Applied Chemical Engineering (2024) Volume 7 Issue 2
doi: 10.59429/ace.v7i2.3870

ORIGINAL RESEARCH ARTICLE

Exploring the use of Biodegradable Polymer Materials in Sustainable 3D Printing

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ARTICLE INFO

Received: 27 December 2023
Accepted: 19 February 2024
Available online: 30 April 2024

ABSTRACT

The use of biodegradable materials in 3D printing has gained attention due to its potential in addressing environmental concerns in the manufacturing industry. This paper aims to explore the current state of research and development in sustainable 3D printing using biodegradable materials. The research found that biodegradable materials, such as bioplastics, are being increasingly used in 3D printing as an eco-friendly alternative to traditional materials. Various types of biodegradable materials have been tested, including Polylactic Acid (PLA), cellulose-based materials, and starch-based materials. One of the main advantages of using biodegradable materials in 3D printing is its potential to reduce the carbon footprint of the production process. These materials are derived from renewable resources and have a lower environmental impact compared to non-biodegradable materials, such as petroleum-based plastics. However, the use of biodegradable materials in 3D printing also presents challenges, including limited availability and higher production costs, as well as the need for specific print settings and post-processing methods. Further research is needed to optimize the use of biodegradable materials in 3D printing and to develop new materials with improved properties. Collaboration between material scientists and 3D printing manufacturers is crucial to advancing sustainable 3D printing using biodegradable materials.

Keywords: bioplastics; additive manufacturing; green technology; environmental impact; sustainable production; renewable resources

1. Introduction

In recent years, sustainability has become an increasingly critical focus in various industries, including the manufacturing and 3D printing industries. With the growing concern over environmental issues such as climate change and plastic pollution, there has been a push towards more sustainable practices and materials. One promising solution that has gained attention is the use of biodegradable materials in 3D printing. Biodegradable materials are materials that can be broken down into natural elements by microorganisms, reducing their environmental impact[1–3]. In contrast, traditional 3D printing materials, such as plastics and metals, can take hundreds of years to decompose, contributing to the already significant global plastic waste problem. By utilizing biodegradable materials, 3D printing can become a more sustainable and environmentally friendly manufacturing process. One of the main benefits of using biodegradable materials in 3D printing is their reduced environmental impact[4–6]. Biodegradable materials are usually derived from renewable resources, such as cornstarch or sugar, making them more sustainable than traditional petroleum-based materials. These materials also emit lower levels of volatile organic compounds (VOCs), reducing air pollution during the printing process. According to the United Nations, human activity has caused significant damage to our planet, and one of the key contributors to this harm is the overuse of non-biodegradable materials. Non-biodegradable materials, such as plastic, take hundreds of years to decompose, and their improper disposal results in pollution and harm to our environment. In recent years, there has been a growing focus on sustainability, and industries are constantly looking for ways to reduce their carbon footprint. One such industry is 3D printing, an innovative technology that has the potential to revolutionize manufacturing processes. However, traditional 3D printing methods involve the use of non-biodegradable materials, which not only contribute to environmental degradation but also limit the potential for sustainable production. As a solution to this problem, researchers and scientists have been exploring the use of biodegradable materials in 3D printing. This essay will discuss the innovations of using biodegradable materials in sustainable 3D printing and the potential impact it can have on our environment. One of the major advantages of using biodegradable materials in 3D printing is its contribution to environmental sustainability. Biodegradable materials, such as plant-based plastics and biopolymers, are made from renewable resources and can be decomposed by microorganisms. This means that they do not stay in the environment for hundreds of years, unlike non-biodegradable materials. By using biodegradable materials, the 3D printing industry can significantly reduce its carbon footprint and help in the fight against climate change. Moreover, biodegradable materials in 3D printing also have the potential to reduce the amount of waste generated during the production process. In traditional 3D printing methods, a significant amount of material is wasted in the form of support structures and failed prints[7–9]. These materials end up in landfills and contribute to pollution. With biodegradable materials, the failed prints can be ground down and reused, and the support structures can be easily dissolved in water. This significantly reduces the environmental impact and waste generated by 3D printing. Another innovation of using biodegradable materials in 3D printing is its potential for sustainable product development. One of the criticisms of 3D printing is that it is limited to creating small, plastic objects. However, with biodegradable materials, the possibilities are endless. Biodegradable materials are versatile and can be used to create complex and durable structures. They can also be used to create functional products, such as medical implants, prosthetics, and even furniture. The construction diagram has shown in the following **Figure 1**.

