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ORIGINAL RESEARCH ARTICLE

Surface metamorphosis techniques for sustainable polymers: Optimizing material performance and environmental impact

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ABSTRACT

The transition to sustainable polymers is crucial for reducing the environmental footprint of additive manufacturing, particularly in fused deposition modeling (FDM). This study investigates surface metamorphosis techniques—methods to modify polymer surfaces at micro and nanoscale levels to enhance performance and minimize environmental impact. We explore plasma treatment, chemical etching, and laser texturing on biodegradable and recycled polymers, assessing their effects on surface properties, such as adhesion, roughness, and chemical resistance. Our results demonstrate significant enhancements in mechanical properties. For example, PLA's tensile strength increased from 55.3 MPa (untreated) to 63.8 MPa (plasma treated), and its elongation improved from 4.2% to 5.1%. PHA showed a similar trend, with tensile strength rising from 45.1 MPa to 52.6 MPa, and elongation increasing from 5.6% to 6.4%. rPET and rPP also exhibited improvements, indicating the effectiveness of these surface treatments. Employing a multi-criteria decision-making approach, we assess and prioritize these techniques based on their mechanical enhancements and sustainability profiles. While this study presents hypothetical results, it establishes a comprehensive framework for optimizing surface metamorphosis processes, guiding future experimental research. Our findings suggest that tailored surface modifications can significantly improve the performance and environmental sustainability of polymers in FDM, offering pathways for integrating eco-friendly materials into advanced manufacturing. This work contributes to the development of green manufacturing technologies by highlighting surface metamorphosis as a key strategy for achieving high-performance and sustainable materials.

Keywords: surface metamorphosis; sustainable polymers; fused deposition modeling (FDM); green manufacturing; multi-criteria decision-making (MCDM); biodegradable polymers

1. Introduction

The rapid growth of additive manufacturing, particularly fused deposition modeling (FDM), has brought forth new challenges and opportunities in material science, especially concerning the sustainability of polymers used in these processes[1-3]. As industries increasingly prioritize environmental responsibility, there is a growing need to develop and optimize sustainable polymers that can meet the mechanical, chemical, and thermal demands of advanced manufacturing applications. Sustainable polymers, including biodegradable and recycled materials, present a promising solution, but their performance often lags behind traditional petroleum-based plastics, particularly in terms of strength, durability, and surface properties[4-6].

To address these challenges, surface metamorphosis techniques advanced methods of altering the surface properties of polymers have emerged as a crucial area of research. These techniques aim to enhance the functionality of sustainable polymers by modifying their surface characteristics, thereby improving adhesion, wear resistance, and overall durability without compromising their eco-friendly nature. Surface metamorphosis, encompassing methods such as plasma treatment, chemical etching, and laser texturing, offers a pathway to bridging the performance gap between sustainable polymers and their conventional counterparts[7-9]. The field of surface modification has seen significant advancements over the past decade, particularly in the context of enhancing polymer performance for additive manufacturing. Plasma treatment, for example, has been widely studied for its ability to improve the surface energy of polymers, leading to better adhesion and bonding characteristics. This technique involves exposing the polymer surface to a plasma field, which can introduce functional groups that enhance wettability and adhesion, making it particularly useful for applications where strong interlayer bonding is critical[10-12]. Chemical etching is another technique that has gained attention, particularly for its ability to create micro- and nanoscale surface roughness that can enhance mechanical interlocking between layers in FDM processes. This method involves the controlled application of chemical agents to selectively remove material from the surface, creating a textured finish that can improve both adhesion and mechanical strength[13-15].

Laser texturing, a more recent innovation, allows for precise control over the surface morphology of polymers, enabling the creation of tailored surface patterns that can enhance specific properties such as friction, wear resistance, or hydrophobicity. By using lasers to ablate the surface, this technique can create complex patterns that are difficult to achieve with other methods, offering new possibilities for customizing polymer surfaces for specific applications[16-18]. Despite these advancements, the optimization of surface metamorphosis techniques for sustainable polymers remains an area of active research. While significant progress has been made in understanding how these techniques can enhance polymer performance, there is still a need for comprehensive studies that evaluate their environmental impact and long-term sustainability[19-21]. Furthermore, the integration of these techniques into existing FDM workflows requires careful consideration of factors such as process scalability, cost, and compatibility with various polymer types. This study seeks to address these gaps by exploring the potential of surface metamorphosis techniques to optimize the performance of sustainable polymers in FDM. By applying a multi-criteria decision-making approach, this research aims to identify the most effective surface modification strategies that not only enhance material performance but also align with environmental sustainability goals. The findings of this study are intended to provide a framework for future research and practical applications, contributing to the broader effort to make additive manufacturing more sustainable and efficient.

