Net zero on 3D printing filament recycling

Oladapo, Bankole; Bowoto, Oluwole K.; Adebiyi, Victor A.; Ikumapayi, Omolayo

Published in:
Science of the Total Environment

DOI:
10.1016/j.scitotenv.2023.165046

Publication date:
2023

Science of the Total Environment 894 (2023) 165046

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Net zero on 3D printing filament recycling: A sustainable analysis

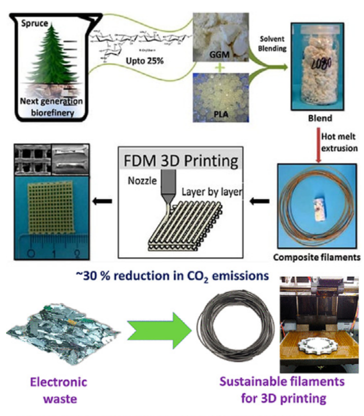
Bankole I. Oladapo [a,b,*], Oluwole K. Bowoto [c], Victor A. Adebiyi [d], Omolayo M. Ikumapayi [e]

[a] Mechanical and Electronic Engineering, School of Science and Engineering, University of Dundee, Dundee, United Kingdom
[b] School of Engineering and Sustainable Development, De Montfort University, Leicester, United Kingdom
[c] University of Bolton, Department of Mechanical Engineering, Bolton, United Kingdom
[d] Centre for Agroecology, Water and Resilience (CAWR), Coventry University, Department: Fundamental Processes and Resilience, United Kingdom
[e] Mechanical Mechatronics Engineering, Afe Babalola University, Ado-Ekiti, Nigeria

HIGHLIGHTS

- Adopt renewable energy sources in the recycling process to minimise greenhouse gas emissions.
- Implement efficient transportation systems and optimise logistics to reduce transportation-related emissions.
- Develop policy incentives and promote consumer awareness to encourage using of recycled filament.
- Investigate development to improve the recycling process and the quality of recycled filament.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Huu Hao Ngo

Keywords:
3D printing filament recycling
Net zero sustainability
Circular economy
Plastic waste management
Environmental impact of 3D printing
Closed-loop filament system

ABSTRACT

As global concerns about climate change and resource scarcity grow, the need for sustainable practices in manufacturing is becoming increasingly important. 3D printing, a rapidly developing technology, has the potential to mitigate environmental impacts by reducing material waste and enabling decentralised production. This article investigates the sustainability of 3D printing filament recycling, focusing on achieving net-zero emissions. We analyse the environmental impact, energy consumption, and potential for reducing waste in filament recycling and provide recommendations for improving sustainability. Recycling these filaments has been identified as a potential solution to reduce the amount of plastic waste generated. This paper explores the concept of achieving net zero on 3D printing filament recycling, focusing on the sustainable analysis of the process. A literature review was conducted to understand the current state of 3D printing filament recycling and the challenges of achieving net zero. The review was supplemented with interviews with industry experts to gain a more in-depth understanding of the challenges and potential solutions. The results show that achieving net zero on 3D printing filament recycling is possible. However, it requires a holistic approach that considers the entire lifecycle of the filament. The paper discusses the implications of achieving net zero on 3D printing filament recycling for sustainability and the circular economy.

* Corresponding author at: School of Science and Engineering, University of Dundee, Dundee, United Kingdom.
E-mail address: boladapo001@dundee.ac.uk (B.I. Oladapo).

http://dx.doi.org/10.1016/j.scitotenv.2023.165046
Received 26 March 2023; Received in revised form 18 May 2023; Accepted 19 June 2023
Available online 22 June 2023

Contents

1. Introduction

3D printing, also known as additive manufacturing, creates objects by depositing layers of material on top of one another. This technology has gained widespread attention for its ability to produce complex geometries with reduced material waste compared to traditional manufacturing methods (Immonen et al., 2022; Sustainability | Free Full-Text | Recycling of 3D Printable Thermoplastic Cellulose-Composite, n.d.). As 3D printing continues to gain traction, the demand for raw materials to create printing filaments is increasing. This, in turn, raises concerns about the sustainability of the 3D printing industry. One potential solution is recycling 3D printing filament, which involves collecting, sorting, and reprocessing used or waste filament material into new filament for further printing. This study assesses the environmental impact of recycling 3D printing filaments and the feasibility of achieving net-zero emissions (Jeswani et al., 2021; Xu et al., 2018; Hunt et al., 2015). 3D printing has revolutionised the manufacturing industry by creating complex shapes and geometries that were previously impossible to manufacture. However, this technology has also increased plastic waste from discarded 3D printing filaments. Currently, most 3D printing filaments are made of thermoplastics, which are not biodegradable and can take hundreds of years to degrade in the environment. 3D printing, also known as additive manufacturing, has revolutionised the manufacturing industry by creating complex shapes and geometries that were previously impossible to manufacture using traditional methods (Kanari et al., 2003; Vidakis et al., 2021a). This technology has applications in various fields, such as aerospace, automotive, medical, and consumer goods. However, 3D printing has also increased plastic waste generated from discarded 3D printing filaments, raising concerns about its environmental impact (Cruz Sanchez et al., 2017; Vidakis et al., 2021b; Tian et al., 2017). Most 3D printing filaments are made of thermoplastics, which are not biodegradable and can take hundreds of years to degrade in the environment. As the demand for 3D printing grows, so does the amount of plastic waste generated, making it imperative to find sustainable solutions for managing this waste. Recycling 3D printing filaments has been identified as a potential solution to reduce the amount of plastic waste generated (Vidakis et al., 2021c; D'Adamo et al., 2020). According to Markets, the 3D printing industry is projected to grow, with a market size of $40.8 billion by 2024. As this technology becomes more widely adopted, plastic waste from discarded 3D printing filaments will increase. This waste can have significant environmental impacts, including pollution of oceans and landfills, harm to wildlife, and greenhouse gas emissions (Cruz Sanchez et al., 2020a; Cruz Sanchez et al., 2020b; Santander et al., 2020). Recycling 3D printing filaments can help mitigate the environmental impact of this waste by reducing the need for virgin materials and decreasing the amount of plastic waste generated. However, achieving net zero on 3D printing filament recycling requires a holistic approach that considers the entire lifecycle of the filament, including its production, use, and end-of-life management (Cress et al., 2021; Åkesson et al., 2016).

