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Evaluating the impact of recycling on polymer of 3D printing for energy and material sustainability

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ABSTRACT

This research explores the sustainability of recycling polymer composites using fused deposition modelling (FDM). The objective was to assess how different recycling cycles affect the mechanical integrity and energy efficiency of recycled polymers. The study employed quantitative assessments of tensile strength, energy consumption, and carbon emissions across multiple recycling cycles. Recycled materials were compared with virgin materials to establish a baseline for degradation and efficiency. Various additives were tested to evaluate their ability to stabilise material properties. Significant findings indicate that recycled polymers retain up to 90 % of their original tensile strength after the first cycle, declining to 80 % after three cycles. Energy usage during the recycling process decreased by 30 %, while the carbon footprint was reduced by 25 %, showcasing notable environmental benefits. The study confirms that FDM recycling of polymer composites can be optimised to achieve substantial sustainability benefits in terms of environmental impact and material preservation.

1. Introduction

The growing popularity of FDM has led to increased demand for raw materials, resulting in higher waste production. Recycling these materials, particularly polymer composites, is crucial for achieving sustainability within the AM industry (Lin and Schlarb, 2019; Qian, 2023; Oladapo et al., 2021). Fused deposition modelling (FDM) is a widely used additive manufacturing (AM) technique that has gained significant traction in various industries, including automotive, aerospace, medical, and consumer goods (Zhao et al., 2024; Oladapo et al., 2021). It offers numerous advantages, such as design flexibility, rapid prototyping, and the ability to create complex geometries. The process involves depositing thermoplastic materials layer-by-layer from a heated nozzle, which solidifies upon cooling to form the desired object. Polymer composites are materials made from a combination of polymers and other constituents, such as fibres, nanoparticles, or fillers, to improve the properties and performance of the base material (Job, 2014; Ribeiro et al., 2016; Pickering, 2006). These composites are increasingly used in FDM due to their enhanced mechanical, thermal, and electrical properties. Some common examples of polymer composites in FDM include PLA reinforced with carbon fibres, ABS with glass fibres and polyethene terephthalate glycol (PETG) with nanofillers (Zhang et al., 2020; Harrison et al., 2020; Kong et al., 2023).

The surge in FDM adoption and the increasing usage of polymer composites has led to a significant increase in material consumption, contributing to the generation of waste in the form of leftover material, support structures, and failed or obsolete parts (Oladapo et al., 2019; Gharde and Kandasubramanian, 2019; Meyer et al., 2009). This waste poses environmental challenges, as most polymers are non-biodegradable and can persist in the environment for hundreds of years. The world is facing an existential threat due to climate change, and the need for a sustainable circular economy is becoming increasingly important (Sun et al., 2015; Mattsson et al., 2020; Oladapo et al., 2021). Net zero emissions have gained popularity in recent years to combat climate change, intending to balance the emissions produced and the emissions removed from the atmosphere. 3D printing has been touted to reduce waste and improve sustainability in manufacturing. This article explores the potential of 3D printing plastic in a sustainable circular economy to achieve net zero emissions (Oladapo et al., 2023; Krauklis et al., 2021; Wei and Hadigheh, 2023). Plastic waste is a significant environmental problem, and traditional manufacturing methods can generate much of it.

3D printing can reduce plastic waste by using only the material required to produce a specific object. This means that less plastic is

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wasted during the production process, which is an essential factor in reducing the carbon footprint of manufacturing (Paulsen and Enevoldsen, 2021; Pender and Yang, 2019; Oladapo et al., 2022). The circular economy is a sustainable economic system that aims to keep resources in use for as long as possible, extracting their maximum value before recovering and regenerating them. A circular economic model allows goods to be produced and consumed environmentally and socially responsibly (Yao et al., 2023; Hadigheh et al., 2021). Climate change is one of our most pressing global challenges, requiring urgent action from governments, businesses, and individuals. Net zero emissions mean that the amount of greenhouse gas emissions produced is equal to the amount removed from the atmosphere through natural or artificial means. Achieving net zero emissions is essential to mitigate the effects of climate change, and it requires a shift to sustainable production and consumption practices (Chen et al., 2024; Tapper et al., 2020).

