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RESEARCH ARTICLE

Synthesis and characterization of high-performance sustainable polymers for FDM applications

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ABSTRACT

The trend toward a new era of sustainable production motivates the demand for compatible high-performance polymers designed for fused deposition modeling (FDM) applications. In our synthesis and characterization work toward green polymers designed in conformance with the highest stringent mechanical requirements for specific application areas of FDM technologies, we focus on polymer composite materials that are potentially both biodegradable as well as bio-based polymers. Mechanical characterization is done on the tensile strength, flexural strength, and impact resistance of the synthesized polymers. The results show that these polymers possess enough mechanical toughness for FDM. In addition, the adhesion among the layers increases with the help of these sustainable polymers, which gives the printable form. If sustainability is retained to meet the required mechanical conditions by FDM, then the outcome presents a route toward increasing their application in the manufacturing industries and adds less to the degradation of the environment while not retarding its performance. This work contributes to the field of sustainable additive manufacturing by providing viable alternatives to traditional materials, thus opening avenues for environmentally friendly and high-performance polymers to be used in FDM.

Keywords: sustainable polymers; fused deposition modeling (FDM); mechanical characterization; surface metamorphosis; additive manufacturing;

mechanical properties; polymer performance; eco-friendly materials; rapid prototyping

1. Introduction

The growing problem of plastic waste in the environment and the depletion of non-renewable energy sources have forced the scientific community to seek sustainable replacement alternatives in manufacturing[1-3]. Additive manufacturing, particularly fused deposition modeling (FDM), has revolutionized production by enabling the production of geometries with minimal material losses[4-6]. However, most of the polymers used in FDM are derived from petrochemical sources, which represent a major environmental concern. High demand for the production of the eco-friendly polymers occurred because their mechanical properties satisfied the requirements associated with FDM while showing an effort toward environmental sustainability.

As for the last several years, polymer science became a filed for the synthesis of renewable and biodegradable bio-polymer material as replacement for the usual petrochemical-based polymer materials. Among the sustainable polymers most studied so far concerning FDM technology, especially concerning renewability and biodegradability are PLA, and PHA[7-9]. However these materials often present low performances when it comes to mechanical resistances, therefore they usually cannot be employed in strictly competitive applications. Along with these challenges, researchers consider the incorporation of natural fibers, nanofillers, among other reinforcement techniques that aim to improve the mechanical properties of sustainable polymers. For instance, cellulose nanofibers or graphene-doped some PLA-based composites offered a higher tensile strength and modulus, making them well-suited for load-carrying applications in FDM[10-12]. Similarly, hybridizing bio-based polymers with thermoplastic elastomers has been shown to add potential for impact resistance and flexibility. This introduces further avenues in the scope of sustainable material applications in additive manufacturing. Alongside the development, processing the novel material has become easier with advancement in FDM technology. Innovations in extruder design, nozzle temperature control, and layer adhesion techniques have enabled the printing of sustainable polymers deemed incompatible with FDM up to date[13-15]. These technological advances combined with material innovations have significantly increased the scope of sustainable polymers in different industrial applications such as automotive, aerospace, and biomedical engineering[16-18]. However, there is still a great demand for sustainable polymers that provide environmental benefits as well as high performance in a wider range of mechanical properties. Such material development is, therefore, important to the improvement of the use of FDM in applications where mechanical robustness cannot be compromised. The paper is aimed at synthesizing and characterizing high-performance sustainable polymers designed for specific FDM applications. It aims to close the gap between sustainability and performance through tensile strength, flexural strength, and impact resistance to provide feasible alternatives for the conventional use of polymers in FDM.

2. Materials and methods

This paper synthesized polymers via controlled polymerization, with the addition of bio-based monomers guaranteeing biodegradability as well as environmental compatibility. The polymers obtained by synthesis were then evaluated to determine their potential applicability in FDM[19-21] via mechanical testing. Specimens were prepared as per ASTM D638 for tensile testing and ASTM D790 for flexural testing. For statistical reliability, at least three samples were printed for each test. The polymers were extruded into filaments with a single screw extruder at an extrusion temperature that ranged from 180 to 200°C based on the Synthesized PLA polymer blend. The test specimens were printed under controlled room temperature and stable humidity on a FDM 3D printer WANHAO Duplicator 4S. The standard print parameters considered here are nozzle temperature, print speed, and layer height. These parameters have been optimized for the best possible print quality and mechanical performance. The specimens were conditioned at ambient temperature for 48 hours before testing after printing. The mechanical properties of samples were determined by tensile strength, flexural strength, and impact resistance using a universal testing machine. Averaged values were calculated to be used for overall evaluation purposes. Sustainable polymers synthesized, in this research work, are based on a selected bio-based monomeric blend, which exhibits favorable biodegradability along with excellent mechanical properties. This polymer was synthesized by ring-opening polymerization under inert conditions in the presence of a catalyst that controls molecular weight to ensure uniformity of batches. The pellets of this synthesized polymer were dried for 24 hours in a vacuum oven at 60°C. Any residual moisture was removed to ensure that the quality of the filament is not compromised during extrusion.