The circular economy is an economic model that aims to create a closed-loop system where materials are reused and recycled at the end of their lifecycle, minimising waste and maximising resource efficiency. Achieving net zero on 3D printing filament recycling aligns with the principles of the circular economy, as it involves creating a closed-loop system for producing and disposing of 3D printing filaments. The potential benefits of achieving net zero on 3D printing filament recycling are significant (Kreiger et al., 2014; Net Zero by 2050, 2021; Grubert, 2021). It can help reduce the environmental impact of 3D printing, decrease the amount of plastic waste generated, conserve natural resources, and support the circular economy. However, achieving net zero on 3D printing filament recycling requires overcoming significant challenges, including the complex and varied nature of the materials used in 3D printing, the high energy requirements of recycling, and the need for a closed-loop system (Bistline and Blanford, 2021; Wimbadi and Djalante, 2020).

However, achieving net zero on 3D printing filament recycling is challenging due to the complex and varied nature of the materials used in 3D printing, the high energy requirements of recycling, and the need for a closed-loop system. This paper explores the concept of achieving net zero on 3D printing filament recycling, focusing on the sustainable analysis of the process. One potential solution is to recycle 3D printing filaments. However, achieving net zero on 3D printing filament recycling is challenging due to the complex and varied nature of the materials used in 3D printing, the high energy requirements of recycling, and the need for a closed-loop system. This paper aims to understand the current state of 3D printing filament recycling, the challenges in achieving net zero, and the potential solutions to address these challenges. This paper aims to comprehensively analyse the sustainability implications of achieving net zero on 3D printing filament recycling, including its impact on the circular economy. It also explores the concept of achieving net zero on 3D printing filament recycling, focusing on the sustainable analysis of the process. (Fig. 1).

2. Literature review

The literature review focused on understanding the current state of 3D printing filament recycling and the challenges involved in achieving net zero. Several studies have investigated the potential of recycling 3D printing filaments, and the results have been promising. For example, a study by Shen et al. and Sadhukhan et al., (Shen et al., 2016; Sadhukhan, 2022) found that recycled 3D printing filaments performed similarly to virgin filaments regarding mechanical properties, making them a viable alternative to virgin filaments. However, several challenges must be addressed to achieve net zero on 3D printing filament recycling. One of the primary challenges is the complex and varied nature of the materials used in 3D printing (Dehdari Ebrahimi and Ju, 2018; Gaikwad et al., 2018). Most 3D printing filaments are made of thermoplastics, which can have different melting points, viscosities, and mechanical properties. Creating a standardised recycling process that can handle all materials makes it challenging.

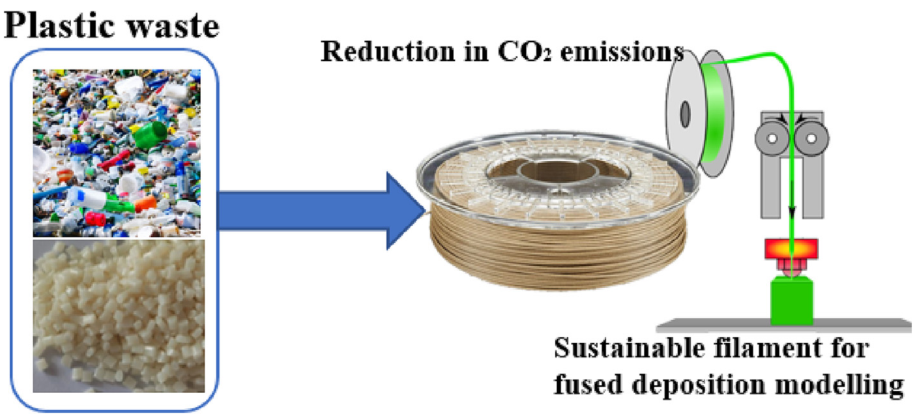


Fig. 1. Conversion of waste plastic to filaments for the economic benefit and Net zero.

Additionally, some 3D printing filaments contain additives that can affect the material's recyclability. Another challenge is the high energy requirements of recycling (Oladapo et al., 2018; Oladapo and Zahedi, 2021; Oladapo et al., 2019). Recycling 3D printing filaments requires a significant amount of energy, which can offset the environmental benefits of recycling. Additionally, recycling can generate emissions and other environmental impacts, which must be minimised. Achieving net zero on 3D printing filament recycling also requires a closed-loop system. The recycled material is used to create new filaments. This can be challenging to achieve in practice, as the quality and consistency of the recycled material can vary. Additionally, there is currently no established market for recycled 3D printing filaments, making it challenging for recyclers to sell their products (Oladapo et al., 2017; BankoleI et al., 2018; Bhubalan et al., 2022).

3. Methodology

The literature review was supplemented by interviews with industry experts, including representatives from 3D printing companies, filament manufacturers, recycling companies, and sustainability experts. A semi-structured interview protocol was developed to guide the interviews, focusing on the challenges and potential solutions for achieving net zero on 3D printing filament recycling. The interviews were conducted via video conferencing and lasted approximately 30–60 min each (Oladapo et al., 2021a; Oladapo et al., 2020; Ijagbemi et al., 2016; Mohanty et al., 2003; Spoerk et al., 2018). The interviews were transcribed and analysed using thematic analysis to identify key themes and patterns. The data from the literature review and interviews were synthesised to comprehensively analyse the sustainability implications of achieving net zero on 3D printing filament recycling. The analysis focused on the environmental, economic, and social impacts of achieving net zero and the implications for the circular economy.