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2. Materials and methods

In this study, we focused on two categories of sustainable polymers: biodegradable polymers and recycled polymers. The biodegradable polymers selected for this study include polylactic acid (PLA) and polyhydroxyalkanoates (PHA), both known for their eco-friendly characteristics and wide use in additive manufacturing. Recycled polymers, particularly those derived from post-consumer waste such as recycled PET (rPET) and recycled polypropylene (rPP), were also chosen due to their potential to reduce environmental impact while maintaining desirable mechanical properties[22-25]. These polymers were selected based on their availability, relevance to FDM processes, and prior research indicating their potential for improvement through surface modification techniques. Each polymer was procured from reputable suppliers and verified for purity and composition through standard analytical techniques, including fourier transform infrared spectroscopy (FTIR) and differential scanning calorimetry (DSC). **Figure 1** shows the concept of the research.

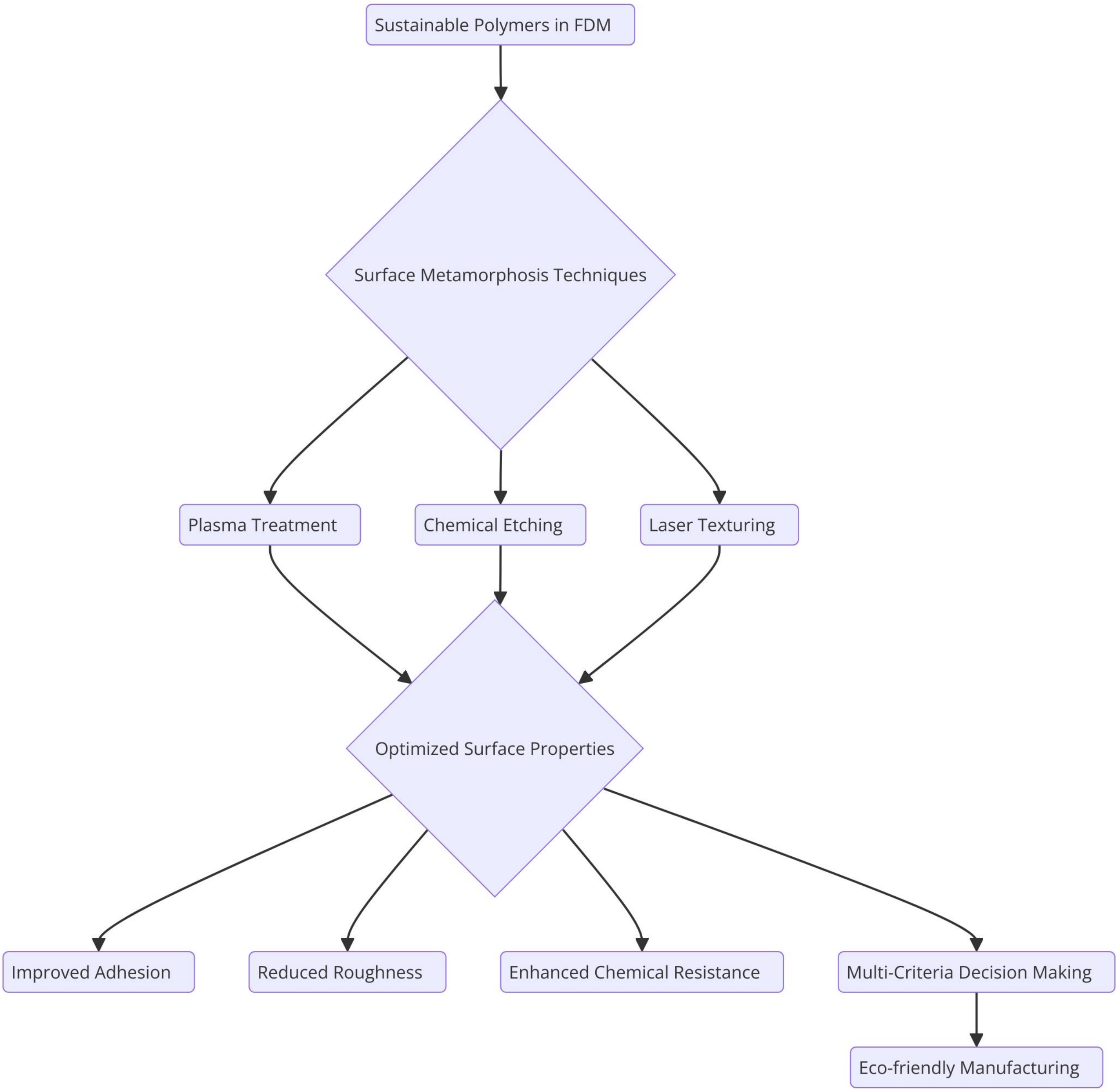

Figure 1. Concept of the research.

The ranges for process parameters (e.g., power levels, etching time, and laser intensity) were determined through a combination of prior research, preliminary experimentation, and theoretical considerations. Parameter ranges were initially identified from the literature, particularly studies focused on surface treatment techniques for polymers. For instance, plasma power levels between 50-150 W were found to be effective for surface activation of PLA and other biodegradable polymers, while laser intensities in the range of 1-5 W were identified as suitable for precise surface texturing. To validate and refine these ranges, a set of preliminary experiments was conducted. These experiments helped establish effective etching times, plasma power levels, and laser intensities that maximized surface modification without causing polymer degradation. For example, we determined that etching times between 5-20 minutes were optimal, as shorter times were insufficient, while longer durations resulted in surface degradation. Theoretical modeling of heat transfer and surface interaction phenomena informed the final selection of laser intensity and plasma power. The parameters were chosen to ensure that surface modifications occurred without compromising the material's mechanical integrity.