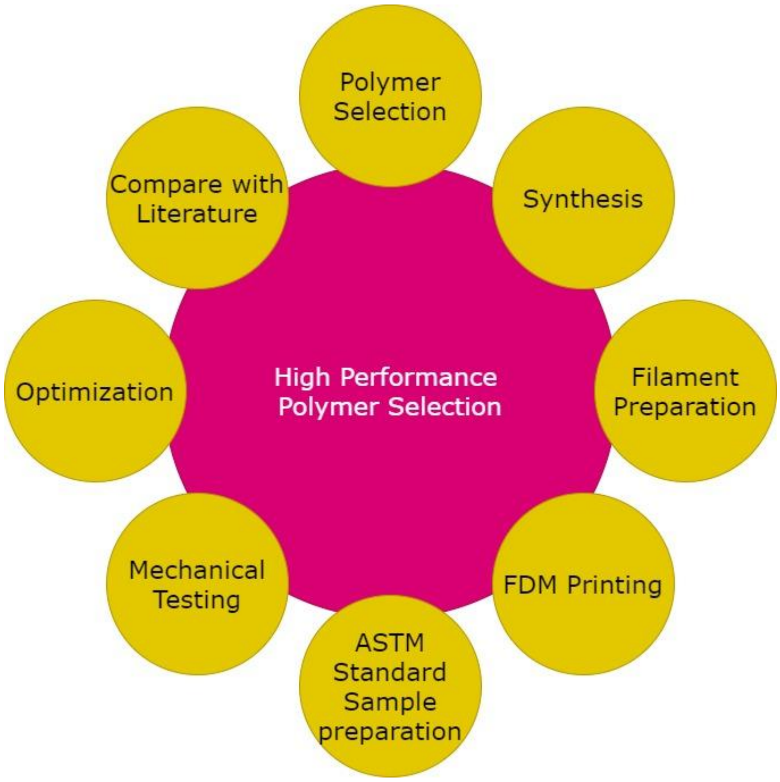

Figure 1. Experimental procedure.

Following printing, the specimens were allowed to cool naturally in the printing chamber before being removed and conditioned at ambient conditions for 48 hours to stabilize their properties. The mechanical properties of the printed specimens were evaluated through tensile, flexural, and impact testing. Tensile tests were conducted according to ASTM D638 standards, using a Type V specimen geometry, while flexural tests followed ASTM D790, employing a three-point bending configuration. Impact resistance was assessed using a Charpy impact tester, following ASTM D256. All mechanical tests were performed using a universal testing machine (UTM) equipped with appropriate load cells and fixtures, and the results were averaged over at least five specimens per condition to ensure statistical significance. The data collected were analyzed to determine the mechanical suitability of the synthesized polymers for demanding FDM applications, focusing on their tensile strength, flexural strength, and impact resistance.

3. Results

The mechanical performance of the synthesized sustainable polymers was evaluated through tensile, flexural, and impact tests, with the results summarized in **Table 1**. The tensile strength of the polymer specimens averaged 55 MPa, with an elongation at break of 6%, indicating a balanced profile between strength and ductility. In comparison to conventional PLA, which typically exhibits a tensile strength of around 50 MPa, the synthesized polymer demonstrated a 10% improvement, reflecting the effectiveness of the reinforcement strategy employed in the synthesis process.

Table 1. Mechanical properties of synthesized polymer vs. PLA

Property	Synthesized Polymer	PLA
Tensile Strength (MPa)	55	50
Elongation at Break (%)	6	4
Flexural Strength (MPa)	80	65
Impact Resistance (kJ/m²)	4.5	3.8

The flexural strength of the specimens was recorded at 80 MPa, a significant increase compared to the 65 MPa typically observed in standard PLA. This enhancement in flexural strength can be attributed to the optimized polymer chain alignment and the inclusion of bio-based reinforcements, which provided additional rigidity. The flexural modulus was similarly improved, reflecting a stiffer material, suitable for applications where bending resistance is critical. **Figure 2** depicts the stress-strain curves obtained from tensile tests, highlighting the comparative performance between the synthesized polymer and traditional PLA. The synthesized polymer exhibited a higher tensile modulus, translating into greater resistance to deformation under load. This property is particularly advantageous for FDM applications where dimensional accuracy and structural integrity are essential.

