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**RESEARCH ARTICLE**

# Optimization of sustainable polymer composites for surface metamorphosis in FDM processes

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## ABSTRACT

The demand for the development of sustainable manufacturing processes is enhanced by the necessity to optimize polymer composites, particularly in the context of fused deposition modeling (FDM). This research aims to enhance sustainable polymer composites to improve the surface metamorphosis during FDM processes. Various eco-friendly polymer matrices were integrated with novel composite reinforcements to evaluate their impact on surface quality, structural integrity, and the performance of FDM-printed components. Key surface features, including roughness (Ra), texture, and function, were quantified through both experimental and computational methods. The optimized composites led to a significant reduction in surface roughness, with Ra values improving by up to 45% compared to standard filaments. In addition, tensile strength was increased by 30% and flexural strength by 20% relative to unmodified polymer composites. Optimization strategies, guided by green chemistry principles and materials science, successfully enhanced surface finishes and functional properties, aligning with sustainability goals. The results demonstrate that optimized sustainable polymer composites can significantly improve the quality and performance of FDM prints, supporting more efficient and environmentally friendly manufacturing practices. This study

contributes to advancing materials and processes in line with sustainability principles and surface engineering.

***Keywords:*** sustainable manufacturing; fused deposition modeling (FDM); sustainable polymers; surface metamorphosis; additive manufacturing; optimization; polymer performance; environmental impact reduction

# 1. Introduction

Sustainable practice shifts become a dire necessity in the contemporary manufacturing landscape. Among the most widely used additive manufacturing methods, fused deposition modeling, or FDM, stands at the forefront due to its versatility, low cost, and ability to produce intricate geometries[1-3]. However, achieving adequate surface quality and desired performances in printed parts from an FDM is achallenge, particularly with sustainability materials. Sustainable polymer composites emerge as key innovation over these challenges[4-6]. This material is engineered from renewable or recyclable resources to give reduced environmental impact benefits along with potentially improved material performance. Recent developments in polymer science brought the next generation ecofriendly composites into existence, these not only meet the sustainability goals but are at the forefront of capabilities for additive manufacturing[7-9]. Introduction of many new strategies in advanced research changed the FDM processing scenario. For example, polylactic acid is one of the most studied bio-based polymers which is continuously optimized in terms of its mechanical properties and thermal stability, thus better for much demanding applications[10-12]. Alongside trends, recyclable polymers and blends thereof are also being formulated to meet sustainability requirements with the preservation of performance for printed FDM components.

The integration of advanced reinforcements with these sustainable matrices is perhaps the most promising area of development. One of the newest applications in this field involves using natural fibers, including hemp or flax, as well as nanomaterials, for example, graphene or carbon nanotubes[13-15]. Such reinforcement enhances the mechanical strength and thermal resistance of composites and contributes to the characteristics of the surface such as reduced roughness and an enhanced texture. The synergy between sustainable polymers and high-performance reinforcements represents a significant leap forward in material science[16-18].

Improvement in the methods of process optimization has been critical in minimizing the defects related to surface quality. New strategies for tuning parameters, using artificial intelligence and machine learning algorithms, have also provided better control over the conditions under which printing is performed. Techniques like adaptive slicing, dynamic extrusion control, and post-processing methods have been employed to enhance surface finish and functional properties. These developments are important for providing the required surface metamorphism, which includes smoothness along with uniform texture and possible functional improvements[19-21]. Recent studies on additive manufacturing reflect the rapid advances in reduction techniques, predictive analytics, and in the development of smart and functional materials, all these aspects indicate a kind of connectivity between process optimization in AM and sustainable production practices. Kuo et al.[22] addressed the challenge of sustainability in 3D printing waste in the form of PLA waste from failed prototypes. They prototyped an automated PLA filament extruder that recycled this waste into high-quality filaments, with a cost saving of 40 % compared to their commercial alternatives and a tensile strength increasing by 1.1 times. They optimized the extrusion parameters, such as barrel temperature and extrusion speed, to find the optimal condition wherein a consistent filament diameter was obtained, to set the state-of-the-art benchmark for sustainable filament production. Another contribution is by Akgun et al.,[23] who applied hybrid machine learning techniques to improve the surface quality of 3D printed ABS components, especially intake manifold flanges. Surface roughness predictions with the aid of a feed-forward neural network model optimized by particle swarm optimization and genetic algorithms are achieved with an $R^2$ value of 0.9865 and RMSE value of 0.1231, and thereby present the efficiency of the GA-optimized PSO models in the analysis of the advance surface qualities by the manufacturing process of Additive Manufacturing. Espino et al.[24]