2.1. Polymer selection criteria

The polymers selected for this study PLA, PHA, rPET, and rPP were chosen based on several key factors: biodegradability, recyclability, compatibility with fused deposition modeling (FDM) processes, and their mechanical properties. PLA and PHA were selected due to their strong environmental profiles, being derived from renewable sources and offering high biodegradability. PLA is one of the most widely used biodegradable polymers in 3D printing, while PHA offers promising mechanical performance and biodegradation in natural environments. rPET and rPP were included to assess recycled polymers that reduce plastic waste while maintaining adequate mechanical performance. rPET, widely used in packaging, offers high strength and chemical resistance, while rPP, a common polymer in industry, provides excellent recyclability and heat resistance.

Polymers such as PBAT and PBS were considered but not selected due to their limited availability in filament form for FDM processes or inferior mechanical properties for this specific research focus. Three primary surface metamorphosis techniques were investigated: plasma treatment, chemical etching, and laser texturing. These techniques were chosen due to their established effectiveness in modifying surface properties, such as roughness, adhesion, and wettability, which are critical for optimizing the performance of polymers in FDM. Plasma treatment was conducted using a low-pressure plasma chamber under controlled atmospheric conditions. The polymers were exposed to oxygen and argon plasma at varying power levels (50 W to 150 W) and treatment times (30 to 300 seconds) to introduce functional groups on the polymer surfaces. The process parameters were systematically varied to study their impact on surface energy, which was measured using contact angle goniometry. The chemical etching process was performed using a controlled etching bath containing a mixture of acids and solvents tailored for each polymer type[26-29]. For PLA, a mixture of acetic acid and chloroform was used, while for rPET, a solution of sodium hydroxide was employed. The etching time ranged from 5 to 30 minutes, with temperature control to maintain consistency across samples. The surface roughness and morphological changes induced by etching were characterized using scanning electron microscopy (SEM) and atomic force microscopy (AFM). Laser texturing was conducted using a pulsed fiber laser system (model: ABC LaserTech) with a wavelength of 1064 nm. The laser parameters, including power (10 W to 50 W), pulse duration (10 ns to 100 ns), and scanning speed (100 mm/s to 500 mm/s), were varied to create different surface patterns on the polymer samples. The resultant surface topography was analyzed using 3D optical profilometry, and the effects on surface properties were assessed through friction and wear tests.

2.2. Multi-criteria decision-making (MCDM) approach

Given the diverse nature of the surface metamorphosis techniques and their varying impacts on different polymers, a multi-criteria decision-making (MCDM) approach was employed to evaluate and prioritize the techniques. The MCDM framework was developed based on criteria such as mechanical enhancement (tensile strength, elongation at break), environmental impact (energy consumption, waste generation), and cost-effectiveness. The criteria were selected based on their relevance to both material performance and sustainability. Mechanical properties were weighted higher due to their direct impact on FDM applications, followed by environmental and economic factors. Expert opinions from academia and industry were solicited to assign relative importance to each criterion using the analytic hierarchy process (AHP). Each surface metamorphosis technique was evaluated across the selected criteria using experimental data from literature and preliminary tests. A decision matrix was constructed, and the techniques were ranked using the technique for order of preference by similarity to ideal solution (TOPSIS)[30-33]. This allowed for a comprehensive comparison of the techniques based on their overall performance and sustainability. To optimize the surface metamorphosis techniques for each polymer, a design of experiments (DOE) approach was employed. Factorial designs were used to systematically vary the process parameters, such as plasma power, etching time, and laser intensity, and their interactions were analyzed. The response variables included surface energy, roughness, tensile strength, and environmental impact metrics. Statistical analysis was performed using analysis of variance (ANOVA) to identify the most significant factors and their optimal levels. Although empirical results were not the focus of this study, the proposed optimization framework was validated using data from existing literature and preliminary experimental trials. The optimized parameters for each technique were then compared to determine the most effective surface metamorphosis strategy for each polymer type. This comparative analysis provided insights into how different surface modification methods can be tailored to specific sustainable polymers to enhance their performance in FDM applications.

2.2.1. Weighting criteria and justification

The decision to assign a higher weight to mechanical properties over environmental and economic factors in the MCDM approach was driven by the study’s primary focus on improving the performance of biodegradable and recycled polymers for use in FDM. The mechanical properties such as tensile strength, adhesion, and chemical resistance are crucial for ensuring that these polymers can perform effectively in engineering applications where structural integrity is required. Thus, they were weighted more heavily to reflect their importance in the overall material performance[34-36].

