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Published in:
Science of the Total Environment

DOI:
10.1016/j.scitotenv.2023.167109

Publication date:
2023

Science of the Total Environment 905 (2023) 167109

Contents lists available at ScienceDirect

Science of the Total Environment

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

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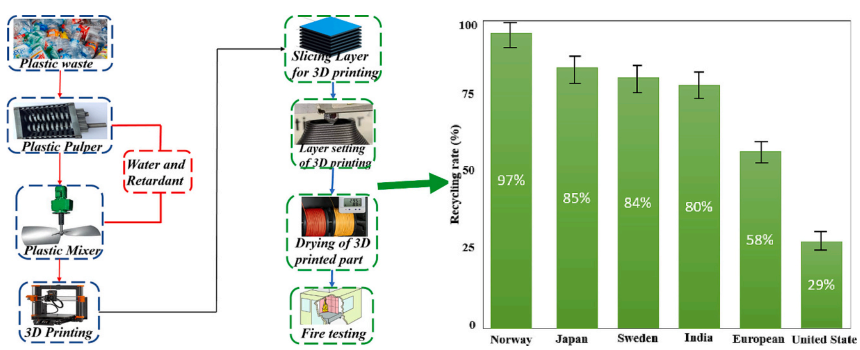
HIGHLIGHTS

- Evaluation of 3D printing and recycling to unlock new sustainable possibilities.
- 3D printing with recycled materials to reduces waste and carbon emissions
- Evaluate recycled materials' comparable quality properties to conventional production.
- Investigate infrastructure applications for potential areas for recycling 3D printing.
- Scaling up requires addressing material consistency and promoting collaboration.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Huu Hao Ngo

Keywords:
3D printing
Recycling
Sustainability
Additive manufacturing
Circular economy
Printability assessment

ABSTRACT

In a world grappling with environmental challenges and the need for sustainable manufacturing practices, the convergence of 3D printing and recycling emerges as a promising solution. This research paper explores the potential of combining these two technologies and comprehensively analyses their synergistic effects. The study delves into the printability of recycled materials, evaluating their suitability for 3D printing and comparing their performance with conventional materials. The environmental impact of 3D printing with recycled materials is examined through a sustainability analysis and a life cycle assessment of recycled 3D printed objects. The findings reveal significant benefits, including enhanced resource efficiency, waste reduction, and customisation possibilities. The research also identifies challenges and opportunities for scaling up the use of recycled materials in 3D printing, highlighting the importance of collaboration, innovation, and regulations. With potential applications spanning various industries, from prototyping to construction and healthcare, the implications of this research are far-reaching. By embracing sustainable practices, industry collaboration, and innovation, the integration of 3D printing and recycling can pave the way for a more sustainable future, where resource conservation, circularity, and customised production are at the forefront of manufacturing.

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https://doi.org/10.1016/j.scitotenv.2023.167109
Received 2 July 2023; Received in revised form 14 August 2023; Accepted 13 September 2023
Available online 16 September 2023

1. Introduction

3D printing, also known as additive manufacturing, has recently gained significant attention and revolutionised various industries. This innovative technology allows for the creation of 3D objects by depositing successive layers of material, typically plastic or metal, based on a digital design (Ramachandraiah, 2021; Alami et al., 2023; Khosravani and Reinicke, 2020). The ability to fabricate complex geometries with precision and efficiency has made 3D printing an indispensable tool in engineering, medicine, architecture, and consumer products. While 3D printing has proven to be a game-changer in many respects, it poses certain challenges, particularly regarding sustainability and environmental impact (Liu et al., 2021; Giorgini et al., 2020; Hwang et al., 2022). The conventional materials used in 3D printing, such as virgin plastics, often contribute to the growing problem of waste generation and resource depletion. Recognising the need for more sustainable practices, researchers and industry professionals have turned their attention to recycling with 3D printing. The convergence of 3D printing and recycling holds immense potential for revolutionising manufacturing processes and promoting sustainability (Singh et al., 2021a; Zhao et al., 2018a). We can unlock new possibilities and address environmental challenges by harnessing the capabilities of 3D printing technology and recycling principles. In this section, we will explore the various dimensions of this synergistic combination and delve into its potential applications. One of the key benefits of integrating 3D printing with recycling is its enhanced resource efficiency (Shanmugam et al., 2020; Zhao et al., 2018b; Zhao et al., 2018c). Traditional manufacturing methods often extract and consume finite resources, leading to environmental degradation and depletion. However, using recycled materials as feedstock for 3D printing can reduce the demand for virgin resources and minimise waste generation. Recycling empowers us to repurpose discarded objects and materials, diverting them from landfills and incinerators (Zhong and Pearce, 2018; Zenkiewicz et al., 2009; 3D printing filament as a second life of waste plastics—a review, n.d.). By transforming these materials into printable filaments or powders, we can give them a new lease of life, effectively extending their usefulness. This conserves valuable resources and reduces the energy consumption and carbon emissions associated with traditional manufacturing processes. Combining 3D printing and recycling offers unparalleled design freedom and customisation options. Conventional manufacturing techniques often impose limitations on the complexity of geometries and the range of materials that can be used (BI Oladapo VB., 2016; Oladapo and Zahedi, 2021; Olawale et al., 2023). However, 3D printing allows for the creation of intricate, customised objects with ease. We can explore various material properties and characteristics by incorporating recycled materials into 3D printing (Oladapo et al., 2021a; Oladapo et al., 2021b; Oladapo et al., 2021c). For example, plastic waste can be transformed into printable filaments, producing objects with varying rigidity, flexibility, or even transparency. This versatility opens up new possibilities for design innovation, enabling the creation of unique products tailored to specific needs and preferences (Oladapo et al., 2019; Oladapo et al., 2021d; Oladapo et al., 2023a). (Fig. 1).