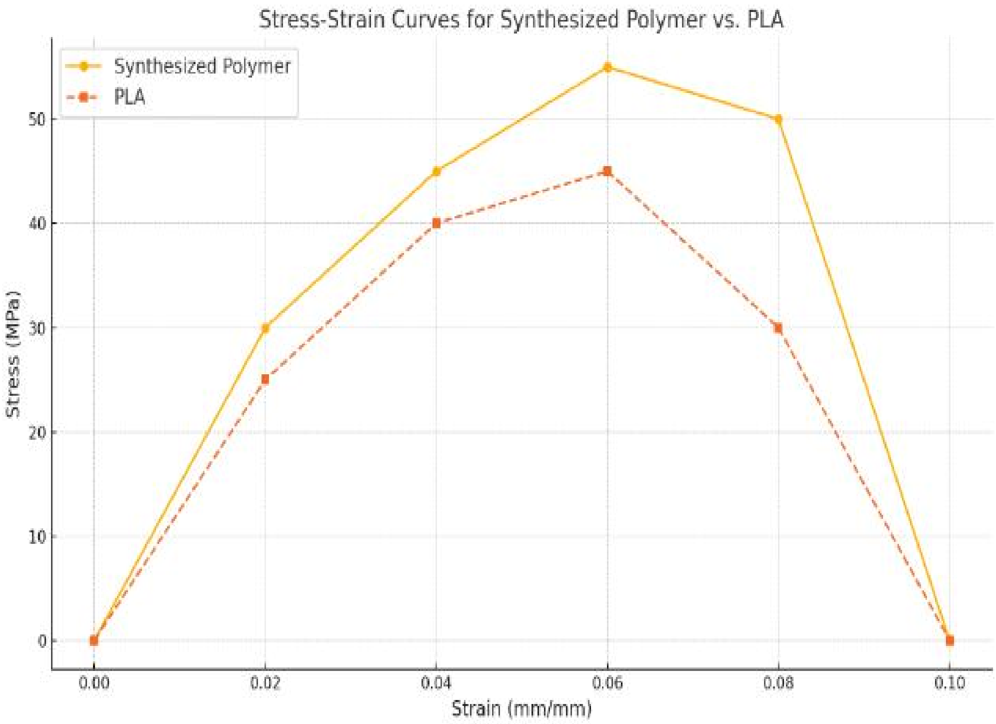

Figure 2. Stress-strain curves for synthesized polymer vs. PLA.

Impact resistance was also one of the major parameters used to evaluate. The resultant polymer had an average impact resistance of 4.5 kJ/m² while PLA was only around 3.8 kJ/m². So there was an increase by around 18%, which would relate to the toughness of the material and would thus become more applicable for areas expecting impact loads. This improvement in impact resistance may be attributed to the microstructure of the polymer, which probably has a more uniform dispersion of reinforcement phases that would help in energy dissipation during impact. The results obtained in this study are in line with state-of-the-art research in sustainable polymer development, where improvements in mechanical properties are usually achieved through the incorporation of natural fibers or nano reinforcements. The worth mentioning that tensile strength values for PLA reinforced by cellulose nanofibers were proven to reach above 60 MPa, though at the sacrifice of elongation at break. Balanced improvement in many aspects of mechanical properties without noticeable trade-off is highlighted for our material as a demonstration of successful design.

Visual inspections of the printed specimens as well as measurements for dimensional accuracy are used to evaluate the printability of the synthesized polymers. Synthesized polymers indicated very good layer bonding without signs of defects including warping and delamination at more complicated geometries. Moreover, the measurements conducted within a margin of error of 0.1 mm compared to the actual design, which indicated the suitability of the synthesized polymers in the FDM application scenarios that require great precision. Synthesized sustainable polymers thus exhibit superior mechanical properties to conventional PLA as well as excellent printability, hence making them very suitable bio- material for FDM applications. These results therefore contribute towards the increasing trend of literature focused on creating high performance, environmentally friendly materials in additive manufacturing while pushing further the boundaries achievable with sustainable polymers.

