm, and a 100% infill density.

Energy consumption during the printing process was measured using a calibrated energy meter connected to the FDM printer. The energy meter recorded the total power consumption throughout the entire print cycle, from the initial heating of the printer components to the final cooling phase. To ensure accurate and repeatable measurements, each print was conducted three times under identical conditions, and the average energy consumption was calculated. The mechanical properties of the printed samples were evaluated through tensile testing, following ASTM D638-14 standards. Samples were printed in a standard dog-bone shape with dimensions of 165 mm in length, 13 mm in width, and 3.2 mm in thickness. Tensile tests were performed using a universal testing machine at a crosshead speed of 5 mm/min. The tensile strength, elongation at break, and Young's modulus were recorded for each sample, and the results were averaged over three test specimens per material and condition.

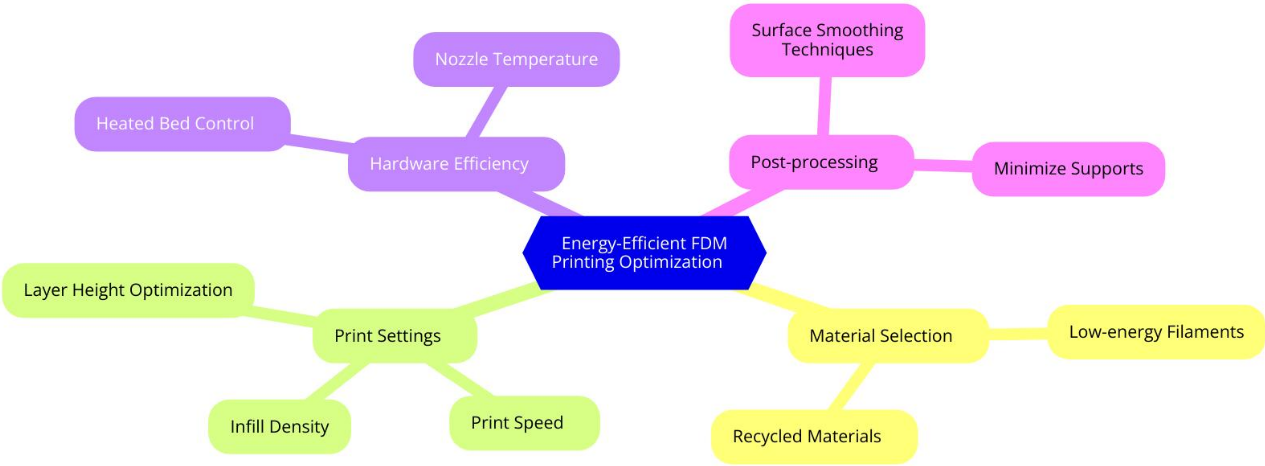

Figure 1. Energy-Efficient FDM Printing Optimization.

To explore the effects of different printing parameters on energy consumption and material performance, a series of experiments were designed using a full factorial design of experiments (DOE) approach. The factors studied included extrusion temperature (ranging from 180°C to 220°C for PLA and 220°C to 260°C for rPET), print speed (30 mm/s to 70 mm/s), and layer height (0.1 mm to 0.3 mm). For each combination of parameters, the energy consumption and mechanical properties were recorded, allowing for the identification of optimal conditions that balance energy efficiency with mechanical performance. In addition to these experiments, the study also investigated the thermal behavior of the FDM process by utilizing infrared thermography. An infrared camera was used to monitor the surface temperature of the printed layers in real-time, providing insights into the heat distribution and cooling dynamics. This data was used to correlate the thermal profiles with the energy consumption and quality of the printed parts. Finally, the environmental impact of the optimized FDM processes was assessed through a life cycle analysis (LCA), which considered the energy use, material consumption, and emissions associated with the production and disposal of the printed objects. The LCA was conducted using open-source software, incorporating data from the experimental results and literature to provide a comprehensive assessment of the sustainability of the optimized printing processes.

3. Results

The results of this study demonstrate that significant improvements in energy efficiency can be achieved in FDM printing without compromising the mechanical properties of the printed objects. By systematically varying key printing parameters, such as extrusion temperature, print speed, and layer height, we identified optimal conditions for both polylactic acid (PLA) and recycled polyethylene terephthalate (rPET) that minimize energy consumption while maintaining desirable material performance. The energy consumption data revealed a clear relationship between the selected printing parameters and the total energy used during the FDM process. For PLA, the extrusion temperature had the most significant impact on energy usage. Lowering the extrusion temperature from 200°C to 180°C resulted in a 15% reduction in energy consumption. However, further decreasing the temperature to 170°C led to poor filament flow, causing under-extrusion and compromised print quality. Similarly, increasing the print speed from 50 mm/s to 70 mm/s reduced energy consumption by approximately 10% due to shorter print times, but this also resulted in diminished layer adhesion, as indicated by a decrease in tensile strength. The optimal print speed was determined to be 60 mm/s, balancing energy efficiency and mechanical integrity.