1.1. Promoting waste reduction and circular economy

Integrating 3D printing and recycling plays a vital role in promoting waste reduction and advancing the principles of a circular economy. In a linear economic model, products are manufactured, used, and discarded, accumulating waste and losing valuable resources (Daniyan et al., 2021; Nasr Azadani et al., 2022; Oladapo et al., 2023b). However, we can close the loop and minimise waste generation by adopting a circular approach. 3D printing with recycled materials aligns perfectly with the principles of the circular economy. It enables us to take discarded objects or waste materials, transform them into printable feedstock, and create new products (Oladapo et al., 2023c; Oladapo et al., 2023d; Oladapo BankoleI et al., 2018). This closed-loop system ensures that materials are continuously reused, reducing the need for raw material extraction and minimising environmental impact. Combining 3D printing and recycling can foster innovation and collaboration across various sectors (Oladapo et al., 2020a; Oladapo et al., 2023e; Oladapo et al., 2022a). Researchers, manufacturers, and entrepreneurs can explore novel applications, materials, and processes, paving the way for groundbreaking advancements. By leveraging the expertise of diverse stakeholders, we can collectively push the boundaries of what is possible in sustainable manufacturing (Oladapo et al., 2021e; Oladapo et al., 2021f; Oladapo et al., 2021g). Moreover, integrating 3D printing and recycling encourages collaboration between different industries. For instance, partnerships between recycling facilities, material scientists, and 3D printing companies can facilitate the development of new, recycled materials optimised for 3D printing processes. This interdisciplinary collaboration drives innovation and accelerates the adoption of sustainable practices on a larger scale (Zander et al., 2019; Woern et al., 2018; Wojtyła et al., 2017).

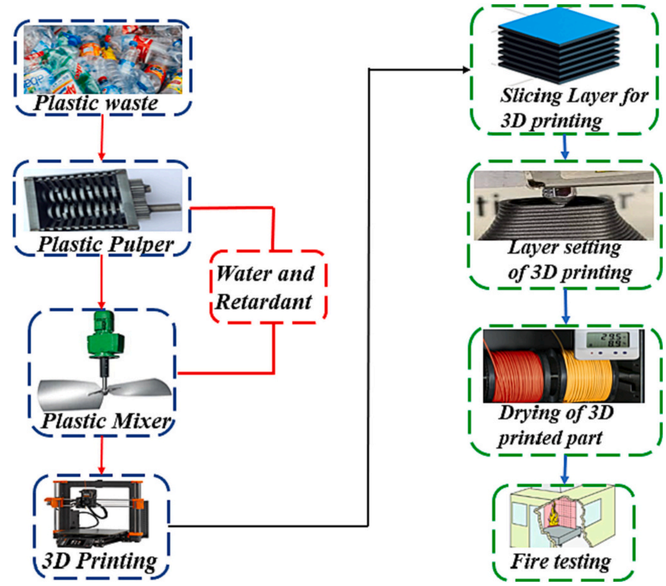

Fig. 1. Specimen production flowchart from packaging waste.

1.2. Research gap

This research comprehensively analyses the convergence between 3D printing and recycling, elucidating their combined potential for sustainable manufacturing. It intricately evaluates the feasibility of recycled materials for 3D printing, comparing them against conventional counterparts and assessing print quality. However, a notable research gap emerges in assessing the long-term durability and stability of 3D-printed objects using recycled materials, essential for ensuring practical applicability (Zander et al., 2018; Tian et al., 2017; Singh et al., 2021b). Furthermore, while the study diligently addresses environmental and economic dimensions, it could benefit from an expanded focus on societal implications and broader industry adoption challenges. Enriching the investigation with insights into innovative recycling techniques, circular design strategies, and comprehensive life cycle assessments could propel the field towards a more holistic understanding and wider practical integration.

1.3. Objective and significance of the study

The objective of this study is to comprehensively explore the synergistic potential of integrating 3D printing and recycling for sustainable manufacturing. By examining the feasibility, environmental impact, and economic viability of utilising recycled materials in 3D printing, this research aims to provide insights into their suitability, performance, and implications. The study is significant in advancing sustainable practices in additive manufacturing, addressing environmental concerns and resource efficiency.

1.4. Research questions and hypotheses

i. How does the printability of recycled materials compare to conventional materials in various 3D printing technologies? Hypothesis: Recycled materials can be successfully processed and printed using different 3D printing methods, demonstrating comparable or improved print quality.
ii. What are the mechanical properties and structural integrity of 3D-printed objects using recycled materials? Hypothesis: 3D-printed objects with recycled materials exhibit mechanical properties comparable to or exceeding those printed with conventional materials.
iii. What is the environmental impact of 3D printing with recycled materials compared to traditional manufacturing processes? Hypothesis: 3D printing with recycled materials reduces carbon emissions, energy consumption, and waste generation, resulting in a lower environmental footprint.
iv. How does the life cycle assessment of recycled 3D printed objects compare to those printed with conventional materials? Hypothesis: Recycled 3D printed objects demonstrate superior life cycle sustainability, considering resource efficiency, waste reduction, and end-of-life scenarios.
v. What are the economic feasibility and resource efficiency implications of integrating recycled materials in 3D printing? Hypothesis: Utilising recycled materials in 3D printing leads to cost savings, enhanced resource utilisation, and improved overall economic viability.
vi. What are the challenges and opportunities for scaling up the use of recycled materials in 3D printing across industries? Hypothesis: Collaborative efforts among recycling facilities, manufacturers, and 3D printing companies can overcome challenges and facilitate the widespread adoption of recycled materials in additive manufacturing.
vii. How can innovative recycling techniques and circular design principles enhance the sustainability of 3D printing processes? Hypothesis: Exploring advanced recycling methods and incorporating circular design strategies can optimise material properties, minimise waste, and promote a circular economy in 3D printing.

2. Literature review

In this section, we will conduct a literature review to explore state-of-the-art 3D printing techniques, advancements in recycling technologies, and previous studies on the intersection of 3D printing and recycling. By examining the existing body of knowledge, we can gain insights into the current advancements, identify gaps, and build upon the research already conducted (Zander et al., 2018; Tian et al., 2017; Singh et al., 2021b).