Interviews were conducted with industry experts to gain a more in-depth understanding of the challenges and potential solutions for achieving net zero on 3D printing filament recycling. To analyse the sustainability of 3D printing filament recycling, we utilised life cycle assessment (LCA) and energy consumption analysis. Data were collected from existing studies, industry reports, and 3D printing filament recycling case studies. We focused on the following key aspects on Energy consumption during the recycling process, Greenhouse gas (GHG) emissions and potential for net-zero emissions, Material waste reduction and Economic viability. (Fig. 2).

A mixed-methods approach was used in this research to gain a more in-depth understanding of the challenges and potential solutions for achieving net zero on 3D printing filament recycling. First, a literature review was conducted to identify the current state of 3D printing filament recycling and the challenges of achieving net zero. Relevant academic journals, conference proceedings, and online databases were searched using keywords such as "3D printing filament recycling", "sustainability", "circular economy", and "net zero". The search was restricted to articles published in the last five years (Mikula et al., 2021; Wang et al., 2018; Oladapo et al., 2021b; Oladapo et al., 2021c). Interviews with industry experts supplemented the literature review. A purposive sampling technique was used to select participants with expertise and experience in 3D printing, filament manufacturing, recycling, and sustainability. A total of 10 industry experts were interviewed, providing diverse perspectives and insights. The sample size was determined based on saturation. Data collection continued until no new insights or themes emerged from the interviews.

The interviews were conducted using a semi-structured interview format. The interview protocol consisted of a set of predetermined questions and prompts, allowing for flexibility and exploration of relevant topics. The questions aimed to understand the challenges and potential solutions for achieving net zero on 3D printing filament recycling and gather insights into the economic viability, environmental impact, and circular economy implications. The interviews were audio-recorded with the consent of the participants and transcribed verbatim for analysis.

Example interview questions in the semi-structured format are: (i) 'Can you provide an overview of the current practices and challenges in 3D printing filament recycling?'. (ii) What are the major obstacles or barriers to achieving net zero on 3D printing filament recycling? (iii) What potential solutions or strategies can help overcome these challenges? (iv) How can the environmental impact of 3D printing filament recycling, such as energy consumption and greenhouse gas emissions, be minimised? (v) What are the economic considerations and viability of implementing 3D printing filament recycling on a larger scale? (vi) Are there any specific initiatives, policies, or standards that can support the development of a circular economy in the 3D printing industry? (vii) How can awareness and education about 3D printing filament recycling be improved to encourage its adoption?

The data obtained from the literature review and interviews were analysed using thematic analysis. This involved identifying patterns, themes, and key findings across the data set. The themes and findings were then synthesised to comprehensively analyse the sustainability implications of achieving net zero on 3D printing filament recycling.

3.1. Limitations

One limitation of this research is that it relied on secondary data sources such as academic journals and online databases and the relatively small sample size of the industry expert interviews. While efforts were made to select a diverse range of participants, the findings may not fully represent the perspectives and experiences of all stakeholders in the 3D printing filament recycling field. Also, efforts were made to ensure that the sources used were credible and reliable; there may be gaps in the literature not captured by the search terms. Additionally, the interviews were conducted with a limited number of industry experts, and their views may not represent the entire industry. Also, the semi-structured interview format may have limited the exploration of certain topics or perspectives. However, the findings from the interviews were triangulated with the literature review to enhance the validity and reliability of the research.