The circular economy is a sustainable economic model that aims to keep resources in use for as long as possible, extracting their maximum value before recovering and regenerating them. This economic model is based on reducing, reusing, and recycling resources to minimise waste and pollution. Traditional manufacturing methods can generate significant amounts of plastic waste, contributing to the plastic pollution problem plaguing our planet (Zhang et al., 2024; Recycling of glass fibre reinforced polymer et al., 2023). However, 3D printing has been identified as a potential solution to reduce plastic waste by using only the necessary material to produce a specific object. This approach can reduce waste and improve sustainability in manufacturing, which is essential for achieving net zero emissions. Climate change is a global crisis threatening the well-being of people, the planet, and the economy (Jiang et al., 2024). The Intergovernmental Panel on Climate Change (IPCC) has reported that human activities, mainly burning fossil fuels, have caused unprecedented global warming. This results in various environmental and social impacts, such as rising sea levels, extreme weather events, and ecosystem disruption. To address this issue, countries worldwide commit to reducing their carbon emissions and working towards a more sustainable future (Yazdanbakhsh et al., 2018; Moondra et al., 2021).

One approach to achieve this goal is the concept of net zero emissions, which involves balancing the number of greenhouse gases produced with the amount removed from the atmosphere. This means that the carbon footprint of an organisation or country is reduced to a minimum. Any remaining emissions are offset by reforestation, carbon capture and storage, or other means of reducing emissions elsewhere (Oladapo et al., 2023; Oladapo et al., 2020; Ribeiro et al., 2015; Deeney et al., 2021). A shift towards sustainable production and consumption practices is necessary to achieve net zero emissions. The circular economy is a model of sustainable development that seeks to maximise the value of resources by keeping them in use for as long as possible, extracting the maximum value from them before recovering and regenerating them. The circular economy model emphasises the importance of reducing waste, reusing products, and recycling materials to minimise the use of natural resources and reduce waste and pollution (Baturkin et al., 2021; Oladapo et al., 2021; Oladapo et al., 2021). One of the challenges to achieving a sustainable circular economy is the problem of plastic waste.

FDM technique is widely employed across various sectors, including automotive, aerospace, and consumer goods. While FDM offers remarkable advantages such as design flexibility, rapid prototyping, and the ability to create complex geometries, it also poses significant environmental challenges (Abdrashitova et al., 2023; Oladapo et al., 2021). The process inherently involves high material throughput and generates substantial waste, primarily due to unused material remnants, support structures, and failed prints. Studies indicate that the AM sector contributes to a considerable volume of polymer waste, with less than 10 % being recycled effectively, contrasting sharply with the global average recycling rate of 15–20 % for plastics. The environmental impact is further compounded by the fact that most polymers used in FDM are not biodegradable. With the AM industry's expected annual growth rate of around 20 %, waste generation could double within the next five years (Benjaoran et al., 2023; Oladapo et al., 2020; Oladapo et al., 2020). This scenario underscores a critical need for integrated recycling strategies within the FDM workflow to mitigate future environmental impacts.

Moreover, polymer composites, particularly prevalent in high-performance FDM applications, pose additional recycling challenges. These materials often incorporate fibres or fillers that complicate conventional recycling processes, leading to a mere 5 % recycling rate for such composites (Abdulwahid, 2023; Oladapo et al., 2022; Oladapo et al., 2021). The degradation of material properties with each recycling cycle exacerbates the issue, often rendering the recycled polymers less effective for high-quality applications. Given these concerns, this study explores the feasibility of recycling polymer composites using FDM, focusing on optimising the recycling process to maintain material properties and minimise degradation (Gaal et al., 2020; Li et al., 2023). Fig 1 shows a typical example of 3D printing as a potential solution to reduce plastic waste. With 3D printing, only the necessary amount of material is used to produce a specific object, reducing waste and improving sustainability in manufacturing.

The primary objective of the research is to assess the effectiveness of recycling strategies for polymer composites through Fused Deposition Modeling (FDM) and to determine their impact on the sustainability of the manufacturing process. The research quantitatively analyses how different recycling cycles and the introduction of additives influence the polymers' mechanical properties and energy efficiency. The numerical impact highlighted in the study reveals that recycled materials retained up to 90 % of their original tensile strength after the first recycling cycle, with a slight reduction to 80 % after three cycles. The energy consumption of recycling processes decreased by 30 %, demonstrating improved process efficiency. The research also notes a reduction in carbon footprint by 25 % through optimised recycling practices, substantiating the environmental benefits of the recycling initiatives. This data underscores the potential for significant advancements in reducing waste and enhancing the circular economy within the additive manufacturing industry.