2.1. State-of-the-art in 3D printing techniques

Over the years, 3D printing has evolved significantly, with various techniques and technologies being developed to meet diverse manufacturing needs. One of the most widely used methods is fused deposition modelling (FDM), where thermoplastic filaments are melted and deposited layer by layer to create objects. FDM offers ease of use, affordability, and versatility in material selection. Another prominent technique is stereolithography (SLA), which utilises a liquid photopolymer resin cured by ultraviolet light to create intricate, high-resolution models (Shah et al., 2019; Singh et al., 2019; Stoof and Pickering, 2018). SLA is known for its accuracy and surface finish quality, making it popular in the jewellery, dentistry, and prototyping industries. Selective laser sintering (SLS) is a technique that involves the use of a high-powered laser to fuse powdered materials selectively, typically plastics or metals, layer by layer (Tymrak et al., 2014; Sun et al., 2008; Singh et al., 2017). SLS enables the production of complex geometries and functional parts with good mechanical properties. Advancements such as multi-material 3D printing, bioprinting, and metal 3D printing have further expanded the possibilities of additive manufacturing. Fig. 2 represents techniques that enable the fabrication of objects with different materials, the creation of living tissues and organs, and the production of metal parts with high precision.

2.2. Advancements in recycling technologies

Recycling has witnessed remarkable advancements, driven by the increasing need for sustainable waste management practices. Recycling technologies have evolved beyond traditional methods, incorporating innovative processes to handle various materials. Mechanical recycling is a commonly used technique that involves sorting, shredding, and reprocessing plastic waste to obtain reusable materials (Singh et al., 2018; Singh et al., 2016; Shah et al., 2008). This method has successfully transformed post-consumer plastic waste into recycled pellets that can be used as feedstock for 3D printing. Chemical recycling, on the other hand, focuses on breaking down plastics into their constituent molecules through processes such as depolymerisation or pyrolysis. These techniques enable the conversion of complex plastic waste into monomers or other valuable chemical compounds, which can be used to produce new plastics or feedstock for 3D printing (Santos et al., 2018; Notta-Cuvier et al., 2014; Pan et al., 2018). Additionally, advancements in recycling technologies have led to specialised processes for recycling other materials, such as metals, ceramics, and biodegradable polymers. These technologies contribute to expanding material options for 3D printing and promote the circular economy by diverting waste from landfills and incineration.

2.3. Previous studies on 3D printing and recycling

A growing body of research has explored the potential of combining 3D printing and recycling, addressing various aspects such as material characterisation, printability assessment, and environmental impact. Previous studies have investigated the mechanical properties of 3D printed objects using recycled materials, comparing them with conventionally printed objects.

Researchers have also explored the influence of different recycling techniques on the properties of recycled filaments or powders (Pillin et al., 2008; Ragaert et al., 2017; Kaur et al., 2018). They have examined the effects of particle size distribution, contamination levels, and processing parameters on the printability and quality of 3D-printed objects. Furthermore, studies have focused on the environmental implications of 3D printing with recycled materials, conducting life cycle assessments (LCAs) to evaluate the process's sustainability and carbon footprint. These studies have provided valuable insights into the environmental benefits and challenges of integrating 3D printing and recycling. However, despite progress, there are still gaps in our understanding of certain aspects, such as the long-term durability and stability of 3D-printed objects using recycled materials (Jawahir and Bradley, 2016; Kumar et al., 2011; Mwanza and Mbohwa, 2017). Further research is needed to address these gaps and provide a more comprehensive understanding of the potential, limitations, and optimisation of 3D printing with recycled materials. In the following sections of this paper, we will present our methodology, experimental setup, and analysis to contribute to the existing body of knowledge in the field (Saidu et al., 2023; Olorunsola et al., 2021; Oladapo et al., 2021h). By building upon the previous studies and advancements, we aim to expand our understanding of the synergistic potential of 3D printing and recycling and its implications for

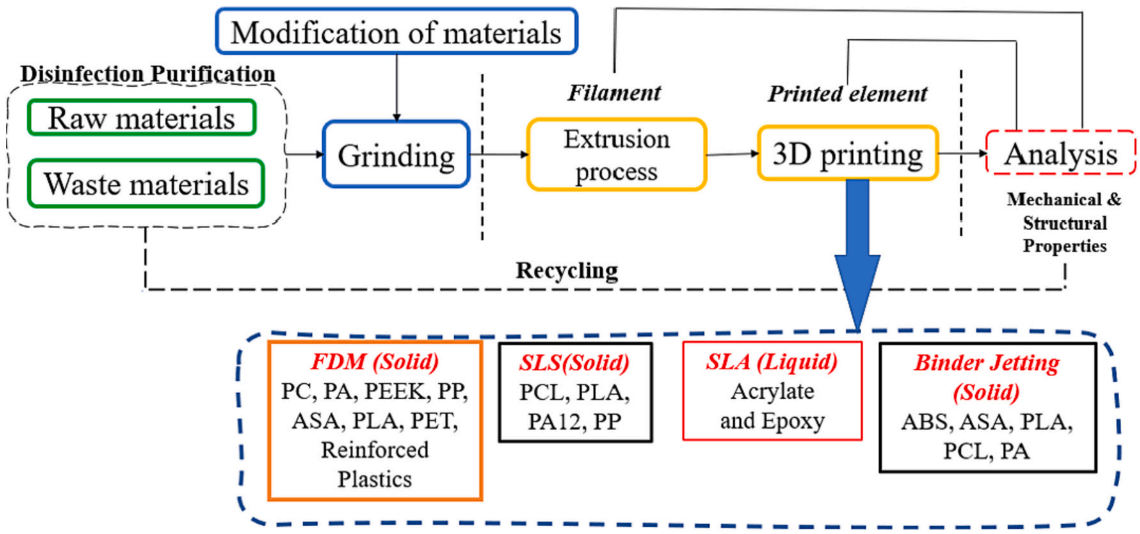

Fig. 2. The employed polymers in AM process, acrylonitrile styrene acrylate, PCL and Manufacture of filament from waste materials.

sustainable manufacturing.

3. Methodology

In this section, we will outline the methodology employed in our research, including the selection of materials for 3D printing and recycling, the experimental setup and equipment used, the procedure for preparing recycled materials, and the printing parameters and techniques employed. Careful consideration was given to selecting materials to explore the potential of 3D printing and recycling. We aimed to work with commonly available materials that have the potential for recycling and can be used in 3D printing processes. Plastics, such as polyethene terephthalate (PET), acrylonitrile butadiene styrene (ABS), and polylactic acid (PLA), were chosen as the primary materials due to their widespread use and recyclability.