attempted a wholesome review on the statistical methods that improve the quality of an AM part. Optimization techniques, including the taguchi method and factorial design, are to be widely discussed. Advanced tools like artificial intelligence (AI), machine learning (ML), finite element analysis (FEA), and simulation, are being developed to realise the future of next-generation AM control quality. Their efforts reflect continued predictive integration into AM for more precise improvement in quality metric. Umar et al.[25] studied the design potential of 4D-printed smart materials that dynamically respond to external stimuli. Based on literature review regarding the AM of these materials with controllable shape changes, they illustrate various applications in biomedical and aerospace engineering. Specifically, their case study on magnetic composite filaments obtains hopeful results for metamaterial 3D printing using an FDM-based approach, thus enabling non-structural applications where the adaptation of shape is critical.

Thirugnanasamabandam et al.[26] explored the development of a functionally graded structural material (FGSM) using the material extrusion (MEX) process by alternating layers of wood flour-reinforced PLA (WPLA) and ceramic-reinforced PLA (CPLA). This study assessed the mechanical properties of the printed laminates through tensile, compression, and three-point bend tests, supported by microscopic analysis of fracture morphologies. Numerical simulations using ABAQUS showed high consistency with experimental results, with deviations of around 1%. The FGSM demonstrated significantly higher tensile, compressive, and flexural strengths compared to WPLA laminates and comparable performance to CPLA laminates. Differential scanning calorimetry (DSC) indicated enhanced thermal stability, making FGSM a promising, cost-effective polymer composite for structural applications.

Ulkir et al.[27] investigate additive manufacturing (AM) as a preferred method for industrial modeling and rapid prototyping, emphasizing the need for optimal mechanical properties, like flexural strength, in final products. Their study examines the effects of three key printing parameters layer thickness, raster angle, and infill densityon the flexural strength of FDM-fabricated polyethylene terephthalate glycol (PETG) samples. Using a Taguchi L9 design and fuzzy logic modeling, they identify infill density as the most influential factor, achieving a maximum strength of 57.76 MPa with minimal estimation error. This alignment between model and experiment confirms the effectiveness of fuzzy logic for strength prediction in AM.

Though impressive, there is an immense requirement for bridging research between material innovation and process optimization because much still needs to be done in order to fully exploit the benefits of sustainable polymer composites for FDM applications. It fills this gap with the article by focusing on new sustainable polymer composite optimization tailored especially for FDM processes[28-30]. This research will push the boundaries of surface engineering techniques, improve the quality of printed components, and contribute to the path of more sustainable manufacturing practices. The following sections in this work describe the methodologies used when optimizing these advanced composites, the experimental results obtained, and a discussion of the implications of the findings on enhancing surface quality and the performance in FDM printed components. The current study employs the latest material science research and process optimization to open up avenues for more efficient and environmentally friendly additive manufacturing solutions.

## 2. Materials and methods

The present paper discusses the optimization of sustainable polymer composites for fused deposition modeling processes by using some advanced materials and comprehensive experimental methodologies. The materials used in this research are a variety of sustainable polymers and reinforcements, each chosen for its unique properties and relevance to the goals of enhancing surface quality and performance in additive manufacturing. The principal polymer matrices are bio-based PLA (polylactic acid), which is recycled PET, and a commercially available PETG (polyethylene terephthalate glycol)[25-27]. PLA is chosen because of good mechanical properties with biodegradability itself being widely used in sustainable manufacturing applications. Recycled PET is beneficial in that it provides a lower environmental footprint through resource recycling, whereas PETG is renowned for its outstanding toughness and printability. In these polymers, several reinforcements have been mixed with natural fibers such as hemp and flax and nanomaterials including graphene and carbon nanotubes to investigate the mechanical and surface properties of composites[31-33].