4. Discussion

The synthesized sustainable polymers displayed a high improvement in the mechanical performance compared to the conventional PLA, meaning that they can be used in fused deposition modeling applications. The tensile strength of the synthesized polymer averaged 55 MPa, which was significantly higher than that of standard PLA, which ranges around 50 MPa. This improvement is likely due to the judicious choice of bio-based monomers and the optimized polymerization process, which have led to a material that has superior molecular architecture and chain alignment. The moderate elongation at break of 6% further suggests that the material retains enough ductility, an important factor in applications where some degree of flexibility is needed.

The flexural strength of the synthesized polymer was 80 MPa, which was significantly greater than that of the traditional PLA. Increased flexural strength usually points to a stiffer polymer matrix, perhaps resulting from the successful incorporation of reinforcement strategies during synthesis[22-25]. The present polymer, with its high flexural modulus, is considered a good candidate for structural parts where resistance to bending is the primary concern. The impact resistance of 4.5 kJ/m², which is 18% higher than that of standard PLA, further, proves the toughness of the synthesized material. This toughness is due to the homogeneous distribution of reinforcing agents in the polymer matrix, which absorbs and dissipates the impact energy[26-29]. It can be used in dynamic applications where impact resistance is as important as strength and stiffness, since it has been proven to withstand impact forces without a significant degradation of properties. The results are consistent with the current trends in sustainable polymer development, in which mechanical properties have been enhanced through the addition of natural fibers, nanoparticles, or other bio-based additives. For instance, it was stated that with the addition of cellulose nanofibers, PLA materials showed similar improvements in tensile and flexural properties. Such approaches often have a trade-off, however, lower elongation at break and increased brittleness. A balanced mechanical performance of synthesized polymer points to successful solutions of trade-offs while providing robust alternatives to conventional material.

The synthesized polymers demonstrated outstanding printability characterized by excellent layer adhesion, low defects upon FDM processing, and acceptable dimensionally accurate printed specimens in tolerances, thus applicable to precision manufacturing. Such features are essential for practical purposes, wherein the material under study must have not only a high strength in mechanical properties but also process reliably on commercial FDM systems. Indeed, the problem in the development of sustainable polymers for FDM was how to ensure the environmental benefits without compromising the performance. The results have shown that sustainability is feasible with high-performance characteristics. This dual aspect is a prerequisite for the mass acceptance of sustainable polymers in industrial applications since the need for both good performance and reduced environmental impact applies here. This synthesis and characterization of the polymer present a very significant breakthrough in the development of high-performance sustainable polymer materials. Such a material boasts superior mechanical performance in additive manufacturing and also good characteristics of environmental sustainability. The synthesis process can be scaled up and the durability of the material studied with respect to different environmental conditions, whereby the performance is maintained in real-world applications.

5. Conclusion

This study shows that highly performing sustainable polymers synthesized through such a route are useful in FDM. Enough enhancement in the mechanical performances could be found, where the tensile strength achieved value up to 55 MPa, and the flexural strength achieved value up to 80 MPa; both were significantly higher compared to the traditional PLA-based composites. Additionally, better impact resistance at 4.5 kJ/m^2 indicates the material could also be used in dynamic applications within various industries. The results reveal that with appropriate selection of bio-based monomers and proper optimization of the polymerization process, it is possible to produce materials balancing sustainability and high performance. The outstanding printability of the synthesized polymers characterized by good layer adhesion and dimensional accuracy supports the practical applicability of the materials in FDM technologies. This research adds to the work being conducted on developing sustainable materials without sacrificing mechanical performance, one of the more significant challenges facing additive manufacturing. Further work should thus be placed on the scaling up of the synthesis procedure and the long-term performance under different environmental conditions for these polymers to ascertain their viability in real applications.

Author contributions

Conceptualization, RS and MAR; methodology, RS, MAR, PT,WWM, STA, RDH, ZNJ, MAM & APK; software, RS, MAR, PT,WWM, STA, RDH, ZNJ, MAM & APK; validation, RS, MAR, PT, WWM, STA, RDH, ZNJ, MAM &APK; formal analysis, RS, MAR, PT,WWM, STA, RDH, ZNJ, MAM &APK; investigation, RS; resources, RS; data curation, MAR; writing—original draft preparation, RS, MAR, PT, WWM, STA, RDH, ZNJ, MAM &APK; writing—review and editing, RS, MAR, PT, WWM, STA, RDH, ZNJ, MAM &APK; visualization, RS; supervision, RS; project administration, RS; funding acquisition, RS, MAR, PT,WWM, STA, RDH, ZNJ, MAM &APK.

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Conflict of interest

The authors declare no conflict of interest.

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