3.1. Experimental setup and equipment

Our experiments were conducted in a well-equipped laboratory dedicated to additive manufacturing research. The laboratory was equipped with multiple 3D printers, including fused deposition modelling (FDM), stereolithography (SLA), and selective laser sintering (SLS) machines. Each 3D printer was configured to accommodate different materials and print geometries. In addition to the 3D printers, the laboratory was equipped with material characterisation instruments, such as a universal testing machine for mechanical property analysis, a scanning electron microscope (SEM) for surface morphology examination, and a Fourier-transform infrared (FTIR) spectrometer for material composition analysis (Fig. 3).

3.2. Preparing recycled materials and printing parameters

A well-defined procedure was followed to prepare recycled materials suitable for 3D printing. First, plastic waste was collected and sorted based on its polymer type and colour. The sorted waste was then cleaned thoroughly to remove any contaminants or impurities. After cleaning, the plastics were shredded into small pieces using a machine. Once shredded, the plastic waste was subjected to a recycling process specific to each polymer type. The shredded plastic was melted and extruded into filament form for mechanical recycling using an extrusion machine. Chemical recycling techniques, such as depolymerisation or pyrolysis, were employed to convert plastic waste into usable feedstock. The printing parameters and methods varied depending on the specific 3D printing technology. The filament diameter, nozzle temperature, print speed, and layer height were optimised for FDM printing to achieve the desired print quality and mechanical properties. In SLA printing, the exposure time, layer thickness, and support structures were carefully adjusted to ensure accurate and high-resolution prints. The powder size, laser power, scan speed, and layer thickness were optimised for SLS printing to achieve proper powder fusion and sintering. Post-processing techniques, such as sanding, polishing, or chemical treatments, were employed to enhance the surface finish and aesthetics of the printed objects. Multiple test specimens were printed using conventional and recycled materials throughout the experiments. These specimens were subjected to mechanical testing, such as tensile strength, flexural strength, and impact resistance, to evaluate the recycled materials' performance compared to the conventional materials. Following this methodology, we aimed to assess the printability, mechanical properties, and environmental implications of 3D printing with recycled materials. The experimental setup and procedure allowed us to explore the potential of recycling as a viable approach for obtaining sustainable feedstock for 3D printing while optimising the printing parameters to achieve high-quality prints.

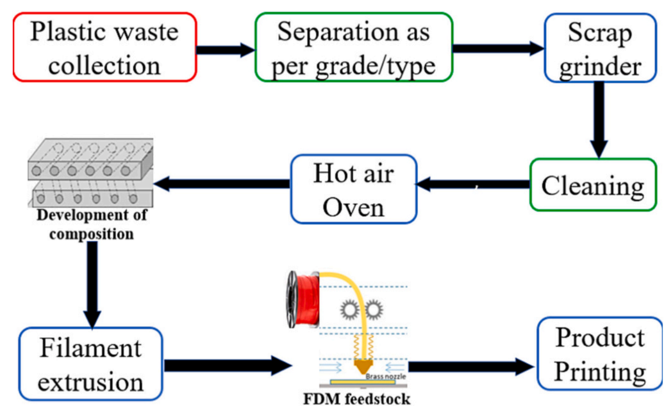

Fig. 3. Waste plastic to 3D printed hot air oven preparation of extruded filament.

4. Result

4.1. Properties analysis of recycled materials

This section will discuss the characterisation of the recycled materials used in our study. We focused on analysing the physical and mechanical properties of the materials, assessing their structural integrity, and evaluating the surface finish and aesthetics of the printed objects. To understand the properties of the recycled materials, we conducted a series of physical and mechanical tests. First, we used standard testing to examine the recycled filaments or powders' density, melt flow index, and viscosity. These parameters provided insights into the flow behaviour and processability of the materials during 3D printing. Next, we performed mechanical tests to evaluate the printed objects' strength, elasticity, and toughness. Tensile tests were conducted to measure the ultimate tensile strength, yield strength, and elongation at break. Flexural tests were performed to assess the bending strength and modulus of elasticity. Impact tests were conducted to determine the material's resistance to sudden loads and impact strength (Oladapo et al., 2020b; Oladapo et al., 2020c; Oladapo et al., 2022b). Assessing the structural integrity of the 3D-printed objects was crucial to ensure their reliability and performance. We visually inspected the printed objects for any visible defects, such as layer adhesion issues, warping, or delamination. The structural integrity was also evaluated through non-destructive testing techniques, such as ultrasonic testing or X-ray imaging, to detect internal defects or irregularities that may affect the overall strength and stability of the objects.

The surface finish and aesthetics of the printed objects significantly impact their visual appeal and functional performance. We thoroughly evaluated the surface quality, examining smoothness, texture, and surface defects (Jimah et al., 2023; Oladapo et al., 2021i; Oladapo et al., 2020d). This assessment involved visual inspection, tactile examination, and surface roughness measurements using profilometers or similar instruments. Moreover, we assessed the printed objects' colour accuracy, clarity, or transparency, particularly when using recycled filaments with pigments or additives. This evaluation involved comparing the printed things with colour standards and analysing their light transmission properties using spectrophotometers or colourimeters (Oladapo et al., 2021j; Idrees et al., 2018; Hunt et al., 2015). To ensure comprehensive evaluation, we sought input from a panel of experts or users to gather subjective feedback on the surface finish, aesthetics, and overall quality of the printed objects. Their observations and preferences provided valuable insights into the user experience and acceptability of recycled materials in various applications. By characterising the recycled materials, including physical and mechanical properties analysis, structural integrity assessment, and surface finish and aesthetic evaluation, we aimed to comprehensively understand their suitability and performance in 3D printing applications. The results of these analyses formed the basis for assessing the viability and potential of using recycled materials in 3D printing processes (Fig. 4).