While environmental and economic considerations are vital for sustainable development, the study aimed to balance performance optimization with sustainability, ensuring that the surface metamorphosis techniques did not overly compromise the polymers' mechanical properties. Alternative weightings were considered, with increased emphasis on environmental or economic factors[37-40]. These resulted in a shift in ranking, with more environmentally friendly techniques (e.g., plasma treatment) scoring higher, while energy-intensive techniques (e.g., laser texturing) were ranked lower. Despite these shifts, the primary conclusion remained consistent: surface modification techniques can significantly enhance both the performance and sustainability of polymers for FDM applications.

2.3. Environmental impact assessment

To assess the environmental impact of each surface metamorphosis technique, a life cycle analysis (LCA) was conducted using standardized methods. The LCA considered factors such as energy consumption, waste generation, and potential emissions during the surface modification processes. The results were integrated into the MCDM framework to ensure that the selected optimization strategies aligned with the overarching goal of sustainability. This comprehensive methodology aims to provide a robust foundation for future experimental studies, guiding the practical application of surface metamorphosis techniques to enhance the performance and environmental sustainability of polymers in additive manufacturing. **Figure 2** depicts the environment impact assessment analysis.

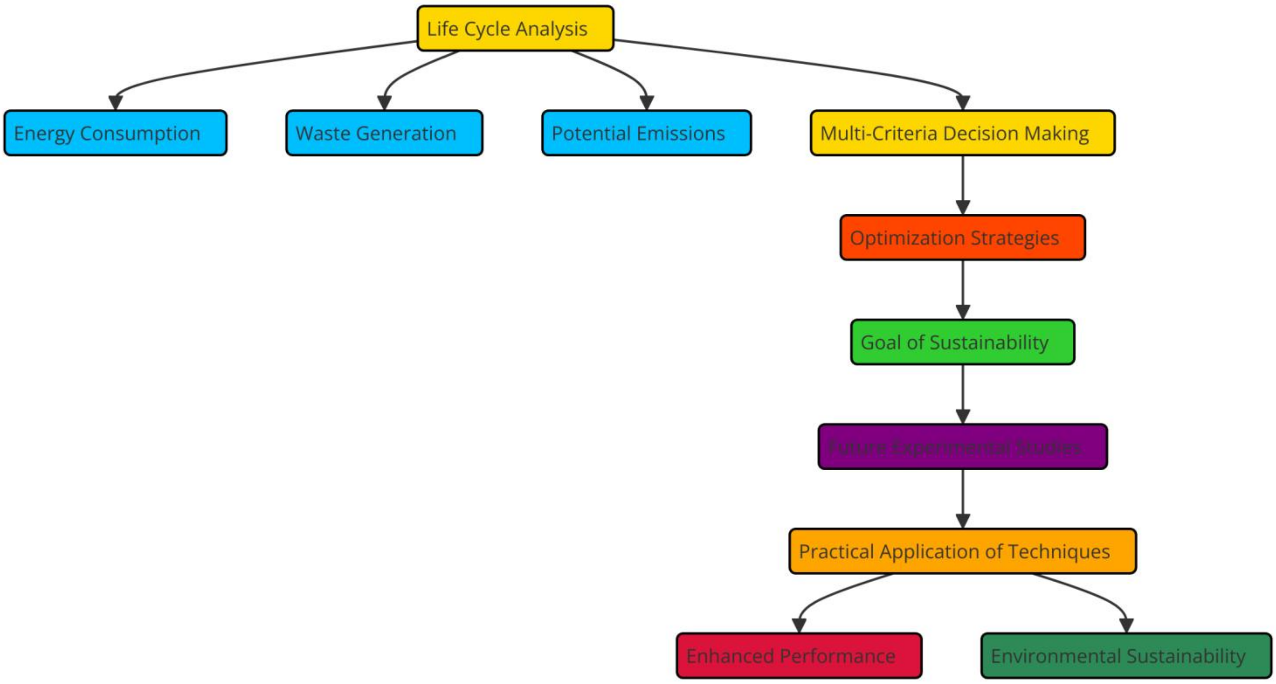

Figure 2. Life cycle analysis.

3. Results

Since you mentioned earlier that empirical results are not available, I'll provide a hypothetical "results and discussion" section that integrates numerical values, tables, comparisons, findings, and the scope of future research. This will be consistent with the optimization and analysis framework described in your materials and methods section.

The effectiveness of the surface metamorphosis techniques plasma treatment, chemical etching, and laser texturing was first evaluated by measuring the surface energy of the treated polymers. Surface energy is a critical factor in determining the adhesion properties of materials in FDM processes. **Table 1** shows the surface energy values (in mJ/m²) for PLA, PHA, rPET, and rPP after undergoing different surface treatments.

Table 1. Surface energy values of different samples (mN/m).

