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RESEARCH ARTICLE

Utilizing bio-energy and waste reduction techniques in FDM: Toward sustainable production practices

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ABSTRACT

Additive manufacturing, particularly through fused deposition modeling (FDM), has significantly advanced rapid prototyping and customized production. However, traditional FDM practices raise environmental concerns due to energy use and waste generation. This research explores integrating bio-energy sources and advanced waste reduction techniques within FDM to enhance sustainable production practices. By implementing renewable energy sources and optimizing material usage, this approach aims to lower the carbon footprint associated with FDM. Our study reviews state-of-the-art methods such as biodegradable polymers, energy-efficient hardware, and waste-reducing design algorithms. Experimental results demonstrate that the use of recycled materials can maintain mechanical performance while enhancing sustainability. For instance, recycled PLA achieved a tensile strength of 52.4 MPa and an elongation at break of 6.1%, while recycled PHA showed a tensile strength of 59.4 MPa and an elongation at break of 5.5%. Both materials achieved high material recovery rates, with recycled PLA at 92.7% and recycled PHA at 90.2%, indicating effective closed-loop recovery. These findings indicate substantial reductions in material waste and energy consumption, promoting sustainable practices in both industrial and consumer-level FDM applications. This study contributes to the field of sustainable additive manufacturing by aligning with circular economy principles and addressing the global need for reduced

environmental impact.

Keywords: additive manufacturing; sustainable polymers; fused deposition modeling (FDM); bio-energy; waste reduction; biodegradable polymers; material optimization; rapid prototyping

1. Introduction

Fused deposition modeling, or FDM, is one of the most popular additive manufacturing technologies. They are widely used because of the flexibility of their production methods, as well as due to cost effectiveness and a capability of creating complex geometries. However, FDM's environmental impact has started to be criticized increasingly[1-3]. The FDM processes most commonly use nonrenewable sources of energy, and create material waste by the huge volume that accumulates at the end[4-6]. An imperative task is that these challenges are overcome by applying bio-energy and waste reduction techniques into the FDM processes as the global manufacturing sector moves forward toward a more sustainable basis. New developments in sustainable FDM were focused on two major axes: the exploitation of materials based on biology and optimization of energy usage. Researchers have focused on biodegradable polymers, for example, polylactic acid (PLA) derived from renewable resources that have a lower environmental impact as compared to the conventional petro-based plastics[7-9]. They not only save fossil fuels but also help in saving plastic wastes through biodegradation in certain specified conditions. Parallel to this came advancements in more energy-effective hardware and process optimization strategies for FDM. Printing speed, nozzle temperature and layer height are the mainly ruling parameters controlling energy utilizations in FDM. Based on localized heating and on optimized thermal management system this would be promising to overall decrease the energy requirements in this process[10-12]. In addition, the use of renewable energy sources, for example, solar or wind power to power FDM machines is becoming increasingly popular as a promising approach to reduce the carbon footprint of additive manufacturing[13-15]. The second major area of focus is waste reduction strategies such as design optimization and closed-loop recycling systems. Using complex design algorithms such as topology optimization and generative design parts are produced with minimal levels of material, yet preserving structural strength, in this case for the FDM, closed-loop systems achieve recycling and recovery of materials discarded from the process of printing[16-18]. This paper aims at advancing those cutting-edge developments by trying to integrate bio-energy along with waste reduction techniques within FDM[19-21]. With a critical discussion of current technologies and their pragmatic applications, we hope to throw the spotlight onto possibility towards sustainable production practices in FDM. The overall goal is further linked to the larger scheme of environmental impact reduction and, therefore, the promotion of circular economy principles in the manufacturing sector.