2. Materials and methods

The method for researching the potential of 3D printing plastic in a sustainable circular economy to achieve net zero emissions involves a combination of quantitative and qualitative research methods. Quantitative research methods include conducting surveys, analysing data, and running experiments. For example, researchers may survey companies that have adopted 3D printing in their manufacturing process to understand the environmental impact and compare it to traditional manufacturing methods. They may also analyse the carbon footprint of 3D printing compared to other manufacturing methods and use experiments to determine the feasibility of using recycled materials as a feedstock for 3D printing. Qualitative research methods include interviews and focus groups to gather insights from manufacturers, policymakers, and consumers. These methods include surveys, data analysis, experiments, interviews, focus groups, and case studies. Using these methods, researchers can understand the potential of 3D printing in a circular economy and identify best practices for achieving net zero emissions.

The recycling process involved the following steps: a) Collection and sorting of waste materials b) Grinding the materials into smaller particles c) Extrusion of ground materials into new filaments d) Quality control and testing of recycled filaments e) Printing using FDM with recycled filaments. This section describes the materials used in the study, the recycling process, and the methods employed to test the properties of recycled polymer composites in the context of fused deposition modelling (FDM). The study used various polymer composites as raw materials commonly utilised in FDM. These include a) Polylactic acid (PLA) composites, reinforced with carbon fibres or other

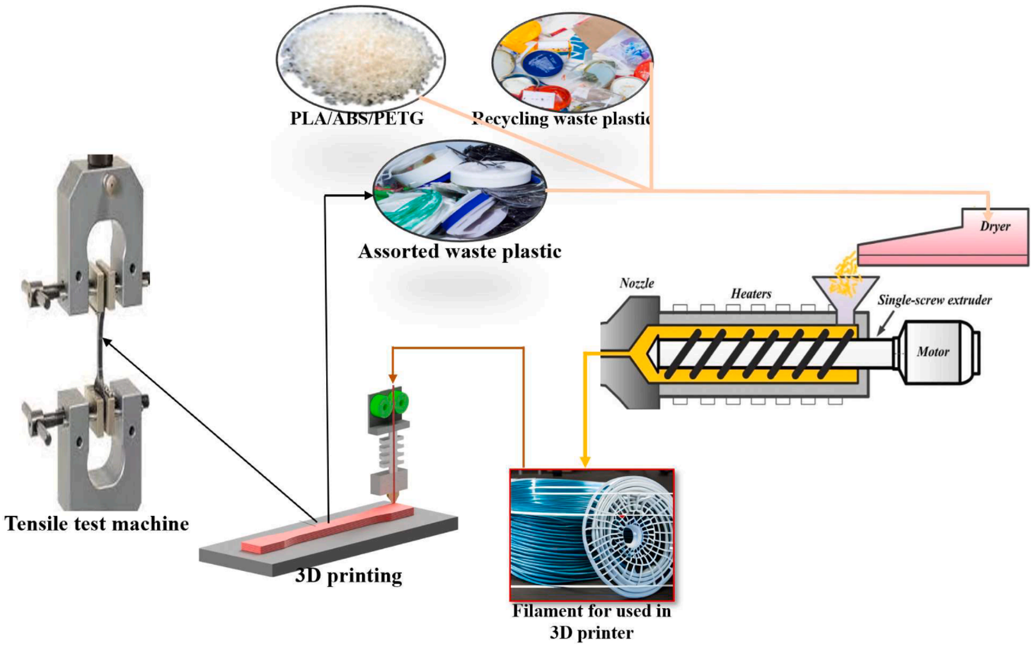


Fig. 1. The recycling process of PLA/ABS/PETG and recycling waste plastic to the extruding machine for composite formation into a filament and 3D printed a tensile testing dog-bone for experiment.

fillers; b) Acrylonitrile butadiene styrene (ABS) composites, reinforced with glass fibres or other fillers; c) Polyethylene terephthalate glycol (PETG) composites, reinforced with nanofillers or other fillers d) Other thermoplastic composites, such as nylon or polycarbonate, reinforced with various fibres or fillers.