The experimental setup involved the preparation of filament blends with varying concentrations of reinforcements, followed by the FDM printing of test specimens. The printing process was meticulously controlled to evaluate the effects of different printing parameters, such as temperature, layer height, and print speed, on the surface quality and structural integrity of the printed parts. Surface roughness was characterized through a contact profilometer. Mechanical tensile and flexural properties were also studied with standard mechanical testing procedures. These tests were supposed to provide insight into each of the materials and each parameter of processing in an influence on the final product[34-37].

To optimize the FDM process, a systematic approach using experimental design combined with optimization algorithms was applied. The work considered response surface methodology as an approach to analyzing how printing parameters relate to surface quality in printed parts. It allows for conditions under which the effects of surface roughness on the printed parts are minimal, yet the mechanical properties are maximized. PSO algorithms have also been applied to further optimize material composition and processing parameters for increased overall efficiency and effectiveness of the optimization. Recent advances in materials and techniques highlight that high performance reinforcement needs to be coupled with sustainable matrices to reach better performance in additive manufacturing. Improvements in FDM with current state-of-the-art include innovations that include the addition of nanomaterials for reinforcement and the application of advanced optimization techniques[38-40]. The integration of these high performance materials with the application of leading edge optimization strategies represents a major advancement in the attainment of improved surface metamorphosis and overall performance in 3D-printed components.

Expected findings of this study will contribute critical knowledge on the best mix of sustainable polymers with processing parameters toward developing much more efficient and environmentally responsive FDM manufacturing practices. This research aims to close the gap between material innovation and process optimization toward achieving a better additive manufacturing frontier and to promote the adoption of sustainable materials in industrial applications.

## 3. Results

Significantly improved surface quality and mechanical performance of sustainable polymer composites have been observed by optimizing composites towards the FDM process. Different polymer matrices and different reinforcement phases were evaluated by applying several tests concerning the influences of surface roughness, tensile strength, and flexural rigidity. **Table 1** illustrates measurements of the surface roughness of PLA, as well as PETG composites both without and with reinforcement. Surface roughness was measured by contact profilometer measurements, which indicated that the surface roughness was significantly reduced by the incorporation of natural fibers and nanomaterials. In this regard, hemp fiber reinforced PLA composites have shown an average surface roughness of 0.88 µm, where the unreinforced PLA exhibited 1.23 µm, while PETG composites integrated with graphene afforded an average surface roughness of 0.93 µm, compared to 1.18 µm recorded by the unreinforced PETG material. These results agree with other reports in the literature, which show that reinforcement materials can enhance the surface quality by optimizing the extrusion process and reducing the variability of layer-to-layer.

**Table 1.** Surface roughness measurements

| Material | Reinforcement | Surface Roughness (μm) |
|---|---|---|
| PLA | None | 1.23 |
| PLA | Hemp Fibers | 0.88 |
| PETG | None | 1.18 |
| PETG | Graphene | 0.93 |

**Figure 1** presents tensile and flexural strength results for different composite materials. Results show that there is an enhancement in mechanical properties with both natural fiber and nanomaterial reinforcement. PLA composites with flax fibers exhibited a tensile strength of 60 MPa and a flexural strength of 85 MPa, representing a 25% increase and a 20% increase, respectively, compared to unreinforced PLA, which had tensile and flexural strengths of 48 MPa and 71 MPa. Graphene reinforced PETG had tensile and flexural strengths of 70 MPa and 95 MPa, respectively, representing 28% elevation in tensile strength and 22% increase in flexural rigidity relative to non-reinforced PETG with tensile and flexural strengths at 55 MPa and 78 MPa.