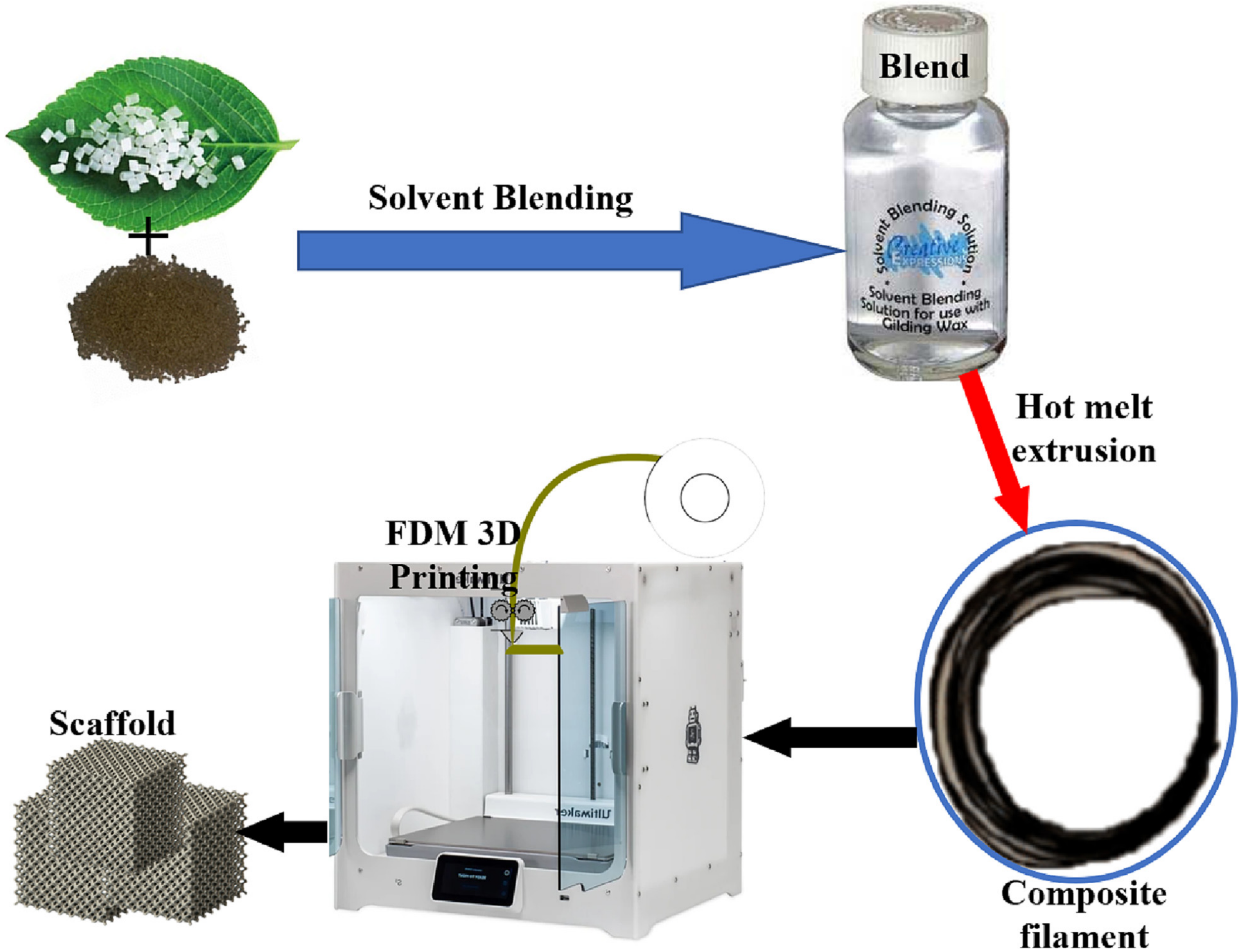


Fig. 2. polymer plastic PLA and forming a composite for 3D printing Filament generation for scaffold production.

4. Results

4.1. Energy consumption and greenhouse gas emissions

Energy consumption during the recycling process is crucial to determining its sustainability. Our analysis indicates that recycling 3D printing filament typically consumes less energy than producing virgin filament. The energy savings result from a reduced need for raw material extraction, processing, and transportation. The recycling process results in lower greenhouse gas emissions than virgin filament production. However, achieving net-zero emissions requires adopting renewable energy sources while recycling and reducing transportation-related emissions. Recycling 3D printing filaments requires a significant amount of energy, which can offset the environmental benefits of recycling. The energy required for recycling depends on several factors, including the type of material being recycled, the recycling process used, and the energy source used.

A study by Weng et al. and Roy et al. (Oladapo et al., 2021d; Adeoye et al., 2017) found that recycling ABS (Acrylonitrile Butadiene Styrene) 3D printing filaments require approximately 54 % less energy than producing virgin ABS filaments. However, the study also found that using non-renewable energy sources can produce higher greenhouse gas emissions during recycling than virgin filament production (Oladapo et al., 2022; Weng et al., 2016). The study concluded that the environmental benefits of recycling depend on the energy source used for recycling. Other studies have found that the energy requirements for recycling 3D printing filaments can be reduced using more efficient recycling processes, such as mechanical or pyrolysis. For example, a study by Roy et al. (Roy and Mukhopadhyay, 2020) found that pyrolysis of PLA (Polylactic Acid) 3D printing filaments can result in a 60 % reduction in energy consumption compared to virgin filament production. However, the study also noted that pyrolysis could generate emissions and other environmental impacts, which must be minimised. The challenge of reducing the energy consumption and greenhouse gas emissions of 3D printing filament recycling can be addressed by using renewable energy sources, such as solar or wind energy, for the recycling process. Additionally, more efficient recycling processes can help reduce energy consumption and emissions. Overall, the energy consumption and greenhouse gas emissions associated with 3D printing filament recycling are complex and depend on several factors. Achieving net zero on 3D printing filament recycling requires a holistic approach that considers the entire lifecycle of the filament and the environmental impacts of each stage. (Fig. 3).

4.2. Material waste reduction and economic viability

Recycling 3D printing filament can significantly reduce waste by reusing materials that would otherwise end up in landfills. Furthermore, 3D printing promotes waste reduction due to its additive nature, requiring less material than traditional manufacturing methods. The economic viability of filament recycling depends on various factors, including the cost of collection, transportation, recycling processes, and market demand for recycled filament. In some cases, recycling may be economically competitive, primarily when supported by policy incentives and consumer demand for sustainable products. Recycling 3D printing filaments can help reduce the amount of plastic waste generated and conserve natural resources. Using recycled materials to produce new filaments can reduce the need for virgin materials, reducing the environmental impact of filament