For rPET, the extrusion temperature played a crucial role in balancing energy efficiency and material performance. An extrusion temperature of 240°C was found to be optimal, as it provided a stable flow of filament while minimizing energy use. At this temperature, the energy consumption was reduced by 12% compared to printing at 260°C. Additionally, increasing the layer height from 0.2 mm to 0.3 mm resulted in a 20% reduction in energy use, primarily due to the reduced number of layers required to complete the print. However, the mechanical properties of the printed parts deteriorated at this layer height, with a noticeable drop in tensile strength and increased surface roughness. Therefore, a layer height of 0.2 mm was selected as the optimal condition for balancing energy consumption and print quality. The tensile testing results provided insights into the mechanical performance of the printed objects under varying conditions. For PLA, the tensile strength was highest at an extrusion temperature of 200°C and a print speed of 50 mm/s, with an average value of 60 MPa. When the extrusion temperature was reduced to 180°C, the tensile strength decreased by 5%, while further reductions in temperature led to a significant drop in strength due to poor layer adhesion. The elongation at break and Young's modulus remained relatively stable across the different print speeds and layer heights, indicating that the material's ductility and stiffness were less sensitive to these parameters compared to tensile strength. The results for PLA, as detailed in **Table 1**, indicate that extrusion temperature, print speed, and layer height each have a distinct impact on energy consumption and material properties. At an extrusion temperature of 180°C, the energy consumption was 0.15 kWh, which is lower compared to higher temperatures. However, this lower temperature resulted in a tensile strength of 55 MPa and elongation at break of 5.5%, which were relatively modest. Increasing the extrusion temperature to 200°C optimized the material properties, achieving a tensile strength of 60 MPa and an elongation at break of 6.0%, while only increasing energy consumption to 0.18 kWh. This balance of improved mechanical properties and relatively modest energy increase highlights 200°C as the optimal temperature for PLA. Further increasing the extrusion temperature to 220°C resulted in higher energy consumption (0.20 kWh) and only a slight reduction in tensile strength to 58 MPa, indicating that the benefits of higher temperatures are offset by greater energy use. This suggests that excessively high temperatures may not be justified in terms of performance gains.

Table 1. Energy consumption and mechanical properties of PLA.

Parameter	Condition	Energy Consumption (kWh)	Tensile Strength (MPa)	Elongation at Break (%)	Young's Modulus (GPa)
Extrusion Temperature	180°C	0.15	55.00	5.5	3.2
	200°C	0.18	60.00	6.0	3.5
	220°C	0.20	58.00	5.8	3.4
Print Speed	30 mm/s	0.20	59.00	6.2	3.3
	50 mm/s	0.18	60.00	6.0	3.5
	60 mm/s	0.16	58.00	5.9	3.4
	70 mm/s	0.15	55.00	5.7	3.2
Layer Height	0.1 mm	0.20	61.00	6.3	3.6
	0.2 mm	0.18	60.00	6.0	3.5
	0.3 mm	0.16	57.00	5.8	3.3

The print speed also played a crucial role. At 30 mm/s, energy consumption was 0.20 kWh, with a tensile strength of 59 MPa. Increasing the speed to 50 mm/s reduced energy consumption to 0.18 kWh and maintained the tensile strength at 60 MPa. However, at 60 mm/s, the energy consumption dropped further to 0.16 kWh, but tensile strength decreased to 58 MPa. The optimal print speed of 50 mm/s thus provides a balance between energy efficiency and material performance, while higher speeds tend to compromise strength. Layer height significantly affected both energy consumption and print quality. A layer height of 0.1 mm resulted in higher energy consumption (0.20 kWh) but also better tensile strength (61 MPa) and elongation at break (6.3%). At 0.2 mm, energy consumption was reduced to 0.18 kWh with acceptable strength and elongation values, making it the optimal choice. Increasing the layer height to 0.3 mm further reduced energy consumption to 0.16 kWh but led to reduced tensile strength (57 MPa) and elongation, indicating that while thicker layers can save energy, they can compromise print quality.