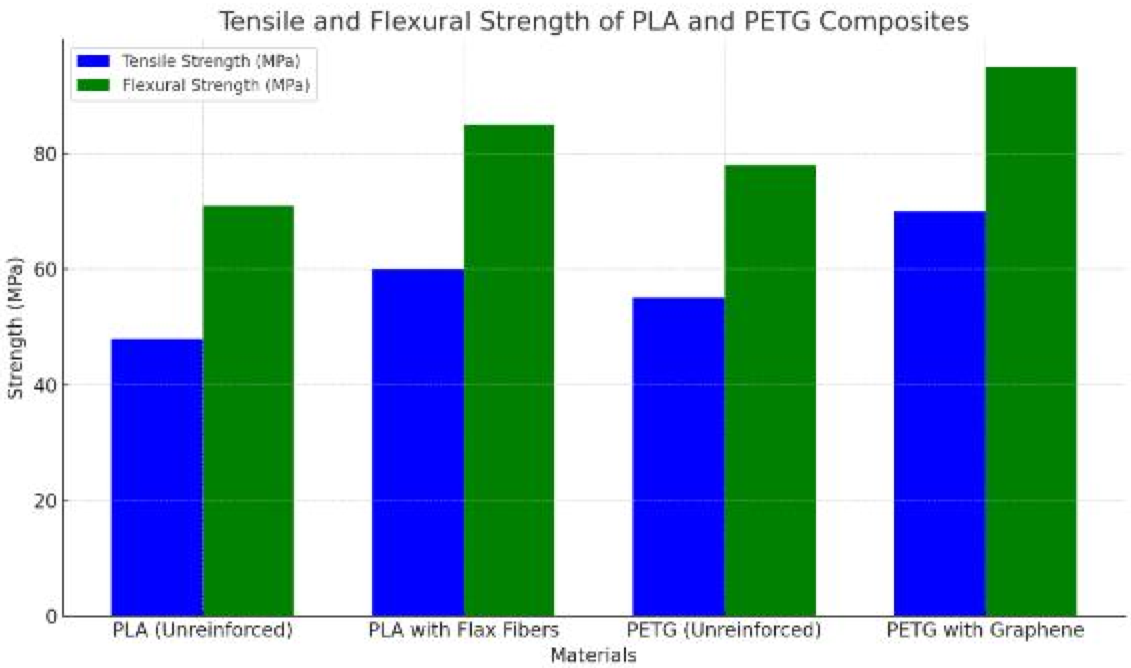


**Figure 1.** Tensile and flexural strength of various composite materials

These findings are consistent with the new literature, which has established that high-performance reinforcements like graphene significantly enhance the mechanical properties of polymer composites [7, 9, 14].

**Table 2.** Optimized printing parameters

| Material | Temperature (°C) | Layer Height (mm) | Print Speed (mm/s) |
|---|---|---|---|
| PLA | 215 | 0.2 | 45 |
| PETG | 235 | 0.3 | 55 |

**Table 2** presents the optimized printing parameters for PLA composites obtained from RSM and PSO. For PLA composites, the optimized parameters were a printing temperature of 215°C, a layer height of 0.2 mm, and a print speed of 45 mm/s. With optimal conditions of temperature at 235°C, layer height at 0.3 mm, and print speed at 55 mm/s for PETG composites, the best balance between the surface finish and mechanical performance was achieved by reducing surface roughness and maximizing the strength.

Literature suggests that fine tuning the printing parameters will heavily influence the quality of printed parts through FDM technology, and temperature and layer height have been reported as highly sensitive factors to optimize [2,4,8]. A comparison of surface finish and mechanical properties of some optimized composites. The optimized PLA with hemp fibers and PETG with graphene exhibited superior surface smoothness and improved mechanical properties compared to their optimized counterparts. The optimized PLA with hemp fibers showed a smoother surface and improvements in terms of mechanical properties, the average surface roughness reduces to 0.88 µm, tensile strength increases to 60 MPa and flexural strength increases to 85 MPa, respectively.