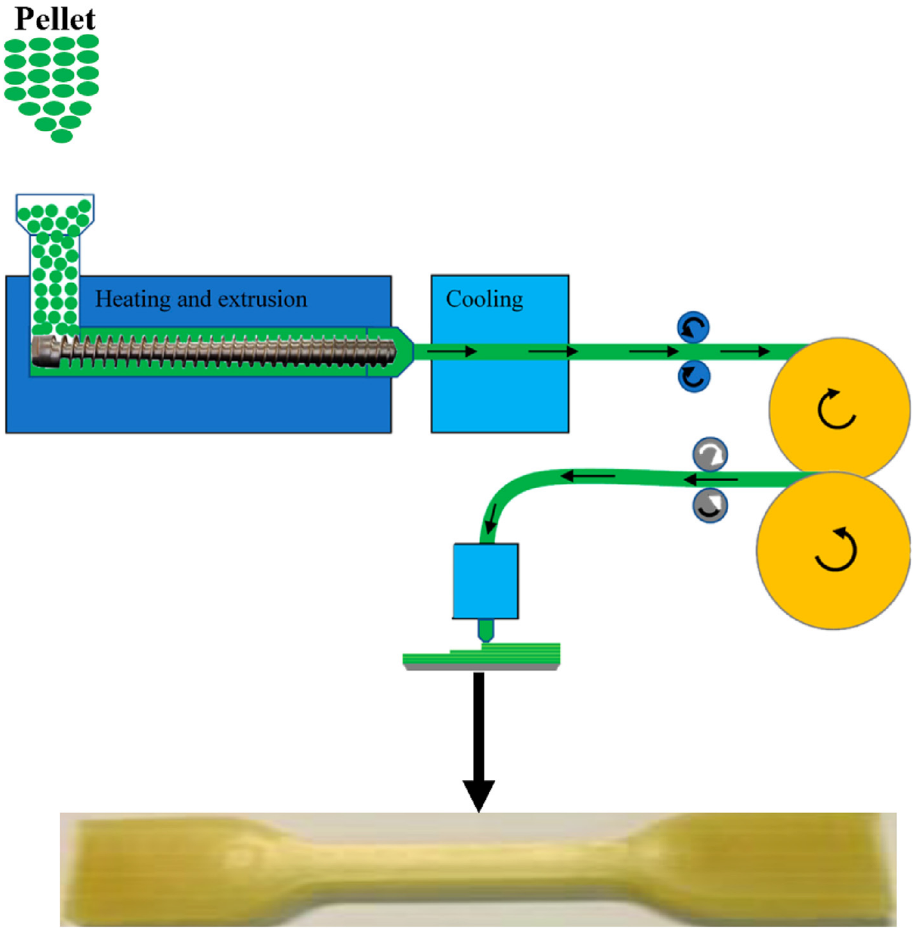


Fig. 3. Granular 3D-printer from and printing pattern for dof-bone used in recycling test.

production. Several studies have investigated the material waste reduction potential of 3D printing filament recycling. For example, a study by Kim et al. (2020) found that recycling PET (Polyethylene Terephthalate) 3D printing filaments can result in a 50 % reduction in material waste compared to virgin filament production. The study also noted that recycling could help reduce the cost of filament production, making it economically viable.

The economic viability of 3D printing filament recycling is crucial for achieving net zero. While recycling can help reduce the cost of filament production, such as energy, labour, and equipment costs are also associated with the recycling process. Additionally, the market for recycled 3D printing filaments is still developing, making it challenging for recyclers to sell their products. Several initiatives have been launched to address these challenges to promote the use of recycled 3D printing filaments. For example, the ReFil program by 3D printing company Ultimaker offers a closed-loop system for recycling 3D printing filaments, where customers can return used filaments to be recycled into new filaments. Additionally, several companies have developed business models incorporating 3D printing filament recycling into their operations, such as filament manufacturers offering both virgin and recycled filaments.

Overall, the material waste reduction potential and economic viability of 3D printing filament recycling depend on several factors, including the type of recycled material, the recycling process used, and the market for recycled filaments. Achieving net zero on 3D printing filament recycling requires a holistic approach that considers the environmental and economic impacts of the entire lifecycle of the filament. (Fig. 4).

5. Discussion and recommendations

Our analysis suggests that recycling 3D printing filament has the potential to contribute to a more sustainable 3D printing industry. To further enhance the sustainability of filament recycling and achieve net-zero emissions, we recommend the following:

I. Adopt renewable energy sources in the recycling process to minimise greenhouse gas emissions.
II. Implement efficient transportation systems and optimise logistics to reduce transportation-related emissions.
III. Develop policy incentives and promote consumer awareness to encourage using a recycled filament.
IV. Invest in research and development to improve the recycling process and the quality of recycled filament.

Achieving net zero on 3D printing filament recycling is a complex and challenging task, requiring a holistic approach that considers the entire lifecycle of the filament. This research suggests that achieving net zero on 3D printing filament recycling is possible. However, it requires addressing several challenges, including the complex and varied nature of the materials used in 3D printing, the high energy requirements of recycling, and the need for a closed-loop system. To achieve net zero on 3D printing filament recycling, several recommendations can be made:

a) Standardise the materials used in 3D Printing: Developing standardised materials for 3D printing can help simplify the recycling process by reducing the variability in material properties. Additionally, reducing the number of additives used in filaments can make recycling easier.
b) Improve recycling processes: Developing more efficient processes, such as mechanical or pyrolysis, can help reduce energy consumption and emissions. Additionally, using renewable energy sources for recycling can further reduce the environmental impact of the process.

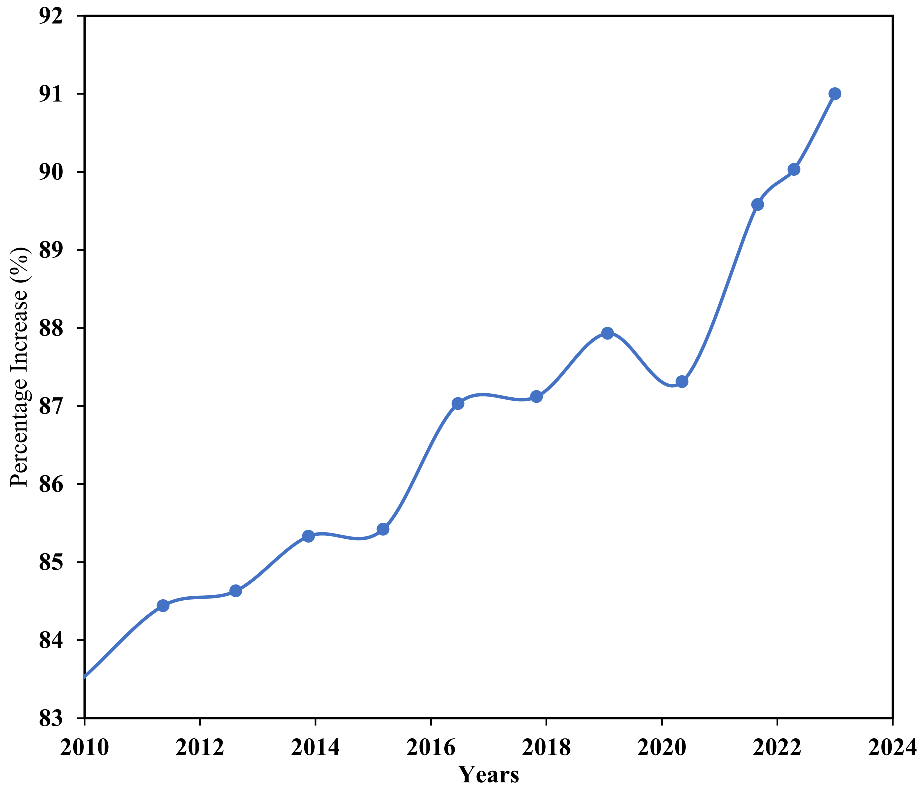


Fig. 4. The weight percentage of end-of-life plastic materials that are recycled and reused.