4.2. *Printability assessment recycled materials*

In this section, we will discuss the printability assessment conducted to evaluate the suitability of recycled materials for 3D printing. We compared the performance of recycled materials with conventional 3D printing materials and analysed the printing performance and quality. We considered several factors to assess the suitability of recycled materials for 3D printing. First, we examined the filament or powder and diameter consistency to ensure smooth and consistent material flow during printing. Any variations in filament diameter or powder particle size could lead to printing issues, such as nozzle clogging or poor layer adhesion (Lithner et al., 2011; Hopewell et al., 2009; Hart et al., 2018). We also evaluated the material's printability across different 3D printing technologies. The recycled textiles were tested on various printers, including FDM, SLA, and SLS machines, to determine their compatibility with other printing processes. This assessment involved observing the material's behaviour during printing, examining the adhesion between layers, and assessing the overall print quality.

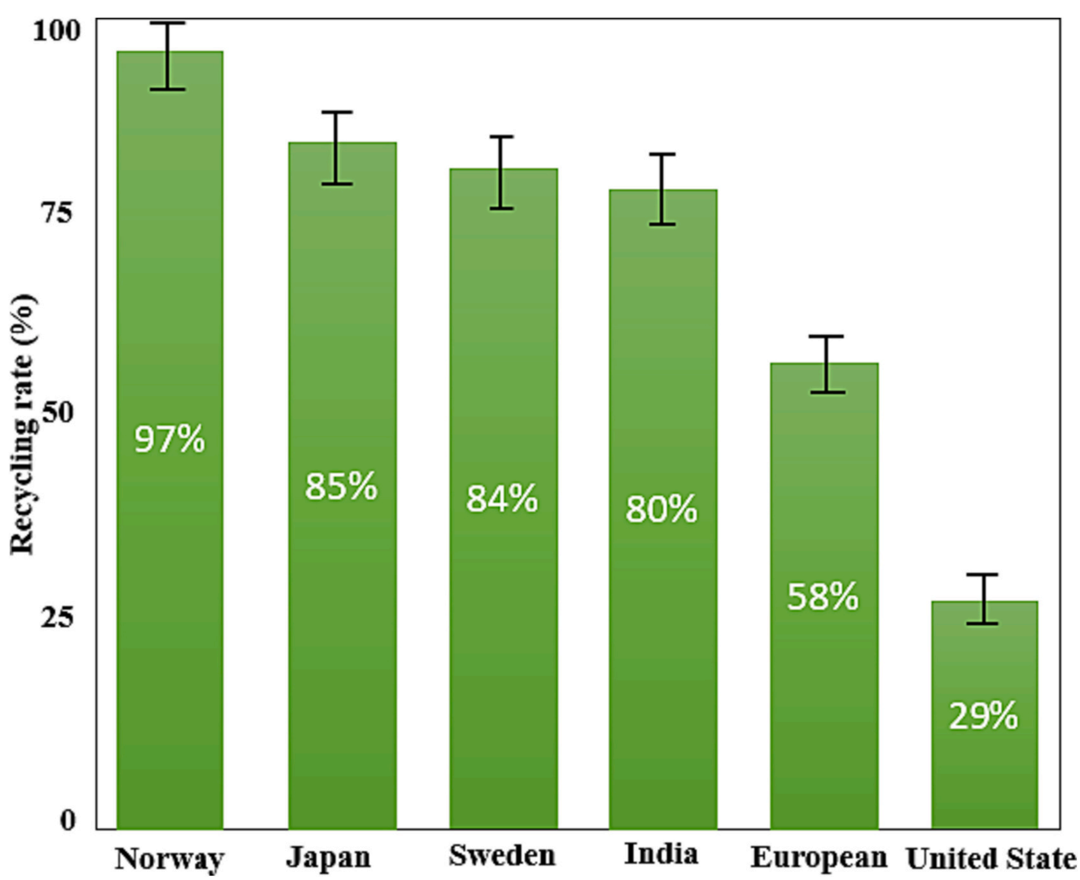

Fig. 4. Production of plastics PET plastic bottle recycling rates among different countries in 2020 and 2023.

4.3. Comparison with conventional 3D printing materials

To gauge the performance of the recycled materials, we compared them with conventional 3D printing materials. We assessed parameters such as print resolution, dimensional accuracy, and surface quality to determine if the recycled materials could achieve similar or comparable results. This comparison allowed us to understand the limitations and advantages of using recycled materials in 3D printing. In addition to print quality, we considered the mechanical properties of the printed objects using recycled materials. We compared them with objects printed with conventional materials. We analysed the printed objects' strength, elasticity, and durability by conducting mechanical tests, such as tensile, flexural, or impact tests. This comparison enabled us to determine the impact of using recycled materials on the mechanical performance of 3D-printed objects (Fig. 5).

4.4. Analysis of printing performance and quality

The printing performance and quality of the recycled materials were thoroughly analysed. We examined layer adhesion, dimensional accuracy, surface smoothness, and fine detail reproduction. The printing parameters, such as nozzle temperature, print speed, layer height, and exposure time, were optimised to achieve the best possible results with recycled materials.We also evaluated the printability of complex geometries and overhangs to assess the material's ability to maintain structural integrity during intricate printing processes. 3D Printing defects, such as stringing, warping, or layer shifting, were closely monitored and analysed to understand the challenges and limitations of using recycled materials. Furthermore, the compatibility of recycled materials with post-processing techniques, such as sanding, painting, or surface treatments, was examined. This evaluation aimed to determine if the recycled materials could undergo post-processing steps without compromising their physical properties or surface finish. Through the printability assessment, including evaluating recycled materials' suitability for 3D printing, comparison with conventional materials, and analysis of printing performance and quality, we gained insights into the capabilities and limitations of using recycled materials in additive manufacturing. These findings provided a comprehensive understanding of the potential applications and optimisation strategies for incorporating recycled materials in 3D printing processes.