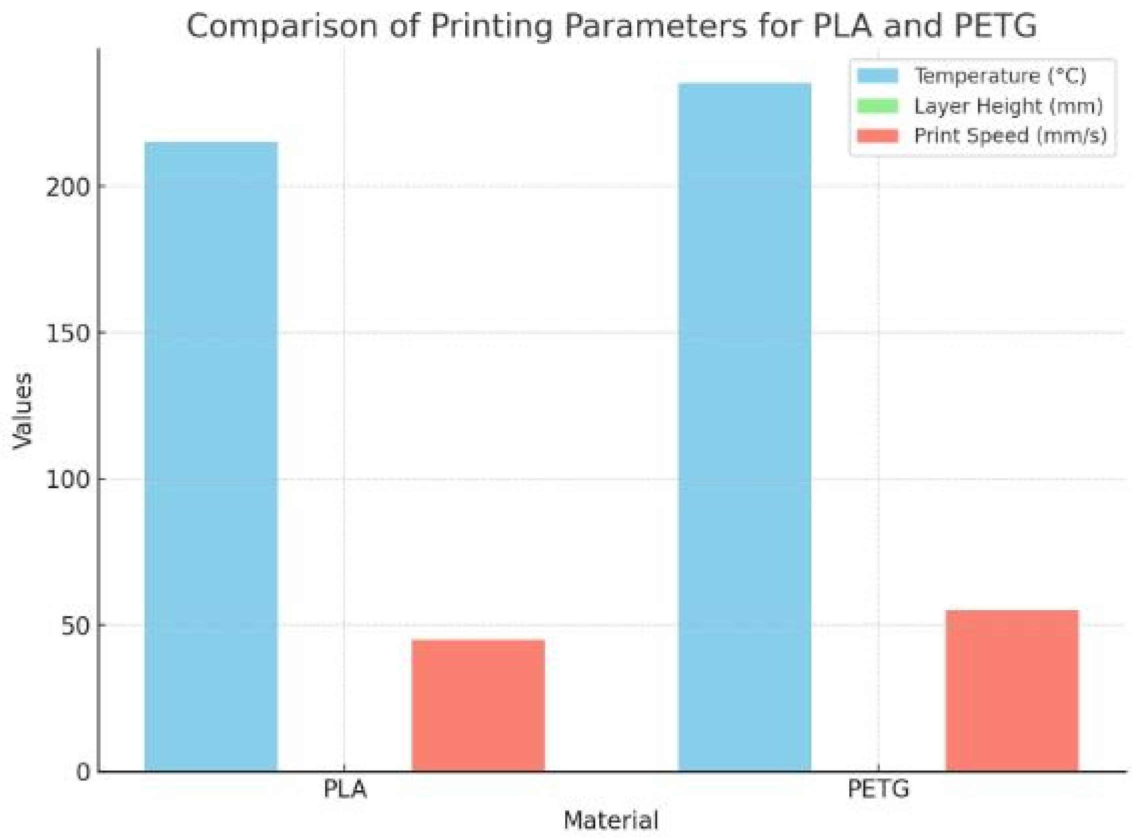


**Figure 2**. Surface finish and mechanical properties

Equally, the graphene reinforced optimized PETG showed a decreased surface roughness of 0.93 µm and improved mechanical strengths at 70 MPa tensile and 95 MPa flexural strengths. These outcomes demonstrate the potential for synergy between advanced materials and optimized parameters in enhancing FDM performance.

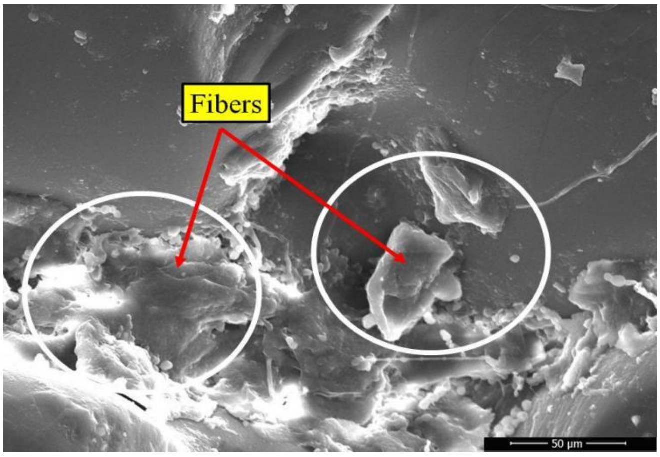


**Figure 3.** Surface roughness microstructure analysis.

**Figure 3** provides insights into the surface roughness and microstructure of a fiber-reinforced thermoplastic polymer. Fibers are visibly embedded within the polymer matrix, as highlighted by the circled regions. The rough texture and irregular morphology observed around the fibers indicate regions of interfacial interaction between the fibers and the matrix, which are critical for the composite's mechanical properties.