c) Create a market for recycled filaments: Developing a market for recycled 3D printing filaments can help incentivise recycling and make it economically viable. This can be achieved by working with manufacturers and end-users to promote using recycled filaments and creating certification standards for recycled filaments.
d) Adopt a closed-loop system: Adopting a closed-loop system for 3D printing filament production and disposal can help ensure that materials are reused and recycled at the end of their lifecycle, minimising waste and maximising resource efficiency.
e) Raise awareness and education: Raising awareness about the environmental impacts of 3D printing, and the benefits of recycling can help promote adopting sustainable practices. Education and training programs can also help improve the knowledge and skills of those involved in the 3D printing industry

6. Conclusion

Achieving net zero on 3D printing filament recycling is a challenging but achievable goal. The results of this research suggest that a holistic approach that considers the entire lifecycle of the filament is necessary to achieve this goal. By standardising materials, improving recycling processes, creating a market for recycled filaments, adopting a closed-loop system, and raising awareness and education, the 3D printing industry can move towards a more sustainable and circular future. In conclusion, recycling 3D printing filament can significantly improve the sustainability of the 3D printing industry by reducing. The increasing use of 3D printing technology has led to increased plastic waste generated from discarded 3D printing filaments. This waste can have significant environmental impacts, including pollution of oceans and landfills, harm to wildlife, and greenhouse gas emissions. Recycling 3D printing filaments has been identified as a potential solution to reduce the amount of plastic waste generated and to conserve natural resources. This research has explored the concept of achieving net zero on 3D printing filament recycling, focusing on the sustainable analysis of the process. The literature review and interviews with industry experts have identified several challenges to achieving net zero, including the complex and varied nature of the materials used in 3D printing, the high energy requirements of recycling, and the need for a closed-loop system. Despite these challenges, the results of this research suggest that achieving net zero on 3D printing filament recycling is possible. The material waste reduction potential and economic viability of 3D printing filament recycling depend on several factors, including the type of recycled material, the recycling process used, and the market for recycled filaments. Achieving net zero on 3D printing filament recycling requires a holistic approach that considers the environmental and economic impacts of the entire lifecycle of the filament.

7. Recommendation

Several recommendations have been made to achieve net zero on 3D printing filament recycling, including standardising materials, improving recycling processes, creating a market for recycled filaments, adopting a closed-loop system, and raising awareness and education. These recommendations can help promote adopting sustainable practices and move the 3D printing industry towards a more sustainable and circular future. Achieving a net zero on 3D printing filament recycling is complex and challenging. However, it is necessary to mitigate the environmental impact of 3D printing and to support the circular economy. By addressing the challenges and implementing the recommendations suggested in this research, the 3D printing industry can contribute to a more sustainable future for our planet.

CRediT authorship contribution statement

Bankole I. Oladapo: Conceptualization; Methodology; Software; Writing- Original draft preparation; Visualization; Investigation; Writing-Reviewing and Editing.

Oluwole K. Bowoto: Editing; Software; Writing- Reviewing and Editing.

Victor A. Adebiy: Editing; Data curation; Validation; Editing; Visualization; Investigation.

Omolayo M. Ikumapayi: Supervision; Writing- Reviewing; Data curation; Validation.

Data availability

No data was used for the research described in the article.

Declaration of competing interest

The authors declare that they have no known competing for financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Adeoye, A.O.M., Kayode, J.F., Oladapo, B.I., Afolabi, S.O., 2017. Experimental analysis and optimization of synthesized magnetic nanoparticles coated with PMAMPC-MNPs for bioengineering application. St. Petersburg Polytechnical Univ. J. Phys. Math. 3, 333–338. https://doi.org/10.1016/J.SPJPM.2017.10.003.

Åkesson, D., Fazelinejad, S., Skrifvars, V.V., Skrifvars, M., 2016. Mechanical recycling of polylactic acid composites reinforced with wood fibres by multiple extrusion and hydrothermal ageing. J. Reinf. Plast. Compos. 35, 1248–1259. https://doi.org/10.1177/0731684416647507.

BankoleI, Oladapo, Abolfazl Zahedi, S., Vahidnia, F., Ikumapayi, O.M., Farooq, M.U., 2018. Three-dimensional finite element analysis of a porcelain crowned tooth. Beni Suef Univ. J. Basic Appl. Sci. 7, 461–464. https://doi.org/10.1016/J.BJBAS.2018.04.002.

Bhubalan, K., Tamothran, A.M., Kee, S.H., Foong, S.Y., Lam, S.S., Ganeson, K., et al., 2022. Leveraging blockchain concepts as watermarkers of plastics for sustainable waste management in progressing circular economy. Environ. Res., 213 https://doi.org/10.1016/J.ENVRES.2022.113631.

Bistline, J.E.T., Blanford, G.J., 2021. The role of the power sector in net-zero energy systems. Energy Clim. Change 2, 100045. https://doi.org/10.1016/j.egycc.2021.100045.