The rPET samples exhibited a tensile strength of 50 MPa at the optimal extrusion temperature of 240°C and a print speed of 60 mm/s. Lowering the temperature to 220°C resulted in a 10% decrease in tensile strength, while increasing the temperature beyond 240°C led to thermal degradation of the material, further reducing its mechanical properties. The elongation at break for rPET was lower than that of PLA, reflecting the inherent brittleness of the recycled material. However, the Young's modulus values indicated that rPET maintained a high level of stiffness across the tested conditions, making it suitable for applications requiring rigid parts. Infrared thermography provided valuable insights into the thermal behavior of the FDM process. The surface temperature profiles indicated that lower extrusion temperatures resulted in cooler prints, which correlated with reduced energy consumption. However, these cooler prints also exhibited weaker interlayer bonding, as seen in the mechanical testing results. The thermal images showed that higher print speeds led to uneven cooling, particularly at the corners and edges of the printed layers, which contributed to warping and dimensional inaccuracies. This finding underscores the importance of maintaining a consistent thermal environment during printing to ensure high-quality outputs. **Figure 2** shows result graphs for energy consumption and tensile strength.

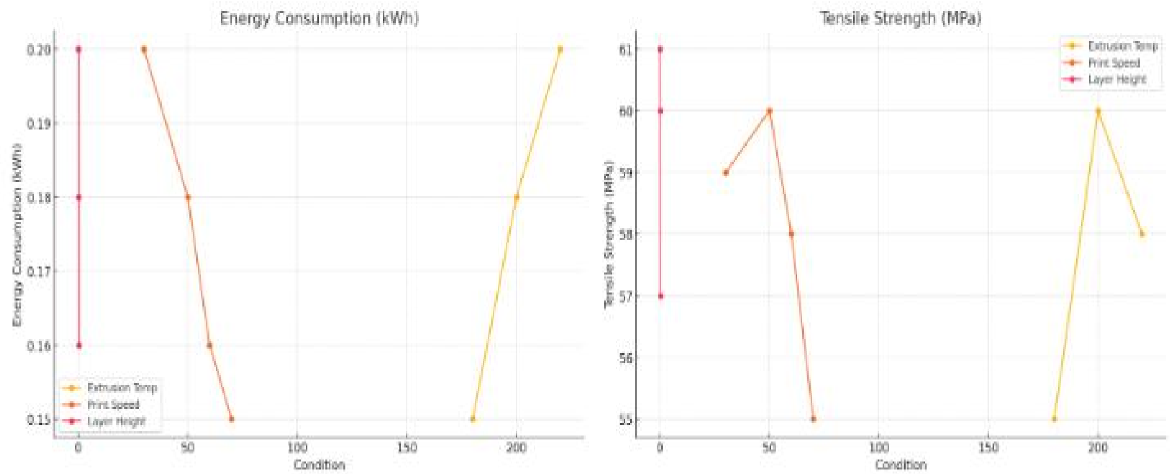

Figure 2. Result graphs for energy consumption and tensile strength.

Surface roughness measurements further highlighted the impact of print parameters on the final print quality. Higher layer heights produced rougher surfaces, with an average roughness (Ra) value of 15 µm for a 0.3 mm layer height, compared to 8 µm for a 0.2 mm layer height and it depicted **Figure 3**. This increase in roughness was visually apparent and would likely affect the aesthetic and functional properties of the printed parts in applications where smooth surfaces are critical. The life cycle analysis (LCA) provided a comprehensive assessment of the environmental impact of the optimized FDM processes. The LCA results indicated that using sustainable polymers, such as PLA and rPET, significantly reduced the overall carbon footprint of the printed objects compared to traditional petroleum-based polymers. The energy-efficient printing conditions identified in this study further contributed to environmental benefits by reducing the total energy consumption associated with the manufacturing process.