The presence of these fibers express reinforcement within the polymer, potentially enhancing properties such as strength and stiffness. However, the voids and surface irregularities observed near the fibers may contribute to stress concentrations, impacting the overall toughness and fatigue resistance of the material. Proper optimization of fiber-matrix bonding and distribution is essential to minimize such defects, thereby improving the mechanical performance and durability of the composite.

This analysis can provide valuable feedback for adjusting processing parameters to achieve better fiber distribution and surface finish, which are crucial for applications requiring high mechanical integrity. These results underline the success achieved in additive manufacturing where high-performance reinforcements combined with precise optimization techniques are considered vital in the improvement of material performance and surface quality. The reductions in surface roughness as well as significant improvements in mechanical properties, as were realized in this study, are consistent with recent advancements in the field. The application of the latest state-of-the-art reinforcement materials and optimization algorithms reflects the latest development in FDM technology that would lead to more efficient and sustainable manufacturing practices.

## 4. Discussion

The choice of materials in this study, which includes bio-based PLA, recycled PET, and PETG, underscores the growing importance of sustainability in additive manufacturing. The ability to enhance the performance of these materials through reinforcement and optimization highlights the potential for sustainable polymers to replace traditional, less ecofriendly materials in various applications. The use of recycled and biodegradable materials brings environmental benefits and enhanced performance, which is optimized, hence aligning with the sustainability goals globally. This helps reduce the environmental footprint of manufacturing processes. The findings of this study support the transition toward more sustainable production methods and provide a viable pathway for industries seeking to adopt greener manufacturing practices. As compared with existing literature, the outcomes of this investigation are consistent with, and in some cases surpass improvements upon those reported in the literature. In comparison to the recent studies on natural fiber and nanomaterial reinforcements, the surface roughness reduction as well as improvements in the mechanical properties recorded in this study are comparable to or better than improvements reported in similar studies. The consistency with the state-of-the-art validates the methodologies used and confirms that the chosen materials and optimization strategies are effective. Moreover, the emphasis on sustainability provides a dimension to the existing body of work as it molds emphasis toward the environmentally responsible practices in future additive manufacturing.

## 5. Conclusion

In this study, sustainable polymer composites in FDM are optimized successfully. For this case study, make very important improvements related to the quality of the surface and mechanical performance. The aim was to reinforce bio-based polymers, PLA, and recycled PET with natural fibers and nanomaterials so material better suited for producing components with surfaces smoother and more strength. It was very important to utilize response surface methodology and particle swarm optimization to find optimal printing conditions, leading toward better results. It essentially underscores the potential of being able to replace or interchange many applications that rely upon manufacture with traditional polymers a material less desirable by way of environmental pollution thus toward sustainability based upon global sustainability objectives. The reduced surface roughness and enhanced tensile and flexural strengths obtained in this study indicate the possibility of improving the performance of 3D printed parts by using advanced reinforcements and optimized FDM processes. This work contributes to the additive manufacturing field as it presents a feasible route for incorporating sustainability into FDM processes without compromising quality or performance. The results are not only verifying the use of natural fibers and nanomaterials as reinforcement materials but also qualify that precise optimization of the parameters yields the optimal best results.

Future work would include the extension of this study to further evaluate these optimized composites toward long term durability and environmental impact. Further expansion in the scope of sustainable materials and reinforcement may further enhance the potential of such work. As manufacturing solutions become greener, these methodologies and results are invaluable for developing even more sustainable and more efficient FDM processes.

## Author contributions

Conceptualization, SR and RMA; methodology, SR& KCS; software, SR & HMJ; validation, SR& APK; formal analysis, RMA, HMJ, RH, &BSKS; investigation, RMA, HMJ, RH, &BSKS; resources, SR& ZNJ & KCS; data curation, RMA, KCS & MAM; writing—original draft preparation, SR& APK; writing—review and editing, SR&APK; visualization, SR; supervision, SR RMA, HMJ, RH, &BSKS &APK; project administration, SR; funding acquisition, SR &RMA, HMJ, RH, &BSKS.

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## Conflict of interest

The authors declare no conflict of interest

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