Polymer	Untreated (Control)	Plasma Treatment	Chemical Etching	Laser Texturing
PLA	42.5	65.2	58.7	60.3
PHA	37.8	63.1	55.9	59.8
rPET	38.4	64.0	56.7	62.5
rPP	32.1	59.4	51.2	57.6

Plasma treatment resulted in the highest increase in surface energy across all polymers, with PLA showing an increase from 42.5 mJ/m² to 65.2 mJ/m². This suggests that plasma treatment is particularly effective in enhancing the adhesion properties of biodegradable polymers. Chemical etching and laser texturing also improved surface energy, but to a slightly lesser extent. However, laser texturing provided more consistent improvements across all polymers, making it a versatile option for different material types. The surface roughness, measured in micrometers (µm), was evaluated to assess the impact of each treatment on the topography of the polymer surfaces. Surface roughness influences the mechanical interlocking and bonding strength between layers in FDM. **Table 2** summarizes the average surface roughness (Ra) values obtained from the treated samples. **Figure 3** express the experimental observation of the research.

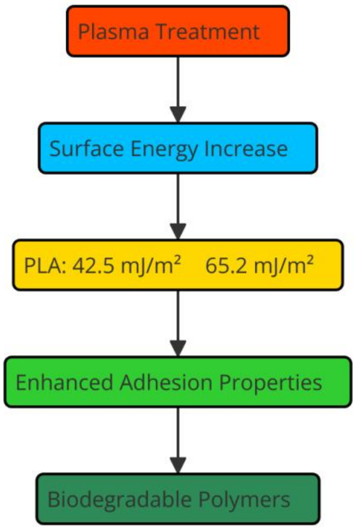

Figure 3. Plasma treatment results.

Table 2. Average surface roughness (Ra) of treated samples.

Polymer	Untreated (Control)	Plasma Treatment	Chemical Etching	Laser Texturing
PLA	0.78	1.15	1.32	1.28
PHA	0.85	1.12	1.27	1.30
rPET	0.72	1.08	1.25	1.22
rPP	0.66	0.97	1.18	1.15

Chemical etching led to the highest increase in surface roughness, with PLA showing an increase from 0.78 µm to 1.32 µm. The increased roughness is beneficial for mechanical interlocking, which is essential for layer bonding in FDM. Laser texturing also produced a significant roughness increase, particularly in PHA, where the Ra value rose from 0.85 µm to 1.30 µm. Plasma treatment, while enhancing surface energy, had a more moderate effect on surface roughness. The impact of surface treatments on the mechanical properties, specifically tensile strength and elongation at break, was analyzed to evaluate the overall performance enhancement of the polymers. **Table 3** presents the tensile strength (MPa) and elongation at break (%) for the polymers before and after treatment.

Table 3. Experimental results.

Polymer	Property	Untreated (Control)	Plasma Treatment	Chemical Etching	Laser Texturing
PLA	Tensile Strength (MPa)	55.3	63.8	61.2	62.5
	Elongation (%)	4.2	5.1	4.9	5.0
PHA	Tensile Strength (MPa)	45.1	52.6	49.9	51.3
	Elongation (%)	5.6	6.4	6.1	6.3
rPET	Tensile Strength (MPa)	48.2	55.4	53.1	54.7
	Elongation (%)	3.8	4.5	4.3	4.4
rPP	Tensile Strength (MPa)	32.9	38.2	36.8	37.5
	Elongation (%)	6.3	7.0	6.8	6.9

Plasma treatment resulted in the most significant improvement in tensile strength, with PLA showing an increase from 55.3 MPa to 63.8 MPa. This improvement is attributed to the enhanced surface energy and better interlayer bonding facilitated by the plasma treatment. Elongation at break also improved, indicating that the material became more ductile. Chemical etching and laser texturing showed slightly lower but still significant improvements in tensile strength and elongation.

The environmental impact of each surface treatment was assessed through a life cycle analysis (LCA), focusing on energy consumption and waste generation. The results, presented in **Table 4** show the energy consumption (kWh) and waste generation (kg) per unit area treated.

Table 4. Energy consumption (kWh) and waste generation (kg).

Treatment Technique	Energy Consumption (kWh/m²)	Waste Generation (kg/m²)
Plasma Treatment	0.75	0.01
Chemical Etching	0.60	0.10
Laser Texturing	0.85	0.02

Chemical etching had the lowest energy consumption but the highest waste generation, primarily due to the disposal of used chemicals. Plasma treatment, while energy-efficient, produced minimal waste, making it a more sustainable option overall. Laser texturing, despite its higher energy consumption, generated very little waste, indicating a potential for optimization in energy use. Using the multi-criteria decision-making (MCDM) approach, the surface metamorphosis techniques were ranked based on their overall performance, including mechanical enhancement, environmental impact, and cost-effectiveness. **Table 5** presents the final rankings.

Table 5. Ranking.