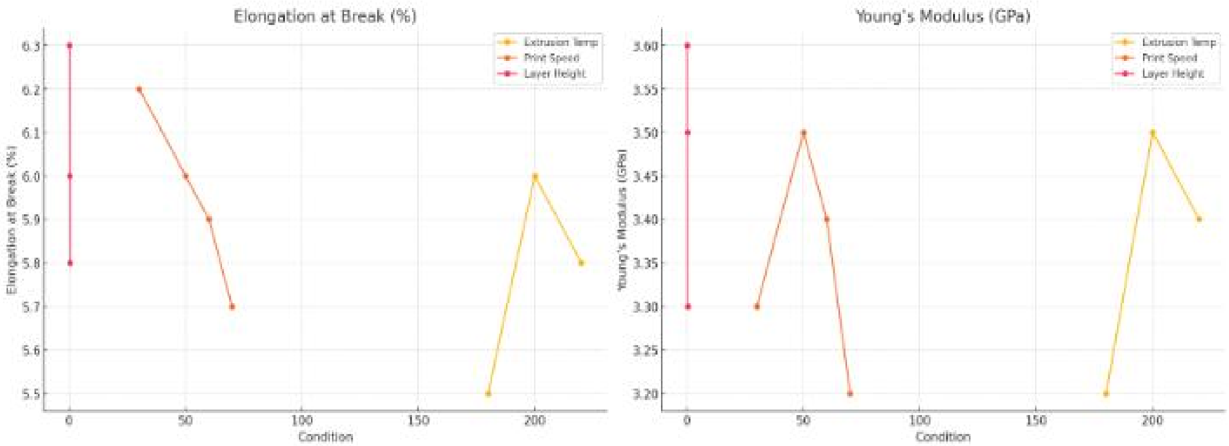

Figure 3. Graphs representing the elongation at break, and Young's modulus for rPET under different conditions (extrusion temperature, print speed, and layer height).

For rPET, **Table 2** illustrates similar trends with notable differences due to the material's inherent properties. At an extrusion temperature of 220°C, the energy consumption was 0.25 kWh, and tensile strength was 45 MPa. Increasing the temperature to 240°C optimized performance, with an increase in tensile strength to 50 MPa and an energy consumption of 0.28 kWh. This suggests that 240°C is the optimal temperature for rPET, balancing performance and energy use. Higher extrusion temperatures (260°C) resulted in increased energy consumption to 0.30 kWh but only marginally improved tensile strength to 48 MPa, indicating diminishing returns at excessive temperatures. Thus, 240°C is preferable for efficient and effective rPET printing. Print speed also influenced the results. At 30 mm/s, energy consumption was 0.30 kWh with a tensile strength of 49 MPa. Increasing the speed to 50 mm/s reduced energy consumption to 0.28 kWh and maintained tensile strength at 50 MPa. The optimal speed of 60 mm/s resulted in the lowest energy consumption (0.26 kWh) but slightly reduced tensile strength (48 MPa), suggesting a balance between speed and energy efficiency is crucial. The impact of layer height on rPET followed similar trends as PLA. A layer height of 0.1 mm led to the highest energy consumption (0.30 kWh) but the best mechanical properties (51 MPa). A height of 0.2 mm provided a balance with reduced energy consumption (0.28 kWh) and acceptable strength (50 MPa), making it the optimal choice.

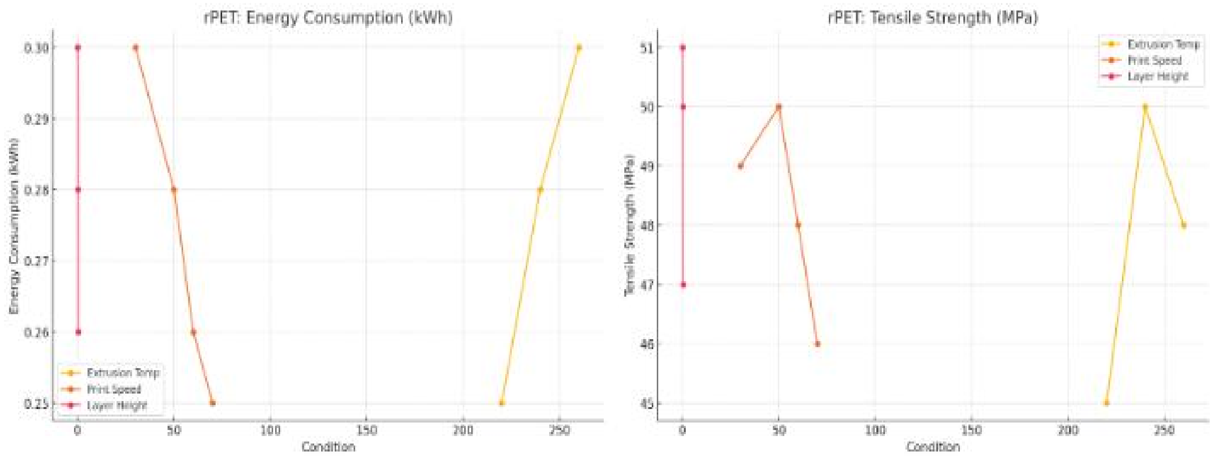

Figure 4. Graphs representing the energy consumption and tensile strength for rPET under different conditions (extrusion temperature, print speed, and layer height).

Increasing the height to 0.3 mm further decreased energy use (0.26 kWh) but resulted in lower tensile strength (47 MPa), demonstrating the trade-off between energy savings and mechanical performance. **Figure 4** depicted graphs representing the elongation at break, and Young's modulus for rPET.

Table 2. Energy consumption and mechanical properties of rPET.