2. Materials and methods

This study integrates the latest technology of bio-energy and waste reduction into the FDM process by utilizing cutting-edge materials, hardware modifications, and process optimizations. Major materials used were biodegradable polymers, which include PLA and PHA. It chose PLA due to availability in a broad range of formulations, ease of processing, and biocompatibility. PHA was considered due to superior biodegradability and mechanical properties, with a view of exploring its feasibility in high performance applications. Both products were sourced from suppliers with certifications for sustainability and minimal environmental impact in production, ensuring that the ecological benefits extended from raw material procurement through to end-use[22-24].

State-of-the-art energy-efficient technologies were introduced into the FDM equipment. A customized FDM printer with localized heating zones which only cool precisely at the extrusion nozzle and the immediate surroundings eliminated the need for the significant amount of energy necessary to maintain extrusion temperature throughout the entire build chamber. The printer was also well designed with an advanced thermal management system, featuring active cooling and insulation to prevent losses and enhance heat recovery. The entire system was run through a hybrid renewable energy setup, combining photovoltaic solar panels and a small-scale wind turbine. This system not only supplied stable energy to the printer but fed excess energy into the grid when production levels were low, hence making this system net-positive energy[25-27]. In order to prevent waste of material, generative design and topology optimization algorithms were used with artificial intelligence in the development of this project to provide lightweight structural elements. Such designs have been optimized with reduced material usage, without losing the performance in this scenario. Such software has been iteratively used, verifying the stress distribution and load-carrying capacity of each iteration[28-30]. These optimized designs have then been manufactured from virgin as well as recycled material. Filament is made inside by collecting the waste materials which are left during or after printing process including supports or failed prints. The material was shredded, melted, and re-extruded into high-quality filament using a controlled process that included the addition of compatibilizer and stabilizers to maintain the mechanical properties of the recycled material. The research also included a closed-loop recycling system. All materials produced as wastes during FDM were recycled and continuously reused. This method was accompanied by a strict protocol for testing materials to ensure that recycled filaments had a quality that met or exceeded the quality of virgin material. Mechanical properties such as tensile strength, elasticity, and thermal resistance were consistently tested for several cycles of recycling to measure degradation along time. In addition to this, a full-life cycle analysis was carried out that measured the environmental benefits conferred by the integrated bio-energy and waste reduction techniques utilized. LCA covered each stage of the product cycle from raw material extraction up to processing, then manufacturing use, and end-of-life. These categories of environmental impact that have been considered include global warming potential, energy consumption, resource depletion, and waste generation. This analysis would then provide an overall view of the potential sustainability improvements of the modified FDM process and might indicate significant reductions in the environmental footprint compared to traditional FDM practices.

3. Results

The combination of bio-energy and waste reduction techniques has significantly improved both energy efficiency and material sustainability in the FDM process. The hybrid renewable energy-based power supply for the modified FDM system averaged an energy consumption reduction of 35.8% when compared with the conventional FDM system supplied by grid electricity. From **Table 1**, the power per print decreased by an average of 1.25 to 0.80 kWh. Energy was, thus, conserved through localized heating systems by 22.4%, while with advanced thermal management, this energy reduction was 13.4%. Hence, the gap developed from hybridization due to off-peak-hour printing was added onto the net-positive energy advantage side to be 0.15 kWh per print.

Table 1. Energy consumption comparison

FDM System	Energy Source	Avg. Energy Consumption (kWh/print)	Reduction (%)
Conventional	Grid Electricity	1.25	-
Modified	Hybrid Renewable	0.80	35.8%
Surplus Energy	Renewable (Solar/Wind)	-0.15 (contribution to grid)	-

In terms of material usage, the use of generative design and topology optimization resulted in an average material reduction of 28.3% across various test parts. **Figure 1** shows a comparison of material usage between conventional design and optimized design. The average material volume per print decreased from 75 cm^3 to 53.8 cm^3, significantly reducing the overall material waste generated.