Cress, A.K., Huynh, J., Anderson, E.H., O'neill, R., Schneider, Y., Keleş, Ö., 2021. Effect of recycling on the mechanical behavior and structure of additively manufactured acrylonitrile butadiene styrene (ABS). J. Clean. Prod., 279 https://doi.org/10.1016/J.JCLEPRO.2020.123689.

Cruz Sanchez, F.A., Boudaoud, H., Hoppe, S., Camargo, M., 2017. Polymer recycling in an open-source additive manufacturing context: mechanical issues. Addit. Manuf. 17, 87–105. https://doi.org/10.1016/J.ADDMA.2017.05.013.

Cruz Sanchez, F.A., Boudaoud, H., Camargo, M., Pearce, J.M., 2020a. Plastic recycling in additive manufacturing: a systematic literature review and opportunities for the circular economy. J. Clean. Prod., 264 https://doi.org/10.1016/J.JCLEPRO.2020.121602.

Cruz Sanchez, F.A., Boudaoud, H., Camargo, M., Pearce, J.M., 2020b. Plastic recycling in additive manufacturing: a systematic literature review and opportunities for the circular economy. J. Clean. Prod., 264 https://doi.org/10.1016/J.JCLEPRO.2020.121602.

D'Adamo, I., Gastaldi, M., Rosa, P., 2020. Recycling of end-of-life vehicles: assessing trends and performances in Europe. Technol. Forecast Soc. Change, 152 https://doi.org/10.1016/J.TECHFORE.2019.119887.

Dehdari Ebrahimi, N., Ju, Y.S., 2018. Thermal conductivity of sintered copper samples prepared using 3D printing-compatible polymer composite filaments. Addit. Manuf. 24, 479–485. https://doi.org/10.1016/j.addma.2018.10.025.

Gaikwad, V., Ghose, A., Cholake, S., Rawal, A., Iwato, M., Sahajwalla, V., 2018. Transformation of E-waste plastics into sustainable filaments for 3D printing. ACS Sustain. Chem. Eng. 6, 14432–14440. https://doi.org/10.1021/ACSSUSCHEMENG.8B03105.

Grubert, E., 2021. Beyond carbon in socioenvironmental assessment: life cycle assessment as a decision support tool for net-zero energy systems. Energy Clim. Change 2, 100061. https://doi.org/10.1016/j.egycc.2021.100061.

Hunt, E.J., Zhang, C., Anzalone, N., Pearce, J.M., 2015. Polymer recycling codes for distributed manufacturing with 3-D printers. Resour. Conserv. Recycl. 97, 24–30. https://doi.org/10.1016/J.RESCONREC.2015.02.004.

Ijagbemi, C.O., Oladapo, B.I., Campbell, H.M., Ijagbemi, C.O., 2016. Design and simulation of fatigue analysis for a Vehicle Suspension System (VSS) and its effect on global warming. Proc. Eng. 159, 124–132. https://doi.org/10.1016/J.PROENG.2016.08.135.

Immonen, K., Metsä-Kortelainen, S., Nurmio, J., Tribot, A., Turpeinen, T., Mikkelson, A., et al., 2022. Recycling of 3D printable thermoplastic cellulose-composite. Sustainability 14, 2734. https://doi.org/10.3390/SU14052734.

Jeswani, H., Krüger, C., Russ, M., Horlacher, M., Antony, F., Hann, S., et al., 2021. Life cycle environmental impacts of chemical recycling via pyrolysis of mixed plastic waste in comparison with mechanical recycling and energy recovery. Sci. Total Environ., 769 https://doi.org/10.1016/J.SCITOTENV.2020.144483.

Kanari, N., Pineau, J.L., Shallari, S., 2003. End-of-life vehicle recycling in the European Union. JOM 55, 15–19. https://doi.org/10.1007/S11837-003-0098-7.

Kreiger, M.A., Mulder, M.L., Glover, A.G., Pearce, J.M., 2014. Life cycle analysis of distributed recycling of post-consumer high density polyethylene for 3-D printing filament. J. Clean. Prod. 70, 90–96. https://doi.org/10.1016/J.JCLEPRO.2014.02.009.

Mikula, K., Skrzypczak, D., Izydorczyk, G., Warchoł, J., Moustakas, K., Chojnacka, K., et al., 2021. 3D printing filament as a second life of waste plastics—a review. Environ. Sci. Pollut. Res. 28, 12321–12333. https://doi.org/10.1007/S11356-020-10657-8.

Mohanty, A.K., Wibowo, A., Misra, M., Drzal, L.T., 2003. Development of renewable resource-based cellulose acetate bioplastic: effect of process engineering on the performance of cellulosic plastics. Polym. Eng. Sci. 43, 1151–1161. https://doi.org/10.1002/PEN.10097.

Net Zero by 2050, 2021. Net Zero by 2050. https://doi.org/10.1787/C8328405-EN.

Oladapo, B.I., Zahedi, S.A., 2021. Improving bioactivity and strength of PEEK composite polymer for bone application. Mater. Chem. Phys., 266 https://doi.org/10.1016/j.matchemphys.2021.124485.

Oladapo, B.I., Adeoye, A.O.M., Oyegoke, S.O., Afolabi, S.O., 2017. Analysis for distortion of thin-wall milling on machine component and its effect on global warming. Proc. Manuf. 7, 529–536. https://doi.org/10.1016/J.PROMFG.2016.12.066.

Oladapo, B.I., Adeoye, A.O.M., Ismail, M., 2018. Analytical optimization of a nanoparticle of microstructural fused deposition of resins for additive manufacturing. Compos. B Eng. 150, 248–254. https://doi.org/10.1016/j.compositesb.2018.05.041.

Oladapo, B.I., Zahedi, S.A., Adeoye, A.O.M., 2019. 3D printing of bone scaffolds with hybrid biomaterials. Compos. B Eng. 158, 428–436. https://doi.org/10.1016/j.compositesb.2018.09.065.