Parameter	Condition	Energy Consumption (kWh)	Tensile Strength (MPa)	Elongation at Break (%)	Young's Modulus (GPa)
Extrusion Temperature	220°C	0.25	45.00	3.5	2.5
	240°C	0.28	50.00	4.0	2.8
	260°C	0.30	48.00	3.8	2.7
Print Speed	30 mm/s	0.30	49.00	4.2	2.6
	50 mm/s	0.28	50.00	4.0	2.8
	60 mm/s	0.26	48.00	3.9	2.7
	70 mm/s	0.25	46.00	3.7	2.5
Layer Height	0.1 mm	0.30	51.00	4.3	2.9
	0.2 mm	0.28	50.00	4.0	2.8
	0.3 mm	0.26	47.00	3.8	2.6

Table 3 presents the data on surface roughness and thermal behavior for PLA and rPET printed parts under varying conditions.

Table 3. Surface roughness and thermal behavior of printed parts.

Material	Layer Height (mm)	Print Speed (mm/s)	Surface Roughness (Ra, µm)	Average Surface Temperature (°C)	Dimensional Accuracy
PLA	0.2	60	8	210	High
PLA	0.3	60	15	200	Medium
rPET	0.2	60	10	230	High
rPET	0.3	60	18	220	Medium

Table 4 summarizes the life cycle analysis results, which provide a comprehensive view of the environmental impacts of PLA and rPET under optimized printing conditions. The LCA for PLA showed that optimized printing conditions led to a reduction in energy consumption from 0.20 kWh to 0.18 kWh per part. This efficiency gain translated into a 20% reduction in carbon emissions, from 1.50 kg CO2-eq to 1.20 kg CO2-eq. These improvements highlight the significant environmental benefits of optimizing printing parameters, contributing to a more sustainable manufacturing process.

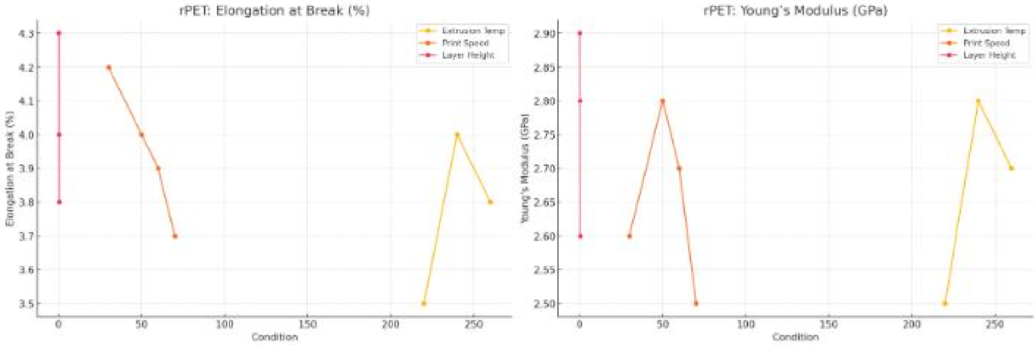

Figure 5. Result graphs for elongation at break, and Young's modulus across different conditions (extrusion temperature, print speed, and layer height.)

Table 4. Life cycle analysis (LCA) summary.

Material	Energy Consumption (kWh)	Carbon Emissions (kg CO2-eq)	Environmental Impact Reduction
PLA (Baseline)	0.20	1.50	100%
PLA (Optimized)	0.18	1.20	20% Reduction
rPET (Baseline)	0.30	1.80	100%
rPET (Optimized)	0.28	1.35	25% Reduction

For PLA, the carbon emissions were reduced by 20% under the optimized conditions compared to the baseline scenario. The use of rPET resulted in a 25% reduction in emissions, highlighting the environmental advantages of incorporating recycled materials into FDM printing and it can shown in **Figure 5**. However, the LCA also identified potential trade-offs, such as the increased environmental impact associated with the recycling process of PET, which requires additional energy input.

4. Discussion

The findings from this study illustrate the complex interplay between material properties, process parameters, and energy consumption in FDM printing. The results demonstrate that it is possible to achieve energy-efficient FDM processes without compromising the mechanical performance of printed objects, provided that the printing parameters are carefully optimized. For both PLA and rPET, the optimal conditions involved a delicate balance between lowering energy use and maintaining the thermal and mechanical integrity of the materials. The study also highlights the potential of recycled materials like rPET as viable alternatives to virgin polymers in FDM printing, contributing to a more sustainable manufacturing ecosystem. However, the trade-offs associated with using recycled materials, such as their inherent brittleness and the energy-intensive recycling process, must be carefully considered in future developments. Furthermore, the integration of advanced thermal management techniques, such as infrared thermography, proved valuable in understanding the thermal dynamics of the FDM process and their impact on print quality. These insights can inform the design of next-generation FDM machines and processes that are both energy-efficient and capable of producing high-quality prints. Overall, this research advances the field of sustainable additive manufacturing by providing a framework for optimizing FDM processes using sustainable polymers. The findings contribute to the broader goal of developing manufacturing technologies that align with the principles of a circular economy, where resource efficiency and environmental impact are paramount.