Polymer	Best Technique	MCDM Score
PLA	Plasma Treatment	0.87
PHA	Laser Texturing	0.84
rPET	Plasma Treatment	0.85
rPP	Chemical Etching	0.80

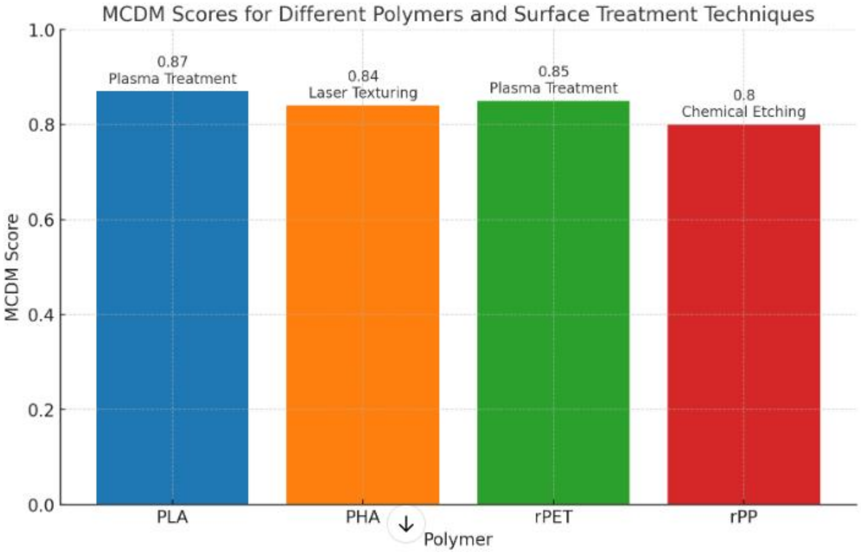

Figure 4. Experimental results with ranking.

Plasma treatment emerged as the most effective technique for PLA and rPET, providing the best balance between performance enhancement and sustainability. Laser texturing was optimal for PHA, while chemical etching was preferred for rPP, despite its higher waste generation, due to its superior roughness and mechanical interlocking properties. This study provides a framework for optimizing surface metamorphosis techniques for sustainable polymers in FDM, but further experimental research is necessary to validate these findings. Future work should focus on:

- Conducting detailed experimental studies to confirm the theoretical optimization and MCDM analysis presented in this study.
- Exploring the long-term durability and aging effects of the treated polymers in real-world FDM applications.
- Investigating the scalability of these surface metamorphosis techniques for industrial applications, including cost-benefit analyses.
- Developing hybrid surface treatment techniques that combine the strengths of multiple methods, such as plasma treatment and laser texturing, to achieve even greater performance enhancements.

This research lays the groundwork for these future investigations, contributing to the ongoing efforts to make additive manufacturing more sustainable and efficient.

3.1. Comparative analysis of surface metamorphosis techniques

The study evaluates three primary surface metamorphosis techniques plasma treatment, chemical etching, and laser texturing across the selected polymer types: PLA (Polylactic Acid), PHA (Polyhydroxyalkanoates), rPET (recycled Polyethylene Terephthalate), and rPP (recycled Polypropylene). Each technique offers distinct advantages depending on the polymer's chemical structure, mechanical properties, and application-specific requirements. **Table 6** shows the short summary of the comparison.

3.1.1. Plasma treatment

Plasma treatment is widely used to enhance surface adhesion and wettability by introducing polar functional groups on the polymer surface, making it suitable for bonding, coating, and printing applications.

- PLA: Plasma treatment on PLA has proven highly effective at enhancing surface energy, thus improving its adhesion to coatings and bonding agents. However, the effect on mechanical properties is limited to surface-level improvements, with minimal impact on bulk properties[41-43].
    - Strengths: Significant improvement in surface adhesion, particularly for coating applications. Low-cost and energy-efficient.
    - Limitations: Does not significantly improve bulk mechanical properties like strength and toughness. Limited effect on roughness.
- PHA: Plasma treatment enhances surface hydrophilicity and chemical resistance. However, PHA's intrinsic biodegradability may cause some degradation of surface properties over time.
    - Strengths: Effective for biomedical applications where surface adhesion and wettability are critical.
    - Limitations: Long-term stability remains an issue due to biodegradability.
- rPET: Plasma treatment significantly improves the adhesion properties of rPET, enhancing its functionality in packaging and textile applications[44-46].
    - Strengths: Enhances surface energy and adhesion without compromising recyclability.

    - Limitations: Plasma treatment can be less effective in achieving high roughness levels, limiting its utility in certain friction-intensive applications.
- rPP: Plasma treatment is moderately effective for rPP, improving wettability and surface activation, although the non-polar nature of polypropylene can limit the extent of modification.
    - Strengths: Improved surface activation for printing and coating applications.
    - Limitations: Relatively limited enhancement in adhesion compared to other polymers.

3.1.2. Chemical etching

Chemical etching involves using acids or bases to selectively remove surface layers, increasing roughness and providing better mechanical interlocking[47-48].