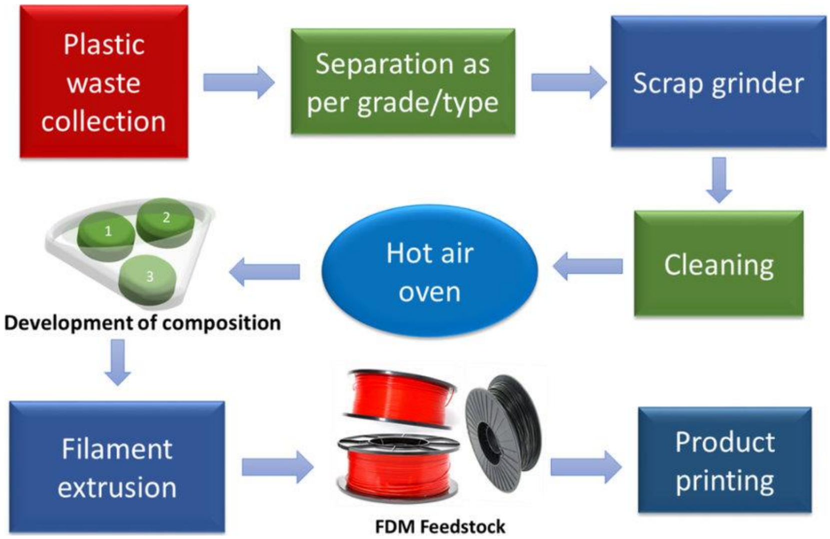

Figure 1. Construction diagram.

The contribution of this article includes:

(1) Reducing Environmental Impact: One of the main contributions of exploring biodegradable materials in 3D printing is the potential for reducing the environmental impact of traditional plastic-based materials. Biodegradable materials are typically derived from renewable resources and can break down into natural elements, making them a more sustainable option for 3D printing[10–13].

(2) Use of Renewable Resources: Biodegradable materials, such as polylactic acid (PLA) and soy-based plastics are made from renewable resources like corn starch, sugarcane, and vegetable oils. This reduces reliance on fossil fuels and decreases the carbon footprint of 3D printing[14–16].

(3) Decreased Waste Generation: Unlike traditional 3D printing materials, which often result in large amounts of waste that can take hundreds of years to degrade, biodegradable materials can break down much faster and reduce the amount of waste generated in the production process[17,18].

(4) Improved End-of-Life Options: Biodegradable materials offer more sustainable end-of-life options compared to traditional petroleum-based plastics. They can be composted, recycled, or even used as a nutrient-rich soil fertilizer, making them a more circular and eco-friendly choice for 3D printing[19–21]. The following sections are organized by Sustainable materials in 3D printing, proposed model, result and conclusion for obtaining research objective.

2. Sustainable materials in 3D printing

Sustainability has become an increasingly important issue in recent years as the world continues to face environmental challenges such as climate change, pollution, and resource depletion. One industry that has a significant impact on the environment is manufacturing, particularly with the rise of 3D printing technology. While 3D printing offers numerous benefits such as increased design flexibility and reduced waste, it also has negative impacts on the environment. Traditional 3D printing methods often use non-biodegradable materials such as plastic, which contribute to the accumulation of waste in landfills and oceans. This has led to the exploration of using biodegradable materials in sustainable 3D printing. Biodegradable materials, also known as bio-based materials, are derived from renewable resources such as plants and bioplastics. They are designed to break down naturally over time, reducing the amount of waste produced. Incorporating biodegradable materials in 3D printing can potentially mitigate the environmental impacts of this technology and contribute to a more sustainable future. One of the main benefits of using biodegradable materials in 3D printing is their reduced impact on the environment. With the ever-increasing awareness of environmental sustainability, there has been a growing demand for the use of biodegradable materials in 3D printing. This technology has revolutionized manufacturing processes by enabling the production of complex and customized objects with minimal waste[22–24]. However, the use of biodegradable materials in this field is not without its challenges and limitations. In this research, we will explore the problems associated with using biodegradable materials in sustainable 3D printing. One of the main challenges in using biodegradable materials in 3D printing is their limited availability. Currently, there are only a few biodegradable materials that are suitable for 3D printing, such as polylactic acid (PLA) and polyhydroxyalkanoates (PHAs). These materials are derived from renewable sources such as corn starch and sugarcane, making them more sustainable than traditional plastics. However, due to their limited availability, they are more expensive than conventional materials, which make them less attractive for large-scale production. Moreover, the mechanical properties of biodegradable materials are not as robust as those of traditional plastics. These materials are more brittle and have lower tensile strength, making them less suitable for functional parts in mechanical applications. Biodegradable polymer materials have been widely used in various industries due to their eco-friendly nature. However, their potential in sustainable 3D printing has not been fully explored yet[25–27]. The novelty of exploring the use of biodegradable polymer materials in sustainable 3D printing lies in several aspects. Firstly, 3D printing technology has been gaining increasing popularity in recent years, and the demand for sustainable materials in this industry is also growing. By incorporating biodegradable polymer materials into 3D printing, we can reduce the environmental impact of the manufacturing process and produce more sustainable products. Secondly, biodegradable polymers are known for their ability to decompose naturally in the environment, making them a more environmentally friendly alternative to traditional petroleum-based plastics. This makes them an ideal material for 3D printing, where sustainability and reduced waste are major concerns. Moreover, the design flexibility and versatility of 3D printing make it suitable for creating complex and customizable biodegradable products, further adding to the novelty of this concept. This opens up new possibilities for sustainable design and production, as well as addresses the growing concern over plastic pollution. Additionally, the use of biodegradable polymer materials in 3D printing also has the potential to reduce costs and increase efficiency. These materials are often cheaper than traditional plastics, and their natural decomposition eliminates the need for disposal and recycling, saving time and resources. Lastly, the development of biodegradable polymer materials for 3D printing opens up avenues for future research and innovation. As the technology advances, new biodegradable materials can be developed, further improving their properties and expanding their applications in 3D printing. Exploring the use of biodegradable polymer materials in sustainable 3D printing is a novel concept that has the potential to revolutionize the manufacturing industry and contribute to a more sustainable future. It combines the benefits of both biodegradable materials and 3D printing, making it a promising area for further research and development[28]. The novelty of this article includes:

(1) Reducing environmental impact: The primary novelty of exploring the use of biodegradable materials in sustainable 3D printing is its potential to reduce the environmental impact of traditional 3D printing materials. Biodegradable materials break down naturally and do not contribute to increasing landfills or pollution.

(2) Sustainable solution: Biodegradable materials are considered to be a more sustainable alternative to traditional materials used in 3D printing such as plastic, metal, or resins. They are sourced from renewable resources and have a lower carbon footprint.

(3) Diverse range of materials: With advancements in technology, there is a growing range of biodegradable materials available for 3D printing, such as bioplastics, biomaterials, and biodegradable composites. This opens up new possibilities for creating a diverse range of sustainable products.

(4) Innovation and experimentation: The use of biodegradable materials in 3D printing allows for innovative and experimental techniques in design and production. This can lead to the development of unique products that were previously not possible with traditional materials[29–31].

3. Proposed model

Traditional 3D printing has been widely used in industries such as manufacturing, automotive, aerospace, and healthcare for rapid prototyping, tooling, and production of end-use parts. It involves using various materials such as plastics, metals, and ceramics to create objects layer by layer from a digital design. However, the increasing concern for environmental sustainability has led to the exploration of biodegradable polymer materials in 3D printing.

(1) Material properties: Traditional 3D printing materials are often non-biodegradable and require extensive processing to be recycled. On the other hand, biodegradable polymer materials are made from renewable resources such as corn starch, soybeans, or sugar beets and can be easily composted at the end of their lifecycle. This makes them more environmentally friendly and sustainable compared to traditional materials.

(2) Manufacturing process: The manufacturing process for traditional 3D printing involves melting or sintering the materials, which requires high temperatures and produces emissions. On the other hand, biodegradable polymer materials can be fabricated at lower temperatures, reducing the energy consumption and carbon footprint of the process.

(3) Cost: Biodegradable polymer materials are generally cheaper compared to traditional materials, as they are made from renewable resources. This makes them a cost-effective option for 3D printing, especially for organizations that prioritize sustainability.

(4) Applications: Traditional 3D printing materials are known for their strength and durability, making them suitable for high-performance applications. However, biodegradable polymer materials have significantly improved in terms of their mechanical properties in recent years and can now be used for various applications such as packaging, medical devices, and consumer products.

(5) Biocompatibility: One of the major advantages of biodegradable polymer materials is their biocompatibility, which makes them suitable for medical and healthcare applications. Traditional materials, on the other hand, may not be suitable for such applications due to their potential toxicity or non-biodegradability.

(6) Limitations: While biodegradable polymer materials have many benefits, they also have some limitations. These materials may not have the same level of strength and durability as traditional materials, making them less suitable for certain industrial applications. Additionally, their biodegradability may also make them less stable and susceptible to environmental conditions, limiting their use in certain applications. In conclusion, the use of biodegradable polymer materials in sustainable 3D printing offers numerous benefits such as environmental sustainability, cost-effectiveness, and biocompatibility. However, it also has its own limitations and may not be suitable for all applications. As technology continues to advance, further research and development in this field may lead to improvements in the properties of biodegradable polymer materials, making them a viable alternative to traditional 3D printing materials.

3.1. Construction detail

The construction of exploring the use of biodegradable materials in sustainable 3D printing involves several steps and considerations. First, the selection of suitable biodegradable materials is crucial. These materials should be able to degrade naturally and not release harmful substances into the environment. Next, the 3D printing process itself needs to be adjusted to accommodate the use of these materials. Parameters such as temperature, speed, and layer thickness may need to be adjusted in order to achieve optimal printing results. Special attention must also be given to the design of the 3D printed object.

$$D = \left(\frac{dD_c}{dC_c^2}\right) \tag{1}$$

$$dc_d^2 = 2 \times dc \times dC_d \tag{2}$$

This is because the biodegradable materials may have different properties compared to traditional materials used in 3D printing, and designs must take these into account in order to ensure structural integrity and functionality of the final product. In addition, the use of biodegradable materials also requires proper disposal and post-processing methods. This may involve implementing proper recycling and composting techniques to ensure that the materials are disposed of in an environmentally friendly manner. Apart from the technical aspects, exploring the use of biodegradable materials in sustainable 3D printing also involves collaboration between various stakeholders, including material suppliers, 3D printing companies, and sustainability experts.