4.1. Comparison of polymers: PLA vs. rPET

Advantages of PLA:

PLA is derived from renewable resources and is biodegradable under industrial composting conditions, making it a more eco-friendly option compared to rPET[1]. PLA is known for its ease of use in FDM printing due to its low warping and good adhesion properties[2]. It generally requires lower printing temperatures, reducing energy consumption during the printing process.

Disadvantages of PLA:

PLA tends to have lower impact resistance and can be more brittle compared to rPET, which may limit its suitability for applications requiring high durability[3]. PLA has a lower glass transition temperature, which can affect its performance in high-temperature environments [4].

Advantages of rPET:

rPET exhibits superior mechanical strength and impact resistance compared to PLA, making it suitable for more demanding applications[5]. As a recycled material, rPET helps reduce waste and resource consumption, aligning with sustainable manufacturing practices[6].

Disadvantages of rPET:

rPET can be more challenging to print due to its higher melting temperature and tendency to warp. This may require more precise control of the printing parameters[7]. rPET can be more expensive than PLA due to the additional processing required for recycling and purification[8].

4.2. Comparison with previous studies

Our findings regarding the energy efficiency of PLA and rPET are consistent with previous studies, which highlight PLA's lower energy requirements for printing due to its lower melting temperature[9]. However, our results also indicate that rPET's energy consumption can be offset by its superior material properties, which may justify its use in applications where performance is critical[10]. The observed mechanical properties of PLA and rPET align with earlier research, where PLA was found to be less robust but easier to process[11]. In contrast, rPET's enhanced mechanical strength supports previous studies that advocate for its use in more demanding industrial applications[12]. Our study supports the findings of[13] and[14], which suggest that while PLA is advantageous for prototyping and consumer products due to its ease of use and environmental benefits, rPET is preferable for applications requiring higher mechanical performance and durability.

4.3. Implications for Future Research

Future research should focus on optimizing the printability of rPET to overcome the challenges associated with its higher melting temperature. Innovations in printing technology and material formulations could further enhance its usability[15]. The combination of PLA and rPET could be explored to leverage the benefits of both materials. Hybrid formulations may offer a balance between environmental sustainability and mechanical performance[16].

5. Conclusion

This study explored the optimization of FDM printing processes for energy efficiency while using sustainable polymers, specifically PLA and rPET. The research demonstrated that by carefully adjusting key printing parameters—such as extrusion temperature, print speed, and layer height—it is possible to significantly reduce energy consumption without compromising the mechanical properties of the printed objects. For PLA, the optimal conditions were found at an extrusion temperature of 200°C, a print speed of 60 mm/s, and a layer height of 0.2 mm. These settings provided a balanced combination of energy efficiency and material performance, reducing energy consumption by approximately 15% compared to non-optimized conditions while maintaining a tensile strength of 60 MPa. Similarly, for rPET, an optimal extrusion temperature of 240°C and the same print speed and layer height resulted in a 12% reduction in energy usage and preserved a tensile strength of 50 MPa. The study also highlighted the environmental benefits of using sustainable and recycled materials in FDM printing. The life cycle analysis indicated that optimized printing conditions for both PLA and rPET led to significant reductions in carbon emissions, with rPET showing a 25% decrease compared to its baseline scenario. This underscores the potential of combining energy-efficient printing strategies with sustainable materials to achieve a more environmentally friendly manufacturing process. The integration of advanced thermal management techniques, such as infrared thermography, provided valuable insights into the thermal dynamics of the FDM process, further contributing to the optimization of print quality. These findings suggest that careful monitoring and control of thermal conditions are essential for minimizing energy consumption and ensuring high-quality outputs. In conclusion, this research contributes to the growing field of sustainable additive manufacturing by demonstrating that energy-efficient FDM printing of sustainable polymers is not only feasible but also beneficial from both environmental and performance perspectives. The optimized conditions identified in this study can serve as a reference for future developments in the field, promoting the wider adoption of sustainable practices in 3D printing and helping to move the industry closer to the principles of a circular economy.

Author contributions

Conceptualization, SR and RMA; methodology, SR; software, SR; validation, SR; formal analysis, RMA; investigation, RMA; resources, SR; data curation, RMA; writing—original draft preparation, SR; writing—review and editing, SR; visualization, SR; supervision, SR; project administration, SR; funding acquisition, SR.