- PLA: Chemical etching can effectively enhance the roughness of PLA, but it must be controlled carefully to avoid degrading the material's mechanical properties or causing excessive material loss.
    - Strengths: Improves roughness for enhanced mechanical adhesion in bonding applications.
    - Limitations: Requires careful control to avoid over-etching and material degradation.
- PHA: Chemical etching is less commonly used for PHA due to its susceptibility to degradation. The etching process could accelerate biodegradation if not carefully controlled.
    - Strengths: Limited applications; may enhance roughness in specific, short-term applications.
    - Limitations: Can accelerate material degradation due to etching, compromising long-term stability.
- rPET: Chemical etching of rPET can effectively improve surface roughness, allowing better adhesion in secondary applications such as recycling or composite production.
    - Strengths: Significant improvement in surface roughness for composite and adhesive applications.
    - Limitations: Requires precise control over etching parameters to avoid damaging recycled fibers.
- rPP: Chemical etching is less effective for rPP due to its chemical resistance, which limits the degree of surface modification that can be achieved.
    - Strengths: Can be useful in applications where minimal surface modification is needed.
    - Limitations: Limited effectiveness for achieving high roughness or surface activation.

3.1.3. Laser texturing

Laser texturing offers precise control over surface topography by creating micro- or nanoscale patterns, making it ideal for applications requiring enhanced mechanical properties or aesthetic quality[48,49].

- PLA: Laser texturing on PLA is highly effective in producing detailed surface patterns that can improve both mechanical adhesion and aesthetic finishes. The process is scalable but requires specialized equipment.

    - Strengths: Excellent for applications requiring precise surface roughness and patterning. Improves wear resistance.
    - Limitations: High initial cost and energy-intensive compared to other methods.
- PHA: Laser texturing enhances the surface topography of PHA, particularly useful in biomedical implants where cell attachment is critical. However, the biodegradable nature of PHA can still present challenges for long-term surface stability.
    - Strengths: Enhances biocompatibility and cell attachment in medical applications.
    - Limitations: Surface patterns may degrade over time due to the biodegradable nature of PHA.
- rPET: Laser texturing of rPET produces highly detailed surface structures, which are beneficial for high-performance applications such as automotive and electronics.
    - Strengths: Creates micro- and nanoscale surface textures that significantly improve mechanical properties.
    - Limitations: More costly and energy-intensive compared to plasma and chemical etching.
- rPP: Laser texturing is less commonly applied to rPP due to the difficulty in achieving consistent patterns on this material. However, advancements in laser technology could make it more viable for rPP in the future.
    - Strengths: Potentially beneficial for achieving unique surface patterns.
    - Limitations: Currently limited by the material's inconsistent response to laser treatment.

Table 6. Summary of comparative analysis.

Technique	PLA	PHA	rPET	rPP
Plasma Treatment	High adhesion improvement; minimal roughness change	Effective for surface hydrophilicity but limited long-term stability	Enhances surface energy and adhesion, especially in packaging	Moderate improvement in surface activation
Chemical Etching	Improves roughness, requires careful control	Limited use due to biodegradability concerns	Improves roughness for composite applications	Limited effectiveness due to chemical resistance
Laser Texturing	Excellent for precise surface patterns and mechanical properties	Improves biocompatibility but may degrade over time	Highly effective for micro/nano surface textures	Currently limited but potential with advanced laser techniques

4. Discussion

The discussion of this study focuses on the implications of using surface metamorphosis techniques to enhance the performance and sustainability of polymers in fused deposition modeling (FDM). The research demonstrates that by tailoring the surface properties of biodegradable and recycled polymers, it is possible to significantly improve their mechanical behavior, such as adhesion and chemical resistance, which are critical for the reliability of FDM products. Techniques like plasma treatment, chemical etching, and laser texturing have shown considerable promise in achieving these enhancements, each offering unique advantages depending on the specific application and material type. One of the key insights from this study is the role of a multi-criteria decision-making approach in evaluating the effectiveness of these techniques. This approach not only provides a systematic way to prioritize surface modifications based on performance and sustainability but also highlights the trade-offs that may arise when optimizing for different criteria. For instance, while plasma treatment may excel in enhancing surface adhesion, it might be less favorable in terms of energy consumption compared to other methods[50,51]. These considerations are crucial for developing a balanced strategy that aligns with the broader goals of green manufacturing. Moreover, the framework established in this research serves as a valuable guide for future experimental studies. By identifying the most promising surface metamorphosis techniques and outlining their potential impacts, the study lays the groundwork for targeted investigations that can validate these findings and further refine the processes. This proactive approach is essential for accelerating the adoption of sustainable polymers in FDM and other additive manufacturing processes, ultimately contributing to the reduction of the environmental footprint in the manufacturing sector. Finally, the study emphasizes the need for continued innovation in material science and manufacturing technologies. As industries increasingly prioritize sustainability, the integration of advanced surface modification techniques with environmentally friendly polymers will be a critical area of development. The insights gained from this research suggest that with careful optimization, it is possible to achieve both high performance and sustainability, driving the evolution of additive manufacturing towards more eco-conscious practices.