5. Discussion

5.1. Environmental impact of 3D printing with recycled materials

In this section, we will conduct a sustainability analysis to assess the environmental and economic aspects of 3D printing with recycled materials. We will examine the environmental impact of 3D printing with recycled materials, perform a life cycle assessment of recycled 3D printed objects, and evaluate the process's economic feasibility and resource efficiency. The environmental impact analysis evaluates the benefits of 3D printing with recycled materials compared to conventional manufacturing processes. We consider the reduction in carbon emissions and energy consumption associated with using recycled materials instead of virgin resources (Chong et al., 2017; Cisneros-López et al., 2020; Gu and Ozbakkaloglu, 2016). By diverting waste from landfills and reducing the need for raw material extraction, 3D printing with recycled materials can significantly lower the environmental footprint. We also assess the potential for waste reduction and the conservation of natural resources. Recycling materials minimise waste generation and the demand for new raw materials. This analysis includes quantifying the amount of waste diverted from disposal and estimating the resource savings achieved through recycling.

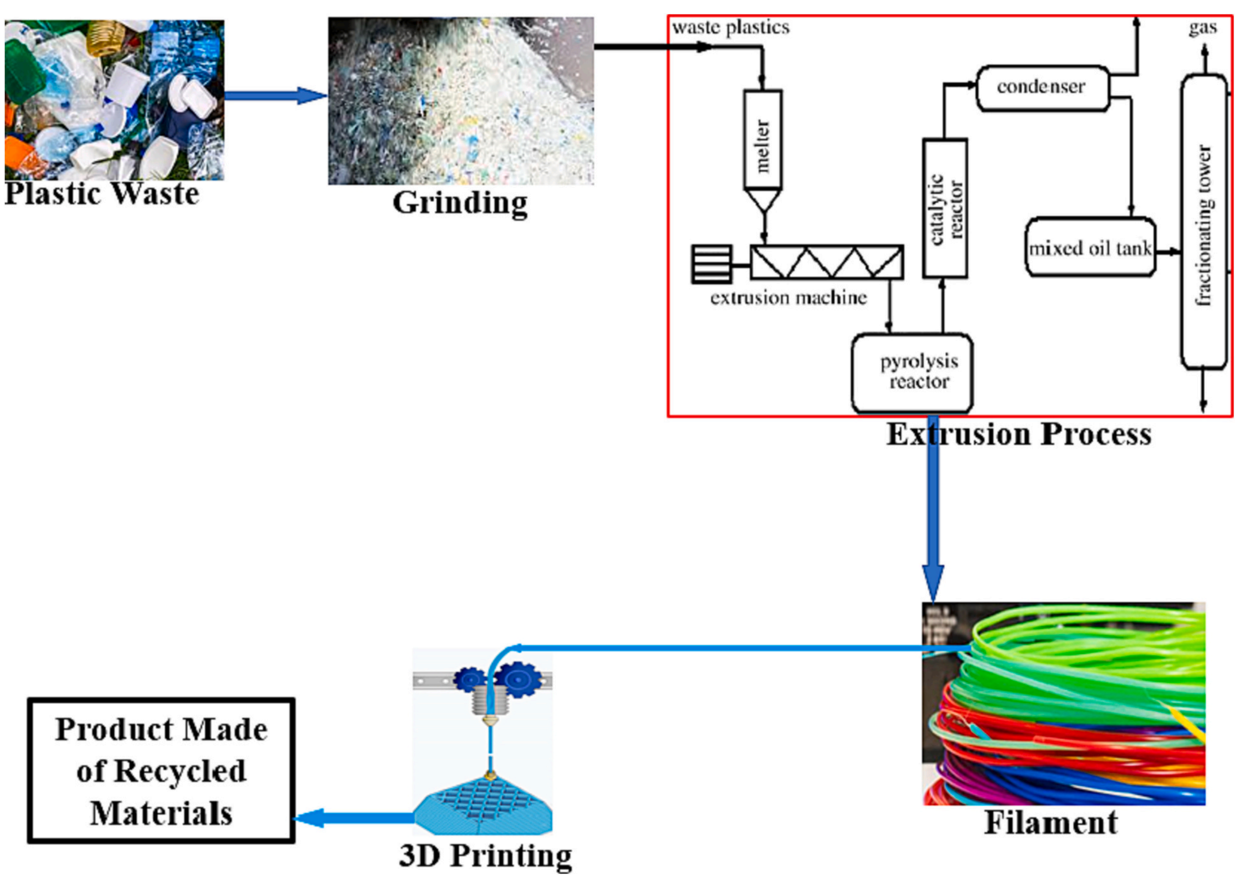

Fig. 5. Typical Recycling scheme for 3D printing materials.

5.2. Life cycle assessment of recycled 3D printed

To comprehensively evaluate the sustainability of recycled 3D printed objects, we conduct a life cycle assessment (LCA). This assessment encompasses the entire life cycle of the objects, from raw material extraction and manufacturing to use, disposal, and potential recycling. The LCA quantifies the environmental impacts at each stage, including greenhouse gas emissions, energy consumption, water usage, and waste generation. We compare the LCA results of objects printed with recycled materials to those printed with conventional materials to determine the environmental advantages of utilising recycled materials. Furthermore, the LCA considers end-of-life scenarios for 3D-printed objects (Gkartzou et al., 2017; Di Maria et al., 2018; Ding et al., 2019). We examine the potential for recycling or upcycling the objects at the end of their use phase, extending their lifespan and reducing waste generation. Fig. 6 shows that by analysing the complete life cycle of recycled 3D printed objects, we gain insights into their sustainability and environmental benefits.

5.3. Economic feasibility and resource efficiency

In addition to the environmental aspects, we evaluate the economic feasibility and resource efficiency of 3D printing with recycled materials. This assessment includes analysing the cost savings achieved using recycled materials instead of purchasing new ones. We consider factors such as the cost of waste collection, sorting, and recycling processes and the potential reduction in material procurement costs. Resource efficiency analysis optimises material usage and reduces waste throughout 3D printing. Recycling materials minimise waste generation and promote a circular economy (Cruz Sanchez et al., 2017; Chariyachotilert et al., 2012; Cao et al., 2004). We quantify the material savings achieved through recycling and assess resource efficiency regarding material utilisation, waste reduction, and overall resource conservation. Through the sustainability analysis, including evaluating the environmental impact of 3D printing with recycled materials. Fig. 7 shows the life cycle assessment of recycled 3D printed objects and the economic feasibility and resource efficiency analysis, and we understand the sustainability benefits and potential economic advantages of incorporating recycled materials in 3D printing processes. These findings contribute to developing sustainable manufacturing practices and support the transition towards a more circular and resource-efficient economy.