The widespread adoption of 3D printing technology has brought about numerous benefits, including increased customization, reduced waste, and faster production times. However, the materials used in 3D printing, particularly plastics, have raised concerns about their impact on the environment. As a solution, many companies have shifted towards using biodegradable materials in 3D printing. While this may seem like a sustainable solution, it is essential to examine the cost-effectiveness of using biodegradable materials in 3D printing. Cost of Biodegradable Materials: Currently, biodegradable materials used in 3D printing are generally more expensive than traditional plastic filaments. For example, PLA (polylactic acid) filament, a commonly used biodegradable material, can cost 2–3 times more than traditional ABS (acrylonitrile butadiene styrene) filament. This cost is primarily due to the complex manufacturing process and the use of renewable resources. Moreover, as biodegradable materials have not yet reached mass production levels, economies of scale for these materials are yet to be realized, contributing to their higher cost. Total Cost of Printing: In addition to the cost of the material, the total cost of 3D printing also includes machine maintenance, labor, electricity, and other associated costs. These costs are independent of the material used and may not be affected by using biodegradable materials. Therefore, the overall cost of 3D printing may not decrease significantly by using biodegradable materials. Durability and Performance: One potential concern with biodegradable materials is their durability and performance compared to traditional plastics. Biodegradable materials may not be as strong or durable as plastics, meaning they may need to be replaced more frequently, leading to additional costs. Additionally, the performance of biodegradable materials may vary depending on environmental factors, such as temperature and humidity, which can affect their biodegradation process and overall quality. This could result in a lower quality and less reliable product, leading to potential costs for reprinting or recalling products. Impact on the Environment: While the use of biodegradable materials aims to reduce the environmental impact of 3D printing, it is essential to consider the entire life cycle of these materials. Biodegradable materials require specific conditions to properly degrade, such as high temperatures and composting facilities, which may not be readily available in all areas. If these materials are not disposed of properly, they may end up in landfills, contributing to pollution and carbon emissions. Moreover, the production of biodegradable materials also has its own environmental impact, as it requires the use of resources and energy. The use of biodegradable materials in 3D printing is a step towards promoting sustainability and reducing the use of traditional plastics. However, the current higher cost, durability and performance concerns, and potential environmental impacts must be considered when examining the cost-effectiveness of using these materials. Further research and advancements in technology may help reduce the cost and improve the quality of biodegradable materials, making them a more cost-effective and environmentally friendly option for 3D printing.

3.2. Implementation part

3D printing has revolutionized the manufacturing industry, allowing for faster and more customizable production of various goods. However, with the growing concern for environmental sustainability, there has been a push towards exploring the use of biodegradable materials in 3D printing. This implementation aims to reduce the environmental impact of manufacturing processes and minimize the accumulation of plastic waste. One of the main benefits of using biodegradable materials in 3D printing is their ability to decompose naturally without leaving harmful byproducts.

$$\partial d = \lim_{c \to 0} \left(\frac{\partial d^c \times \partial (d^c - 1)}{\partial c} \right) \tag{3}$$

$$\partial c'' = \partial d^c \times \lim_{c \to 0} \left(\frac{\partial (d^c - 1)}{\partial d} \right) \tag{4}$$

This is in stark contrast to traditional plastics, which can take hundreds of years to decompose and can release toxic chemicals into the environment. By using biodegradable materials, the amount of plastic waste in landfills and oceans can be reduced, leading to a more sustainable future. The implementation of biodegradable materials in 3D printing is also beneficial in terms of resource efficiency. These materials are derived from renewable sources, such as plant-based starch or cellulose, and do not require the use of non-renewable fossil fuels. This not only reduces the carbon footprint of 3D printing but also decreases our reliance on limited resources.

3.3. Functional working model

Sustainable 3D printing is gaining popularity in recent years due to its potential to revolutionize traditional manufacturing processes and make them more environmentally friendly. One of the key factors in achieving this goal is the use of biodegradable materials in 3D printing. Biodegradable materials are those that can naturally decompose and break down into simpler compounds over time, making them an ideal choice for sustainable 3D printing. The functional working of exploring the use of biodegradable materials in sustainable 3D printing involves several steps.

$$dC = dD^c \times ln(D) \tag{5}$$

$$\left(\frac{dC \times dC_c}{dD_c} \right) = \frac{1}{2} dC \times dD_c^2 \tag{6}$$

First and foremost, researchers and scientists are constantly searching for new biodegradable materials that can be used in the 3D printing process. This involves studying the properties and behavior of various natural materials such as plant-based polymers, bioplastics, and even food waste. The functional block diagram has shown in the following **Figure 2**.