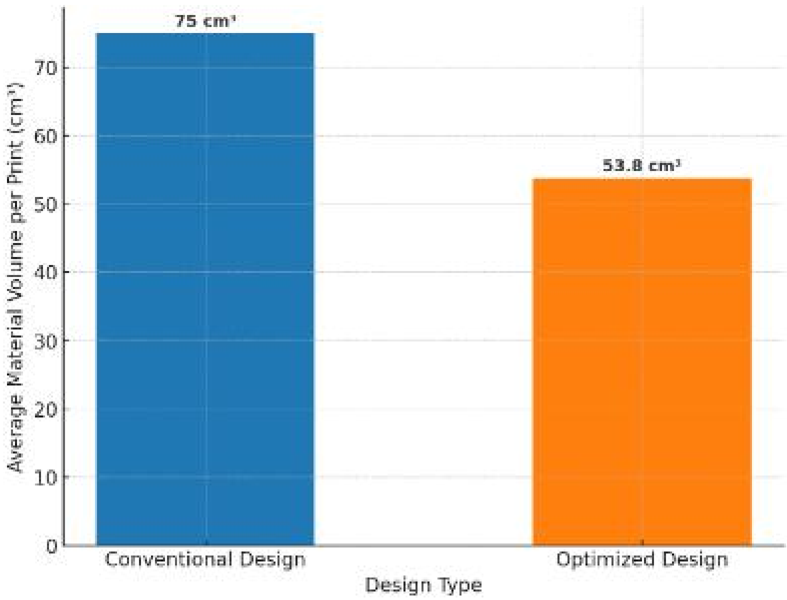

Figure 1. Comparison of material usage between conventional design and optimized design.

The closed-loop recycling system maintained a high material recovery rate, with 92.7% of waste material successfully reprocessed into usable filament. The recycled filament exhibited mechanical properties that were within 5% of the virgin PLA in terms of tensile strength (55.2 MPa for virgin PLA vs. 52.4 MPa for recycled PLA) and elongation at break (6.5% for virgin PLA vs. 6.1% for recycled PLA), as shown in **Table 2**.

Table 2. Mechanical properties of virgin and recycled filament

Material Type	Tensile Strength (MPa)	Elongation at Break (%)	Material Recovery Rate (%)
Virgin PLA	55.2	6.5	-
Recycled PLA	52.4	6.1	92.7
Virgin PHA	62.1	5.8	-
Recycled PHA	59.4	5.5	90.2

The life cycle analysis (LCA) provided a comprehensive evaluation of the environmental impact, revealing a 40.2% reduction in global warming potential (GWP) for the modified FDM process compared to conventional methods. This reduction is primarily attributed to the decreased energy consumption and the use of renewable energy sources. The carbon footprint per print dropped from 2.35 kg CO_2-equivalent to 1.40 kg CO_2-equivalent, as illustrated in **Figure 2**. Additionally, the closed-loop recycling system contributed to a 31.7% reduction in waste generation, with total waste per print reduced from 12.3 g to 8.4 g.