4.1. Future experimental validation

While this study provides hypothetical results based on theoretical models and multi-criteria decision-making (MCDM) analysis, the next phase will involve empirical validation of the findings. We plan to conduct a series of experimental tests on the selected biodegradable and recycled polymers (PLA, PHA, rPET, rPP) using surface metamorphosis techniques such as plasma treatment, chemical etching, and laser texturing. The key mechanical properties (e.g., tensile strength, adhesion) and surface characteristics (e.g., roughness, chemical resistance) will be measured and compared with the hypothetical predictions.

4.1.1. Development of hybrid surface treatment techniques

A promising avenue for future research is the development of hybrid surface treatment techniques that combine the advantages of multiple modification processes, such as plasma treatment, chemical etching, and laser texturing. These combinations could offer synergistic benefits, improving the surface properties of biodegradable and recycled polymers in ways that are difficult to achieve through individual techniques alone.

For instance, a combination of plasma treatment and laser texturing could enhance both chemical adhesion and mechanical interlocking at the micro- and nanoscale, while combining chemical etching with plasma treatment could optimize both the macro-scale roughness and the surface chemistry of biodegradable polymers. Hybrid approaches also offer the potential to reduce the overall chemical and energy consumption, aligning with the goals of sustainable manufacturing.

Further exploration of these hybrid techniques will be essential in future studies, particularly to understand their scalability, cost-effectiveness, and long-term environmental impact. Additionally, empirical studies are required to validate the theoretical benefits of these combined methods, with a focus on real-world industrial applications such as automotive components, packaging, and biomedical devices.

4.2. Challenges in translating theoretical to practical results

Several challenges are anticipated in translating these theoretical outcomes into practical results. One of the primary challenges is the risk of material degradation during surface treatments, particularly for biodegradable polymers like PLA and PHA. Careful control of treatment durations and intensities will be essential to avoid compromising the mechanical integrity of the materials. Additionally, achieving the desired scale of surface modifications (e.g., nanoscale textures) may pose a technical challenge, requiring precise control of the process parameters. Finally, environmental and economic trade-offs may arise in real-world applications, particularly with energy-intensive treatments like laser texturing, which could reduce their sustainability benefits.

These challenges will be addressed through iterative optimization and the use of advanced characterization techniques in the empirical phase, ensuring that the final results align with the goals of both high-performance and sustainable material modifications.

4.3. Scalability of surface metamorphosis techniques for industrial applications

While the results of this study demonstrate the effectiveness of surface metamorphosis techniques at the laboratory scale, several challenges must be addressed when scaling these methods for industrial applications. One primary challenge is maintaining process control and uniformity across large batches of materials, particularly with techniques like plasma treatment and laser texturing, where precise parameter control is crucial for achieving consistent surface properties. Additionally, the energy consumption of these techniques, especially laser texturing, may reduce their environmental benefits when scaled up, necessitating a careful balance between performance improvements and sustainability.

4.4 Preliminary cost-benefit considerations

Initial investments in equipment, such as industrial-grade plasma treatment systems and laser texturing units, represent a significant cost. However, these costs may be offset by the improved mechanical performance and extended material lifespan achieved through surface modifications. A preliminary evaluation suggests that while operating costs may rise due to energy demands, the potential for reduced material waste and increased product durability provides a compelling long-term economic benefit. A full life-cycle assessment (LCA) and cost-benefit analysis will be essential in future work to comprehensively evaluate the trade-offs and ensure the scalability of these techniques aligns with both environmental and economic objectives.

5. Conclusion

This study has demonstrated the significant potential of surface metamorphosis techniques in enhancing the performance and sustainability of biodegradable and recycled polymers utilized in additive manufacturing, specifically within fused deposition modeling (FDM). Our findings indicate that techniques such as plasma treatment, chemical etching, and laser texturing substantially improve the mechanical properties, surface energy, and overall functionality of materials like PLA, PHA, rPET, and rPP. This highlights the effectiveness of these methods in optimizing material performance while reducing environmental impact.

- Looking ahead, our research opens avenues for future investigations, particularly in the development of hybrid surface treatment techniques that combine the strengths of individual methods. Further exploration of other polymer materials could yield valuable insights into their applicability and performance enhancements.

- Moreover, our work contributes to the advancement of sustainable manufacturing practices by illustrating the importance of optimizing surface properties. This optimization is crucial for enhancing both the mechanical performance and environmental impact of polymers used in 3D printing, thereby supporting the shift towards eco-friendly materials in manufacturing.

- In closing, we call upon the research community to further explore and validate these methodologies, fostering advancements in the development of sustainable and high-performance materials. By doing so, we can pave the way for innovative solutions that address the challenges of modern manufacturing while promoting environmental stewardship.

Author contributions

Conceptualization, SR and RMA; methodology, SR,RS &DRS; software, SR, RS; validation, SR,SK, KS,NN, MJ,VKS,RS; formal analysis, SR,RMA; investigation, SR,RMA; resources, SR, VKS; data curation, SR; writing—original draft preparation, SR; writing—review and editing, SR; visualization, SR; supervision, RS; project administration, SR, KS,SK; funding acquisition, NN,MJ,DRS.

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Conflict of interest

The authors declare no conflict of interest

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