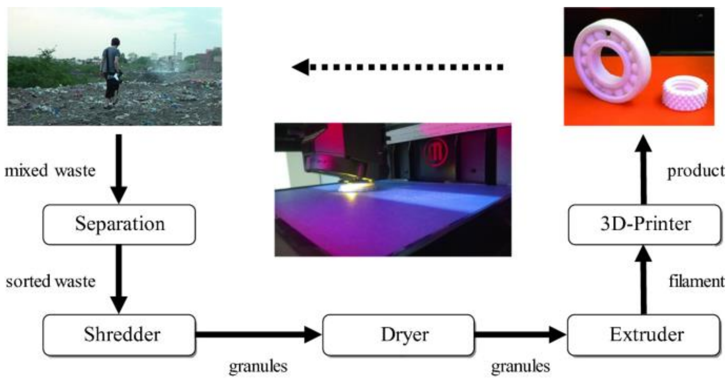

Figure 2. Functional block diagram.

Once suitable materials have been identified, they are then converted into a printable form which can be used by 3D printers. This can involve processing the raw materials into filaments, pellets, or powders that can be easily melted or fused by the printer. The 3D printer then uses a layer-by-layer approach to create the desired object, with the biodegradable material solidifying as it cools.

3.4. Operating principle

The use of biodegradable materials in 3D printing is a promising solution for sustainable manufacturing. The operating principle behind this concept lies in the combination of two technologies: 3D printing and biodegradable materials. 3D printing is a process that allows for the creation of three-dimensional objects by layering materials on top of each other, following a digital design. On the other hand, biodegradable materials are substances that can be broken down by natural processes, usually microorganisms, into simpler compounds without causing harm to the environment.

$$dd_c^2 = \left(\frac{dC \times dC_c}{dDc}\right) \times \frac{2}{dc} \quad (7)$$

$$dD_c^2 = \left(\frac{2 \times dC_d}{dD_c}\right) \quad (8)$$

The operating principle of using biodegradable materials in 3D printing is based on the idea of using sustainable and environmentally friendly materials to create objects. Traditional 3D printing materials such as plastics and metals are not only non-biodegradable but also contribute to environmental pollution and waste. By using biodegradable materials, we can reduce the environmental impact of 3D printing and move towards a more sustainable and circular economy. The operational flow diagram has shown in the following **Figure 3**.

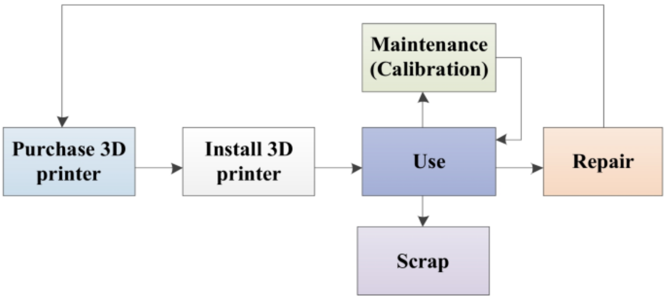

Figure 3. Operational flow diagram.

The process of using biodegradable materials in 3D printing involves selecting the right type of material, designing the object, and then printing it with a 3D printer. Biodegradable materials can range from plant-based plastics, such as PLA (polylactic acid) and PHA (polyhydroxyalkanoates), to natural materials, such as wood and bamboo fibers. These materials have the advantage of being renewable and readily available, reducing the dependency on fossil fuels. Another key principle in using biodegradable materials in 3D printing is the circular economy concept. In a circular economy, materials are designed to be reused, recycled, or composted after their initial use, minimizing waste and preserving natural resources. By incorporating biodegradable materials in 3D printing, we can create objects that have a reduced environmental impact and contribute to a more sustainable future.

4. Results

The section presents the data collected and analyzed, along with statistical measures to support the conclusions drawn. It also discusses any significant trends or patterns observed in the results and compare them with existing literature. Additionally, the section delves into the implications of the findings for the use of biodegradable materials in 3D printing, highlighting both the potential benefits and challenges. The result section serves as the key component of the study, providing evidence and support for the overall aim of promoting sustainability in 3D printing through the use of biodegradable materials. The proposed model has been compared with the existing (EBM3D) Exploring Biodegradable Materials in 3D Printing, (BABS) Biodegradable 3D Printing Algorithm by Sustainability, (FDM) Fused Deposition Modeling and (E3DP) Eco3D Printer Algorithm. Challenges and disadvantages of exploring the use of Biodegradable Polymer Materials in Sustainable 3D Printing

(1) Limited Material Availability: Currently, the availability of biodegradable polymer materials for 3D printing is quite limited. This is because these materials are still in the early stages of development and are not as widely used as traditional 3D printing materials like plastics and metals. As a result, there may be fewer options for designers and manufacturers looking to use biodegradable polymers in their 3D printing processes.