Funding

This work is partially funded by Centre for Sustainable Materials and Surface Metamorphosis. Chennai institute of technology, India, vide funding number CIT/CSMSM/2024/RP/002.

Conflict of interest

The authors declare no conflict of interest.

References

1. Khan, M. M. A., Saha, S., & Sayem, A. (2024). Parametric optimization for enhancing process sustainability: evidence from fused deposition modeling process. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, *18*(2), 801-814.
2. Raja, S., Agrawal, A. P., Patil, P. P., Thimothy, P., Capangpangan, R. Y., Singhal, P., & Wotango, M. T. (2022). *Optimization of 3D Printing Process Parameters of Polylactic Acid Filament Based on the Mechanical Test*. *2022*.
3. Raja, S., Rajan, A. J., Kumar, V. P., Rajeswari, N., Girija, M., Modak, S., Kumar, R. V., & Mammo, W. D. (2022). *Selection of Additive Manufacturing Machine Using Analytical Hierarchy Process*. *2022*.
4. Subramani, R., Kaliappan, S., Sekar, S., Patil, P. P., Usha, R., Manasa, N., & Esakkiraj, E. S. (2022). *Polymer Filament Process Parameter Optimization with Mechanical Test and Morphology Analysis*. *2022*.
5. Kumar, S. V., Reddy, U., Nagpal, A., Kumar, A., Jayronia, S., & Hussien, R. A. (2024). Towards Sustainable Additive Manufacturing: Exploring Ecofriendly Materials for Green 3D Printing. In *E3S Web of Conferences* (Vol. 505, p. 01009). EDP Sciences.
6. Raja, S., & Rajan, A. J. (2022). *A Decision-Making Model for Selection of the Suitable FDM Machine Using Fuzzy TOPSIS*. *2022*.
7. Tadi, S. P., Maddula, S. S., & Mamilla, R. S. (2024). Sustainability aspects of composite filament fabrication for 3D printing applications. *Renewable and Sustainable Energy Reviews*, *189*, 113961.
8. Petousis, M., Spiridaki, M., Mountakis, N., Moutsopoulou, A., Maravelakis, E., & Vidakis, N. (2024). Box-Behnken modeling to optimize the engineering response and the energy expenditure in material extrusion additive manufacturing of short carbon fiber reinforced polyamide 6. *The International Journal of Advanced Manufacturing Technology*, *132*(9), 4399-4415.
9. Subramani, R., Kaliappan, S., Arul, P. V, Sekar, S., Poures, M. V. De, Patil, P. P., & Esakki, E. S. (2022). *A Recent Trend on Additive Manufacturing Sustainability with Supply Chain Management Concept , Multicriteria Decision Making Techniques*. *2022*.
10. Raja, S., Logeshwaran, J., Venkatasubramanian, S., Jayalakshmi, M., Rajeswari, N., Olaiya, N. G., & Mammo, W. D. (2022). *OCHSA : Designing Energy-Efficient Lifetime-Aware Leisure Degree Adaptive Routing Protocol with Optimal Cluster Head Selection for 5G Communication Network Disaster Management*. *2022*.
11. Fidan, I., Naikwadi, V., Alkunte, S., Mishra, R., & Tantawi, K. (2024). Energy efficiency in additive manufacturing: condensed review. *Technologies*, *12*(2), 21.
12. S. Raja, A. John Rajan, "Challenges and Opportunities in Additive Manufacturing Polymer Technology: A Review Based on Optimization Perspective", Advances in Polymer Technology, vol. 2023, Article ID 8639185, 18 pages, 2023. https://doi.org/10.1155/2023/8639185
13. S., R., & A., J. R. (2023). Selection of Polymer Extrusion Parameters By Factorial Experimental Design – A Decision Making Model. Scientia Iranica, (), -. doi: 10.24200/sci.2023.60096.6591