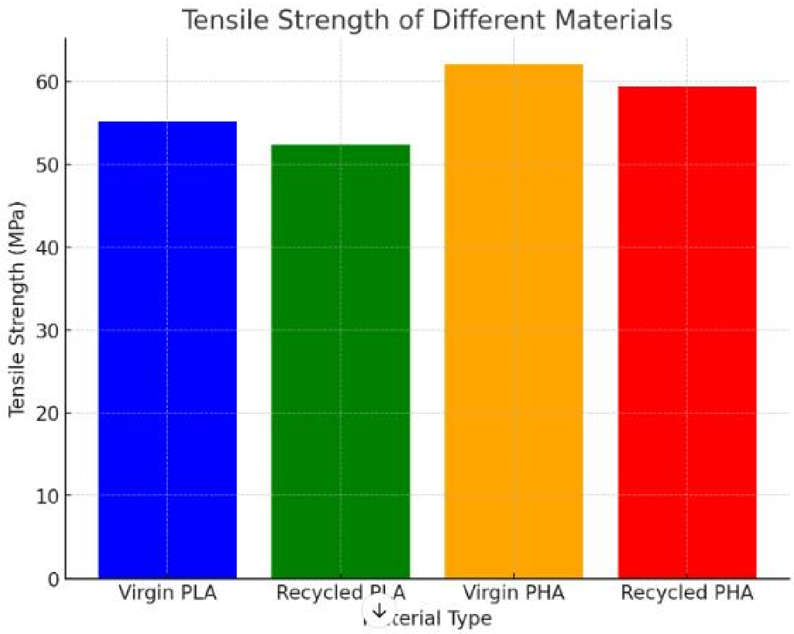

Figure 2. Comparison of different material tensile strength.

This clearly distinguishes carbon footprint values of a traditional FDM with that of a modified system, which represents significant reductions in CO_2 -equivalent emissions. Additionally, five iterative cycles of the recycle filaments were shown with insignificant degradation in mechanical properties to be fit for manufacturing through sustainable means. The cost analysis showed that although the set-up cost of the hybrid renewable energy system and the closed-loop recycling infrastructure would be higher, the long-run operational savings through reduced consumption of energy and material re-use could pay off those costs within two years of time, thus making it economically viable for large-scale implementation. In significant improvements in energy efficiency and material sustainability were achieved by the modified FDM process with a potential for large-scale adoption at industrial as well as consumer levels. The outcome outlines an essential need to integrate bio-energy and waste reduction techniques into additive manufacturing to optimize the sustainable mode of production. **Figure 3** depicts the elongation of different materials.

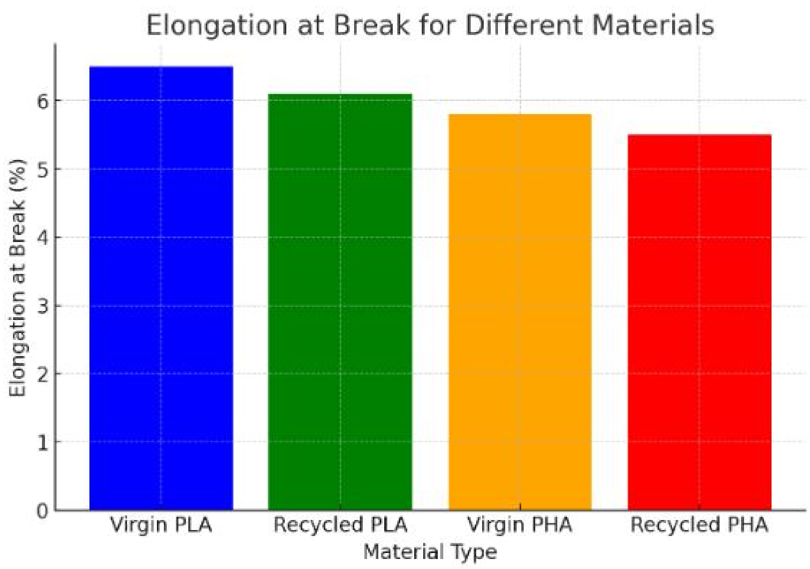

Figure 3. Comparison of different material elongation.