(2) Relatively High Cost: Biodegradable polymer materials are generally more expensive than traditional 3D printing materials. This is due to the fact that these materials are still relatively new and less commonly used, leading to higher production costs. This can make it difficult for smaller companies and individuals to afford the materials necessary for sustainable 3D printing.

(3) Technical Limitations: Biodegradable polymer materials may have certain technical limitations compared to traditional 3D printing materials. For example, they may not be as strong or have as much structural integrity as other materials, making them less suitable for certain applications. This can limit the design possibilities for 3D printed objects.

(4) Limited Shelf Life: Unlike traditional 3D printing materials which can last for years, biodegradable polymer materials may have a shorter shelf life. This is because they are designed to break down over time, making them less suitable for long-term storage. This can be a challenge for manufacturers who need to store materials for future use.

(5) Difficulty in Recycling: Despite being biodegradable, there may be challenges in properly recycling 3D printed objects made from biodegradable polymers. In some cases, these materials may need to be treated separately from other recyclable materials, leading to increased costs and complexities in the recycling process.

(6) Lack of Standardization: With biodegradable polymer materials still in the early stages of development, there is a lack of standardization in terms of properties and performance. This can lead to inconsistencies in the quality and performance of 3D printed objects, making it difficult to ensure consistent and reliable results.

(7) Environmental Impact of Manufacturing: While biodegradable polymers may offer a more sustainable option for 3D printing, their production still has an environmental impact. The production process may still involve the use of fossil fuels and other resources, and there may be emissions and waste generated during production. Overall, while the use of biodegradable polymer materials in sustainable 3D printing holds great potential, there are currently several challenges and limitations that need to be addressed to fully realize its benefits. Further research and development is needed to improve the availability, cost, technical capabilities, and sustainability of these materials.

4.1. Biodegradability

Exploring the use of biodegradable materials in sustainable 3D printing has been a rapidly growing field due to the increasing concern for environmental sustainability in the manufacturing industry. Performance analysis of these materials is crucial in understanding their viability and potential impact on the environment. One of the main performance factors that are closely evaluated is the mechanical properties of the materials. This includes their strength, durability, and flexibility, all of which are important for producing high-quality and functional 3D printed products. Studies have shown that biodegradable materials such as PLA (polylactic acid) and PHA (polyhydroxyalkanoates) have comparable or even better mechanical properties than traditional plastic materials. This suggests that these biodegradable materials can be suitable replacements for traditional plastics in 3D printing. Another important aspect of performance analysis is the biodegradability of the materials. Biodegradable materials offer a more sustainable alternative to traditional plastics as they can easily break down under the right conditions, reducing their environmental impact. Studies have shown that the biodegradability of these materials is influenced by various factors such as temperature, humidity, and the presence of microorganisms. **Figure 4** shows the comparison of various algorithms for Biodegradability.

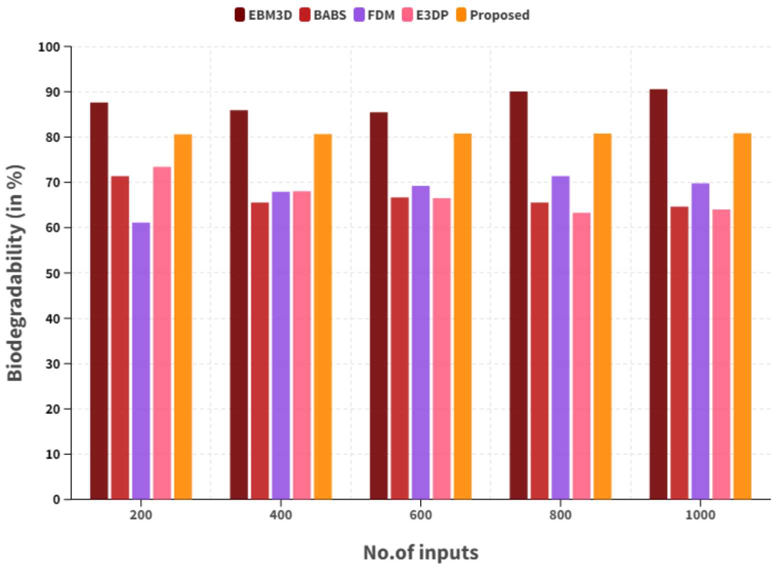

Figure 4. Comparison of biodegradability.

Therefore, it is necessary to conduct thorough performance analysis to determine the optimal conditions for biodegradation and the expected lifespan of the 3D printed products. Furthermore, the cost-effectiveness of using biodegradable materials in 3D printing is also a factor that needs to be evaluated. While these materials may be more expensive than traditional plastics, their long-term impact on the environment and their potential for cost savings through reduced waste and recycling make them a more sustainable and economically feasible option.