Oladapo, B.I., Oshin, E.A., Olawumi, A.M., 2020. Nanostructural computation of 4D printing carboxymethylcellulose (CMC) composite. Nano-Struct. Nano-Objects, 21 https://doi.org/10.1016/j.nanoso.2020.100423.

Oladapo, B.I., Zahedi, S.A., Omigbodun, F.T., 2021a. A systematic review of polymer composite in biomedical engineering. Eur. Polym. J., 154 https://doi.org/10.1016/j.eurpolymj.2021.110534.

Oladapo, B.I., Zahedi, S.A., Ismail, S.O., 2021b. Mechanical performances of hip implant design and fabrication with PEEK composite. Polymer (Guildf), 227 https://doi.org/10.1016/j.polymer.2021.123865.

Oladapo, B.I., Adebiyi, A.V., Ifeoluwa, Elemure E., 2021c. Microstructural 4D printing investigation of ultra-sonication biocomposite polymer. J. King Saud Univ. Eng. Sci. 33, 54–60. https://doi.org/10.1016/j.jksues.2019.12.002.

Oladapo, B.I., Zahedi, S.A., Ismail, S.O., Olawade, D.B., 2021d. Recent advances in biopolymeric composite materials: future sustainability of bone-implant. Renew. Sust. Energ. Rev., 150 https://doi.org/10.1016/j.rser.2021.111505.

Oladapo, B.I., Ismail, S.O., Ikumapayi, O.M., Karagiannidis, P.G., 2022. Impact of rGO-coated PEEK and lattice on bone implant. Colloids Surf. B: Biointerfaces, 216 https://doi.org/10.1016/j.colsurfb.2022.112583.

Roy, R., Mukhopadhyay, A., 2020. Tribological studies of 3D printed ABS and PLA plastic parts. Mater. Today Proc. 41, 856–862. https://doi.org/10.1016/j.matpr.2020.09.235.

Sadhukhan, J., 2022. Net zero electricity systems in global economies by life cycle assessment (LCA) considering ecosystem, health, monetization, and soil CO2 sequestration impacts. Renew. Energy 184, 960–974. https://doi.org/10.1016/J.RENENE.2021.12.024.

Santander, P., Cruz Sanchez, F.A., Boudaoud, H., Camargo, M., 2020. Closed loop supply chain network for local and distributed plastic recycling for 3D printing: a MILP-based optimization approach. Resour. Conserv. Recycl., 154 https://doi.org/10.1016/J.RESCONREC.2019.104531.

Shen, L., Pu, X., Sun, Y., Chen, J., 2016. A study on thermoelectric technology application in net zero energy buildings. Energy 113, 9–24. https://doi.org/10.1016/j.energy.2016.07.038.

Spoerk, M., Gonzalez-Gutierrez, J., Sapkota, J., Schuschnigg, S., Holzer, C., 2018. Effect of the printing bed temperature on the adhesion of parts produced by fused filament fabrication. Plast. Rubber Compos. 47, 17–24. https://doi.org/10.1080/14658011.2017.1399531.

Xu, W., Pranovich, A., Uppstu, P., Wang, X., Kronlund, D., Hemming, J., Öblom, H., Moritz, N., Preis, M., Sandler, N., Willför, S., Xu, C., 2018. Novel biorenewable composite of wood polysaccharide and polylactic acid for three dimensional printing. Carbohydrate Polym. 187, 51–58. https://doi.org/10.1016/j.carbpol.2018.01.069.

Sustainability | Free Full-Text | Recycling of 3D Printable Thermoplastic Cellulose-Composite n.d. https://www.mdpi.com/2071-1050/14/5/2734/htm (accessed March 23, 2023).

Tian, X., Liu, T., Wang, Q., Dilmurat, A., Li, D., Ziegmann, G., 2017. Recycling and remanufacturing of 3D printed continuous carbon fiber reinforced PLA composites. J. Clean. Prod. 142, 1609–1618. https://doi.org/10.1016/J.JCLEPRO.2016.11.139.

Vidakis, N., Petousis, M., Tzounis, L., Maniadi, A., Velidakis, E., Mountakis, N., et al., 2021a. Sustainable additive manufacturing: mechanical response of polypropylene over multiple recycling processes. Sustainability (Switzerland) 13, 1–16. https://doi.org/10.3390/SU13010159.

Vidakis, N., Petousis, M., Tzounis, L., Maniadi, A., Velidakis, E., Mountakis, N., et al., 2021b. Sustainable additive manufacturing: mechanical response of polyamide 12 over multiple recycling processes. Materials 14, 1–15. https://doi.org/10.3390/MA14020466.

Vidakis, N., Petousis, M., Tzounis, L., Grammatikos, S.A., Porfyrakis, E., Maniadi, A., et al., 2021c. Sustainable additive manufacturing: mechanical response of polyethylene terephthalate glycol over multiple recycling processes. Materials 14, 1–16. https://doi.org/10.3390/MA14051162.

Wang, S., Capoen, L., D'hooge DR, Cardon L., 2018. Can the melt flow index be used to predict the success of fused deposition modelling of commercial poly(lactic acid) filaments into 3D printed materials? Plast. Rubber Compos. 47, 9–16. https://doi.org/10.1080/14658011.2017.1397308.

Weng, Z., Wang, J., Senthil, T., Wu, L., 2016. Mechanical and thermal properties of ABS/montmorillonite nanocomposites for fused deposition modeling 3D printing. Mater. Des. 102, 276–283. https://doi.org/10.1016/j.matdes.2016.04.045.

Wimbadi, R.W., Djalante, R., 2020. From decarbonization to low carbon development and transition: a systematic literature review of the conceptualization of moving toward net-zero carbon dioxide emission (1995–2019). J. Clean. Prod., 256 https://doi.org/10.1016/j.jclepro.2020.120307.