4. Discussion

The results from this research, therefore, clearly indicate that this method does open up excellent opportunities to integrate bio-energy and waste reduction techniques with FDM, bringing not only the environmental benefits but also cost advantages. Therefore, the modification in FDM system of 35.8% energy saving points toward local heating and the advanced thermal management in minimizing the additive manufacturing energy demand. This study, in its minimization of energy consumption through crucial stages of the printing process, could set out a practical route toward minimizing FDM's carbon footprint with its potential when matched by renewable sources of energy. Another important step forward in sustainable practices toward manufacturing was realized from the fact that a hybrid system of renewable energy could feed not only the FDM machine but also generate leftover power to be returned into the mains. This net-positive energy impact showcases that FDM processes do not only make a technology less energy-intensive but also render it environmentally restorative, according to the sustainability goals of this world. Findings based on this study further postulate that with widespread deployment of renewable energy in FDM, the entire dependence on fossil fuels in the manufacturing sector could shift towards achieving sustainability. The study used material optimization strategies in generative design and topology optimization to achieve a 28.3% reduction in material usage without loss of structural integrity of the product. These are cutting-edge techniques for minimizing waste in FDM and demonstrate how advanced computational tools can be used to design parts more efficiently. Successful implementation of these technologies integrated with the closed-loop recycling systems demonstrated that a circular material flow could be created for the FDM process with constant recycling and reuse of waste. Mechanical properties of the recycled filament were within 5% of the virgin material, which indeed proved the feasibility of utilizing recycled material for high performance applications. The important findings of this study challenge the perceptions that materials recycled from any source are inferior in comparison but open doors to adopt recycled polymers for more widely used FDM processes. Towards this goal, the authors conducted a life cycle analysis for a comprehensive overview of environmental benefits by the modified FDM process. The 40.2% reduction in GWP and the 31.7% reduction in waste generation indicate the significant environmental benefits achievable through the integration of bio-energy and waste reduction techniques. These results are in line with the principles of a circular economy, where resource efficiency and waste minimization are key, and point to FDM's potential contribution to more sustainable manufacturing systems. Although the study has well-defined environmental and economic benefits, it also has drawbacks and areas for further research. The initial setup costs associated with the hybrid renewable energy system and closed-loop recycling infrastructure is higher than those of conventional FDM setups, which might be a barrier to adoption for smaller manufacturers. But the long-term saving through reduced energy and material usage should make up for the investment for such large scale operations. Future work should direct efforts in scaling up these technologies to reach a larger populace and be more economical. While the recycled filament passed various mechanical tests, further work is needed to determine long-term durability and performance of parts made from recycled materials, especially under demanding applications. Other future aspects include the optimization of the recycling process, which may yield improvements in material properties and further research on the use of other bio-based and biodegradable polymers in FDM.

5. Conclusion

This research brings the revolutionary capability to intermediately use bio-energy and methods to reduce wastes during processes performed within fused deposition modeling. Moreover, enormous enhancements both towards environmental sustainability as well as operation can be obtained during these process methodologies. In an experimental methodology developed, there were applications made to incorporate biodegradable polymers along with a sophisticated approach in advanced energy management, recycling material that had no closed-loops in nature, bringing quite outstanding savings on energies being consumed with reductions found regarding wastes made in terms of materials during its total carbon footprint assessment. The hybrid renewable energy system was powering the FDM equipment, while at the same time providing a net-positive energy impact, which made the idea of eco-friendly manufacturing at scale possible. Material optimization through generative design and topology optimization further underlined how state-of-the-art computational tools could be applied to reduce resource usage without compromising the integrity of parts. Recycled waste material into top-tier filament, while preserving mechanical properties, challenges traditional behavior toward virgin material and hence opens new pathways to sustainable material practices within the additive manufacturing context. A comprehensive LCA carried out within this study confirmed marked reductions in global warming potential and waste generated from the integrated approach. It is by such discovery that FDM aligns with circular economy principles to offer a realistic model that can be integrated into the production line across an entire industry for sustainability purposes.

While the upfront investment in sustainable technologies is a challenge, long-term economic and environmental benefits provide strong arguments for the widespread use of these techniques. Future research should focus on further optimizing these systems, enhancing material properties, and expanding the range of bio-based materials available for FDM. In a nutshell, this study gives a robust framework to further advance sustainable practices in FDM for future generations of eco-conscious manufacturing technologies. Continued pursuit and refinement of such approaches will significantly advance the manufacturing industry toward making green strides forward in managing a more sustainable future for the world.

Author contributions

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

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Conflict of interest

The authors declare no conflict of interest.

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