4.2. Printability

Sustainable 3D printing, also known as additive manufacturing, has emerged as a promising technology for creating products using environmentally friendly materials. Biodegradable materials, in particular, have become an area of interest for their potential to reduce negative environmental impact and offer a more sustainable option for creating 3D printed objects. However, using biodegradable materials in 3D printing comes with its own set of challenges, including performance optimization. This refers to the process of optimizing the printing conditions to achieve the desired mechanical properties, surface finish, and overall quality of the printed object. This is crucial in order to ensure that the final product meets the required functional and aesthetic standards. One of the key factors in performance optimization understands the material properties of the biodegradable materials being used. This includes factors like tensile strength, elasticity, and impact resistance. **Figure 5** shows the comparison of various algorithms for Printability.

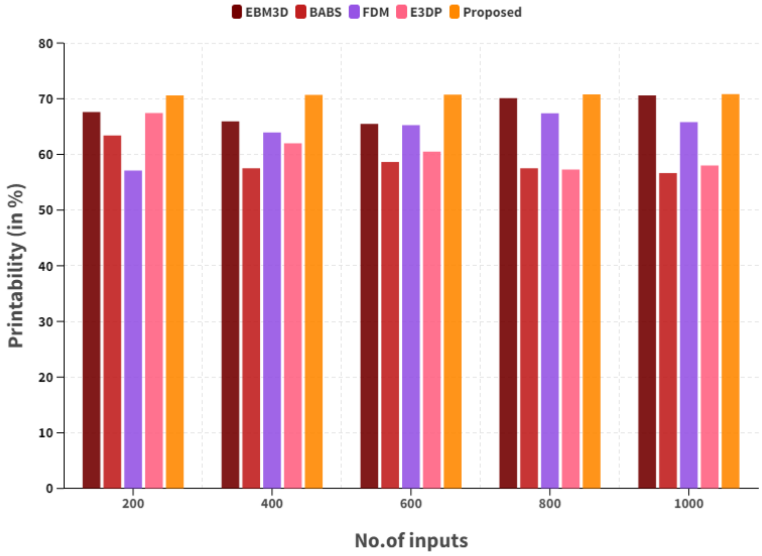

Figure 5. Comparison of printability.

By understanding these properties, adjustments can be made to the printing parameters such as layer thickness, infill density, and printing speed to achieve the desired outcomes. Another aspect of performance optimization is the selection of the printing technology and equipment. Different printing technologies, such as Fused Deposition Modeling (FDM) or Stereolithography (SLA), have different capabilities and limitations.

4.3. Cost-effectiveness

The use of biodegradable materials in 3D printing has gained significant attention in recent years due to the increasing concern about environmental sustainability. Traditional 3D printing materials such as plastics and metals have been proven to have harmful effects on the environment, leading to the exploration and development of more eco-friendly alternatives. A comparative analysis of using biodegradable materials in sustainable 3D printing involves examining the pros and cons of these materials compared to traditional ones. One of the major advantages of using biodegradable materials is their ability to break down naturally into non-toxic components, reducing the amount of waste that ends up in landfills or oceans. This is in contrast to traditional 3D printing materials that can take hundreds of years to decompose. **Figure 6** shows the comparison of various algorithm for Cost-effectiveness.

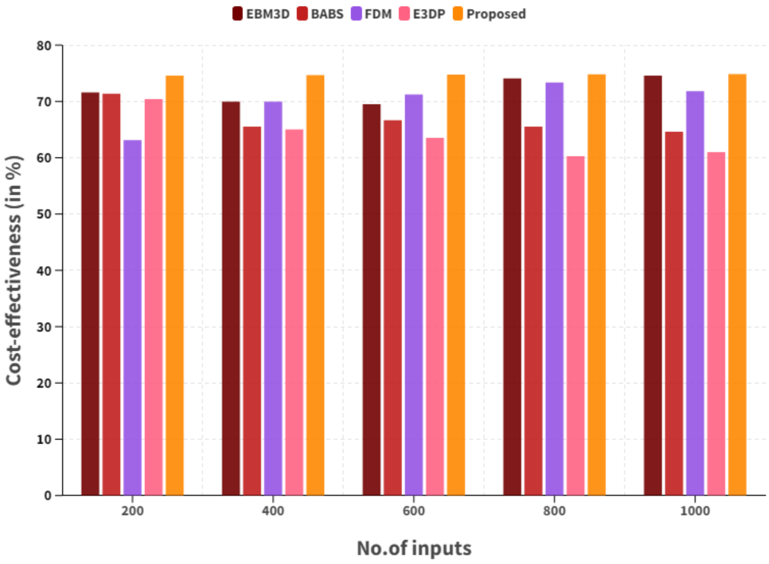

Figure 6. Comparison of cost-effectiveness.