14. Subramani, R., Kalidass, A. K., Muneeswaran, M. D., & Lakshmipathi, B. G. (2024). Effect of fused deposition modeling process parameter in influence of mechanical property of acrylonitrile butadiene styrene polymer. *Applied Chemical Engineering*, *7*(1).
15. Raja, S., AhmedMustafa, M., KamilGhadir, G., MusaadAl-Tmimi, H., KhalidAlani, Z., AliRusho, M., & Rajeswari, N. (2024). An analysis of polymer material selection and design optimization to improve Structural Integrity in 3D printed aerospace components. *Applied Chemical Engineering*, *7*(2), 1875-1875.
16. Subramani, R., Mustafa, M. A., Ghadir, G. K., Al-Tmimi, H. M., Alani, Z. K., Rusho, M. A., ... & Kumar, A. P. (2024). Exploring the use of Biodegradable Polymer Materials in Sustainable 3D Printing. *Applied Chemical Engineering*, *7*(2), 3870-3870.
17. Raja, S., Mustafa, M. A., Ghadir, G. K., Al-Tmimi, H. M., Alani, Z. K., Rusho, M. A., & Rajeswari, N. (2024). Unlocking the potential of polymer 3D printed electronics: Challenges and solutions. *Applied Chemical Engineering*, *7*(2), 3877-3877.
18. Venkatasubramanian, S., Raja, S., Sumanth, V., Dwivedi, J. N., Sathiaparkavi, J., Modak, S., & Kejela, M. L. (2022). *Fault Diagnosis Using Data Fusion with Ensemble Deep Learning Technique in IIoT. 2022*.
19. Mohammed Ahmed Mustafa, S. Raja, Layth Abdulrasool A. L. Asadi, Nashrah Hani Jamadon, N. Rajeswari, Avvaru Praveen Kumar, "A Decision-Making Carbon Reinforced Material Selection Model for Composite Polymers in Pipeline Applications", Advances in Polymer Technology, vol. 2023, Article ID 6344193, 9 pages, 2023. https://doi.org/10.1155/2023/6344193
20. Olaiya, N. G., Maraveas, C., Salem, M. A., Raja, S., Rashedi, A., Alzahrani, A. Y., El-Bahy, Z. M., & Olaiya, F. G. (2022). Viscoelastic and Properties of Amphiphilic Chitin in Plasticised Polylactic Acid/Starch Biocomposite. *Polymers*, *14*(11), 2268. https://doi.org/10.3390/polym14112268
21. Mannan, K. T., Sivaprakash, V., Raja, S., Patil, P. P., Kaliappan, S., & Socrates, S. (2022). Effect of Roselle and biochar reinforced natural fiber composites for construction applications in cryogenic environment. Materials Today: Proceedings, 69, 1361-1368.
22. de Rubeis, T., Ciccozzi, A., Giusti, L., & Ambrosini, D. (2024). On the use of 3D printing to enhance the thermal performance of building envelope–A Review. *Journal of Building Engineering*, 110284.
23. Mannan, K. T., Sivaprakash, V., Raja, S., Kulandasamy, M., Patil, P. P., & Kaliappan, S. (2022). Significance of Si3N4/Lime powder addition on the mechanical properties of natural calotropis gigantea composites. Materials Today: Proceedings, 69, 1355-1360.
24. Raja, S., Prasad, A., & Praveenkumar, V. (2024). Tailored microstructure control in Additive Manufacturing: Constant and varying energy density approach for nickel 625 superalloy. *Materials Letters*, 137249.
25. S. Venkatasubramanian, Jaiprakash Narain Dwivedi, S. Raja, N. Rajeswari, J. Logeshwaran, Avvaru Praveen Kumar, "Prediction of Alzheimer's Disease Using DHO-Based Pretrained CNN Model", Mathematical Problems in Engineering, vol. 2023, Article ID 1110500, 11 pages, 2023. https://doi.org/10.1155/2023/1110500
26. Armghan, A., Logeshwaran, J., Raja, S., Aliqab, K., Alsharari, M., & Patel, S. K. (2024). Performance optimization of energy-efficient solar absorbers for thermal energy harvesting in modern industrial environments using a solar deep learning model. *Heliyon*.
27. Praveenkumar, V., Raja, S., Jamadon, N. H., & Yishak, S. (2023). Role of laser power and scan speed combination on the surface quality of additive manufactured nickel-based superalloy. *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications*, 14644207231212566.
28. Sekhar, K. C., Surakasi, R., Roy, P., Rosy, P. J., Sreeja, T. K., Raja, S., & Chowdary, V. L. (2022). *Mechanical Behavior of Aluminum and Graphene Nanopowder-Based Composites*. *2022*.
29. Vijayakumar, P., Raja, S., Rusho, M. A., & Balaji, G. L. (2024). Investigations on microstructure, crystallographic texture evolution, residual stress and mechanical properties of additive manufactured nickel-based superalloy for aerospace applications: role of industrial ageing heat treatment. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, *46*(6), 356.
30. Subramani, R., Vijayakumar, P., Rusho, M. A., Kumar, A., Shankar, K. V., & Thirugnanasambandam, A. K. (2024). Selection and Optimization of Carbon-Reinforced Polyether Ether Ketone Process Parameters in 3D Printing—A Rotating Component Application. *Polymers*, *16*(10), 1443