5.4. Applications and future of recycled 3D printing

This section will explore the potential applications of recycled 3D printing and discuss the challenges, opportunities, and future research directions. Recycled 3D printing opens up various potential applications across various industries. Here are some areas where recycled materials

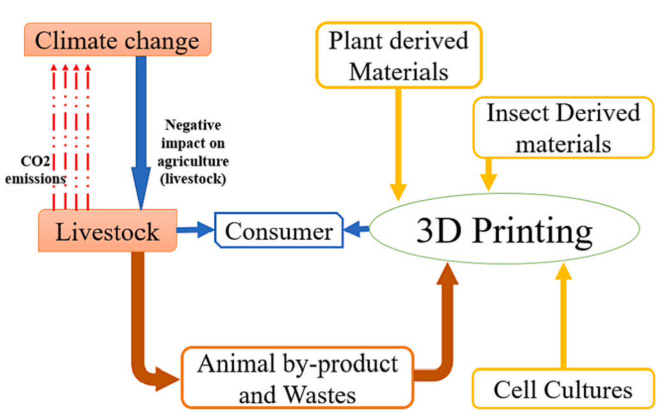

Fig. 6. Schematic illustration of 3D printing of meat analogues and its impact on climate change.

in 3D printing show promise; recycled 3D printing can be utilised for rapid prototyping, allowing designers and engineers to iterate and test their ideas quickly (Chariyachotilert et al., 2012; Cao et al., 2004; Naima and Liazid, 2013). The cost-effectiveness of using recycled materials makes it an attractive option for early-stage product development. 3D printing with recycled materials enables the production of customisable consumer products. Whether it is personalised accessories, household items, or fashion products, creating unique, tailored designs offers a new level of customisation and sustainability. Recycled 3D printing can contribute to sustainable construction practices. Using recycled materials, such as recycled aggregates or plastic waste, in 3D printing construction can reduce the environmental impact and promote resource efficiency. The healthcare industry can benefit from recycled 3D printing in various ways. Customised prosthetics, implants, and medical devices can be produced using recycled materials, offering cost-effective and sustainable solutions. Recycled 3D printing provides an excellent opportunity for educational institutions and research facilities. It allows students and researchers to explore sustainable design principles, material science, and additive manufacturing technologies in a practical and hands-on manner.

5.5. Challenges and opportunities for scaling up

While the potential of recycled 3D printing is promising, some challenges must be addressed to scale up the technology successfully. Ensuring consistent material properties and quality of recycled filaments or powders can be challenging. Standardisation and quality control measures need to be established to meet industry requirements. Different recycling processes may result in variations in material characteristics, which can affect printability and performance. Developing processing techniques that optimise material properties and compatibility with 3D printing technologies is crucial. Establishing an efficient infrastructure and supply chain for collecting, sorting, and processing recyclable materials is essential for scaling up recycled 3D printing. Collaborations between recycling facilities, manufacturers, and 3D printing service providers can help create a robust ecosystem. Fig. 8 shows a recycled 3D printing evolves, it will be essential to establish regulations and standards to ensure product safety, quality, and compliance with environmental regulations. Clear guidelines and certifications can build trust and enable broader adoption of recycled 3D printing.

5.6. Future research directions and innovations

To further advance the field of recycled 3D printing, several research directions and areas of innovation can be explored; research into novel recycling technologies, such as chemical recycling or advanced separation techniques, can enhance the quality and versatility of recycled materials for 3D printing. Investigating new material compositions, additives, and blends can expand the range of recycled materials suitable for 3D printing. This includes exploring biodegradable and biocompatible materials and sustainable alternatives to traditional plastics. Developing optimised printing parameters for different recycled materials, such as temperature profiles, print speeds, and support structures, can improve print quality and reliability. Advanced printing techniques, such as multi-material or hybrid printing, can also be explored to enhance functionality. Integrating circular design principles into the 3D printing process can maximise material efficiency and enable easier recycling or upcycling of printed objects. Designing for disassembly, modular designs, and incorporating recycled materials as part of the design strategy can contribute to a more sustainable approach. Conducting in-depth life cycle assessments (LCAs) and developing sustainability metrics specific to recycled 3D printing can provide a comprehensive understanding of its environmental impact and guide decision-making for sustainable practices. By focusing on these research directions and embracing innovation, we can unlock the full potential of