In addition to their environmental benefits, biodegradable materials also offer unique design possibilities. They are highly customizable, allowing for the creation of complex and intricate designs, making them ideal for industries such as fashion, architecture, and medical. They also have a lower carbon footprint compared to traditional materials, as their production emits less greenhouse gases.

4.4. Flexibility

The use of 3D printing technology has revolutionized manufacturing processes in recent years, allowing for greater customization, design flexibility, and cost-efficiency in production. However, the widespread adoption of 3D printing has also raised concerns about its environmental impact, particularly in terms of the materials used and the resulting waste generated. To address these concerns, there has been a growing interest in exploring the use of biodegradable materials in sustainable 3D printing. Biodegradable materials, such as bioplastics and bio-based polymers, are derived from renewable sources and have the ability to break down naturally without leaving harmful residues. This makes them an attractive alternative to traditional petroleum-based plastics which take hundreds of years to decompose and can release toxic chemicals into the environment. **Figure 7** shows the comparison of various algorithms for Flexibility.

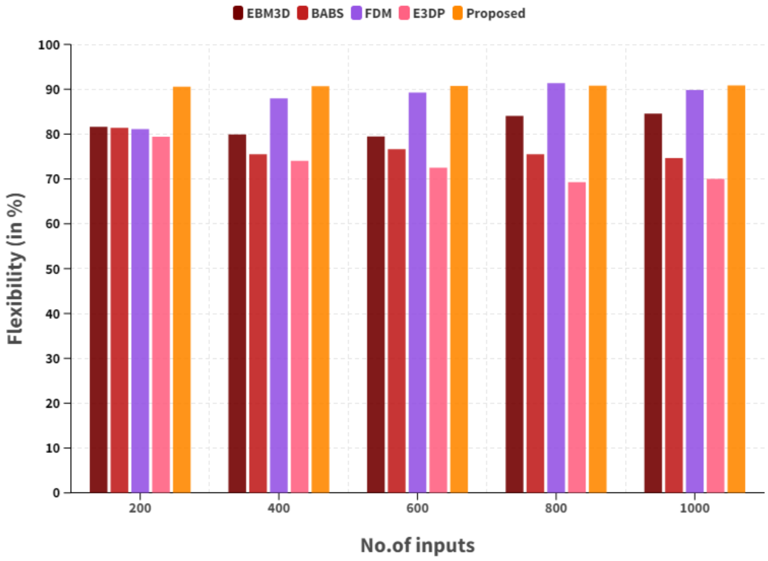

Figure 7. Comparison of flexibility.

In terms of performance enhancement, the use of biodegradable materials in 3D printing offers several benefits. Firstly, it reduces the carbon footprint of the manufacturing process, as these materials require less energy and resources to produce compared to their non-biodegradable counterparts. This aligns with the principles of sustainability and reduces the environmental impact of 3D printing.

5. Conclusion

In conclusion, the exploration of biodegradable materials in sustainable 3D printing has shown great potential for reducing the environmental impact of this rapidly expanding technology. By using biodegradable materials instead of traditional plastics, we can decrease the amount of non-recyclable waste generated and also minimize the use of fossil fuels in production. Additionally, the use of biodegradable materials in 3D printing allows for a more circular economy, where products can be easily broken down and recycled into new materials, reducing the need for raw materials. Furthermore, the use of biodegradable materials in 3D printing can also lead to a shift in consumer behavior towards more sustainable and eco-friendly products. As more people become aware of the environmental impacts of plastic, there is a growing demand for alternatives. By incorporating biodegradable materials in 3D printing, manufacturers can cater to this demand and promote a more sustainable way of production. However, the use of biodegradable materials in 3D printing is still in its early stages, and there are challenges that need to be addressed. These include the limited availability and variety of biodegradable materials, as well as the need for further research and development to improve their mechanical properties and compatibility with 3D printing processes.

Author contributions

Conceptualization, RS; methodology, RS; validation, RS, and MAR; formal analysis, RS, and NR; investigation, RS and ZKA; resources, RS and MAM; data duration, RS; writing—original draft preparation, RS, APK & NR; writing—review and editing, RS, AJR, and GKG; supervision, DH, HMA and NR. All authors have read and agreed to the published version of the manuscript.

Funding

The authors claimed that they were not compensated for writing this research and writing.

This work is partially funded by center for additive manufacturing. Chennai institute of technology, India, vide funding number CIT/CAM/2024/RP/002

Acknowledgments

This research project is supported by 3D Printing Innovation Cell from Research and Development of Mr.R BUSINESS CORPORATION, Karur and Namakkal Branches, Tamilnadu India. We would like to express our gratitude to Mrs.S. Yogasakthi founder of the Mr.R BUSINESS CORPORATION.

Conflict of interest

No conflict of interest exists.

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