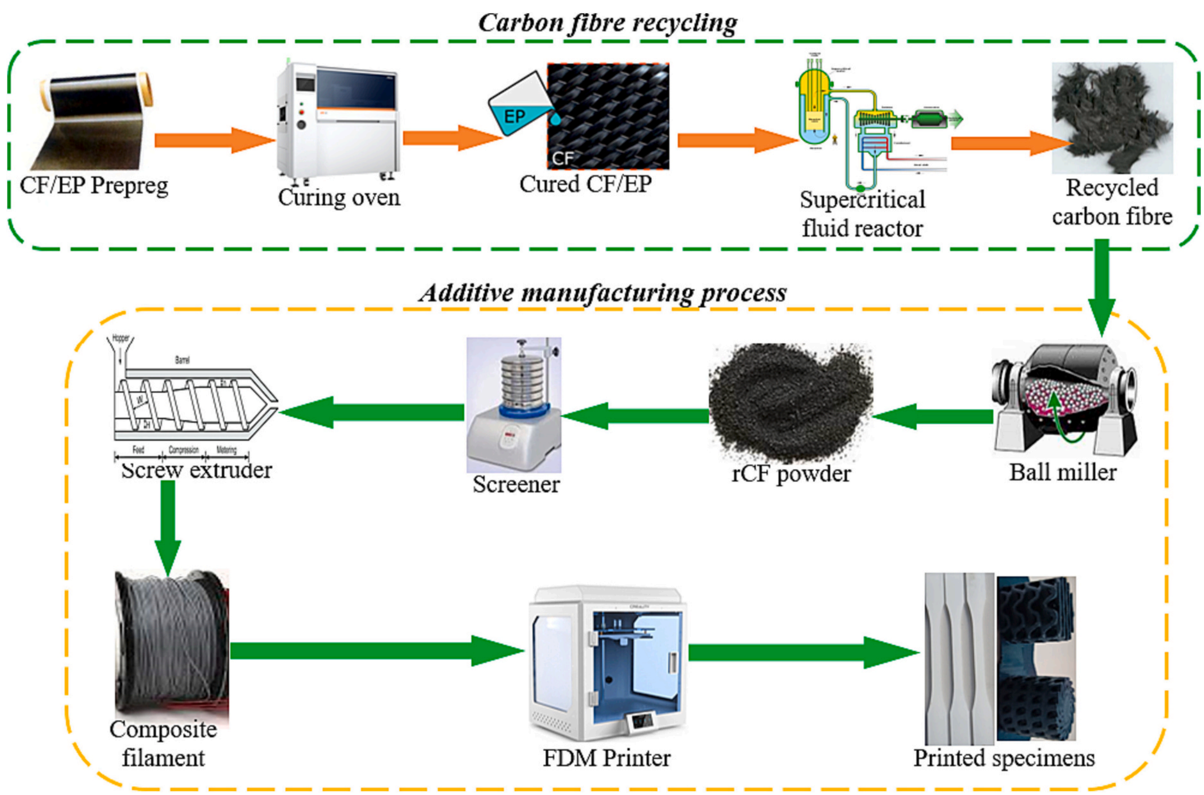

Fig. 7. The experimental process of the integrated carbon fibre polymer recycling via the additive manufacturing-based remanufacturing method.

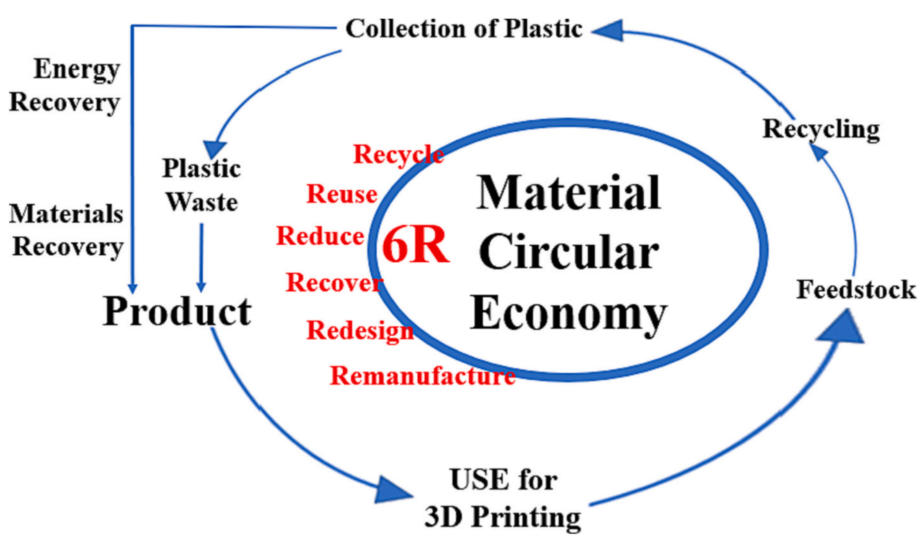

Fig. 8. The basic concept of Material circular economy in the 3D Printing process.

recycled 3D printing, driving its adoption in diverse industries and contributing to a more sustainable and circular economy.

6. Conclusion

This research paper explored the potential of combining 3D printing and recycling as a sustainable manufacturing approach. Through a comprehensive literature analysis, printability assessment, sustainability analysis, and examination of applications and future directions, we have gained valuable insights into the synergistic potential, challenges, and opportunities in recycled 3D printing.

6.1. *Summary of findings*

i. Integrating 3D printing and recycling offers numerous benefits, including enhanced resource efficiency, design freedom, waste reduction, and customisation. Recycled materials can be transformed into printable feedstock, creating complex objects with diverse properties.
ii. The printability assessment revealed that recycled materials could be successfully used in 3D printing processes, with comparable print quality and mechanical performance to conventional materials. However, material consistency and processing compatibility must be addressed for optimal results.

iii. The sustainability analysis highlighted the environmental advantages of 3D printing with recycled materials. It can significantly reduce carbon emissions, energy consumption, waste generation, and reliance on virgin resources. Life cycle assessment (LCA) showed the potential for extended product lifespan and circularity through recycling or upcycling.
iv. Recycled 3D printing has potential applications in prototyping, customised consumer products, infrastructure, medical applications, education, and research. Scaling up the technology requires addressing material consistency, infrastructure, and regulatory challenges. Future research should focus on advanced recycling technologies, material development, process optimisation, circular design principles, and sustainability metrics.

6.2. Implications for 3D printing and recycling industries

The findings of this research significantly impact the 3D printing and recycling industries; integrating 3D printing and recycling presents an opportunity to adopt more sustainable manufacturing practices. By leveraging recycled materials, manufacturers can reduce environmental impact, promote circularity, and conserve resources. Collaboration between recycling facilities, material scientists, 3D printing companies, and other stakeholders is crucial for advancing recycled 3D printing. Innovation in recycling technologies, material development, and process optimisation can drive progress in the field. Establishing regulations and standards for recycled 3D printing ensures product safety, quality, and environmental compliance. Clear guidelines and certifications build trust and facilitate the broader adoption of recycled materials in 3D printing. Integrating 3D printing and recycling can transform various industries, enabling sustainable product development, resource efficiency, and customisation. It offers opportunities for businesses to differentiate themselves and cater to the growing demand for environmentally friendly solutions. Combining 3D printing and recycling presents a promising path towards sustainable manufacturing. The findings of this research contribute to understanding the synergistic potential, challenges, and opportunities in recycled 3D printing. By embracing innovation, collaboration, and sustainable practices, we can drive the adoption of recycled materials in 3D printing and contribute to a more sustainable and circular economy.

CRediT authorship contribution statement

Matthew A. Olawumi: editing and Supervision; Writing- Reviewing and Editing; Data curation; Validation; Editing;

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

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

John O. Akinyoola: Visualization; Investigation; Software; Validation; Editing;

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.

Data availability

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

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