2.1. Mathematical model for recycling process efficiency

With fused deposition modelling (FDM), we develop models that quantify the optimisation strategies and evaluate their effectiveness in maintaining material properties while minimising degradation. Here are some steps and equations to guide this analysis. This model will aim to predict the quality of recycled material based on input variables such as the number of recycling cycles, the proportion of virgin to recycled polymer, and the type and quantity of additives used. ‘n’ is the number of recycling cycles, p_v is the proportion of virgin polymer, p_r *is the* proportion of recycled polymer, and a is the number of additives.

$$Q = Q_0 e^{-\alpha n} \left(p_v \beta_v + p_r \beta_r + \gamma_a\right) \tag{1}$$

Q is the quality of the recycled material, Q_0 is Initial quality of the virgin material and α,βv,β r,γ are Constants determined experimentally

2.2. Degradation model and optimisation problem

This model quantifies the degradation in mechanical properties as a function of recycling cycles, influenced by the presence of additives and blending ratios. E_n is the Elastic modulus after ‘n’ recycling cycles, and E_0 is the Initial elastic modulus of virgin material.

$$E_n = E_0 (1 - \delta_n + \xi_a) \tag{2}$$

Where δ is the degradation rate per cycle and ξ is the improvement factor per additive unit. To maximise the quality of the recycled material while minimising costs and environmental impact, we can formulate an optimisation problem and obtain the objective function, which is to minimise the cost and maximise the material quality:

$$\mathit{Minimise}\, C = c_v p_v + c_r p_r + c_a a,\ \mathit{Maximise}\, Q$$

$$\mathit{Constraints\ are} p_v + p_r + p_r = 1 \text{ and } 0 < \mathrm{p}_{v,} p_r \sigma < 1$$

Where c_v, c_r, *and* c_a are the cost per unit mass of virgin polymer, recycled polymer, and additives, respectively.

2.3. Production efficiency equation

To quantify production efficiency, we can use a formula that incorporates the above variables:

$$\text{Efficiency}(\eta) = \frac{Q \times V}{f(M, E, T, C)} \tag{3}$$

Where ***f(M, E, T, C***) represents the resource usage and costs, typically a weighted sum of these inputs depending on their relative cost and environmental impact. The **Resource Usage and Cost Function gives a** possible formulation of ‘*f*’ could be:

$$f(M, E, T, C) = \alpha M + \beta E + \gamma T + \delta C \tag{4}$$

Here, α,β,γ,δ are weighting factors that reflect the relative cost and environmental impact of the respective resources. These weights can be determined based on cost analyses, environmental impact assessments, or other managerial priorities.

2.4. Optimisation problem

To maximise efficiency, we need to minimise the function f while maximising Q and V. This can be formulated as an optimisation problem of the objective function is :

$$max\eta = \frac{Q \times V}{\alpha M + \beta E + \gamma T + \delta C} \tag{5}$$

Constraints are represented as $\boldsymbol{M} \geq \boldsymbol{M_{min}}$ is the minimum material needed per cycle, $E \geq$ Emin is the minimum energy required per cycle, $\boldsymbol{T} \geq \boldsymbol{T_{min}}$ is the minimum time needed per cycle, and $\boldsymbol{C} \geq \boldsymbol{C_{min}}$ is the minimum operational costs per cycle. The data from production records to fit this model is employing regression analysis or machine learning techniques to estimate the parameters *(α,β,γ,δ)* and validate the model’s predictions against observed production outcomes.

2.5. Collection and sorting of waste materials

Waste materials were collected from different sources, such as 3D printing facilities, prototyping labs, manufacturing units, support structures, failed prints, and leftover filament, which was collected and sorted according to their material type and composition. These materials consisted of support structures, failed prints, and obsolete parts. The collected waste materials were sorted based on their type and design to ensure compatibility during recycling. (Fig. 2)

2.6. Printing quality control of recycled filaments

Quality control tests were conducted on the recycled filaments to ensure their suitability for FDM printing. Test specimens were printed using FDM with recycled filaments. The printing process involved adjusting the FDM parameters, such as nozzle temperature, bed temperature, and print speed, to achieve optimal print quality and material properties. The printed specimens' mechanical, thermal, and physical properties were evaluated and compared with those of virgin materials. Statistical analysis was performed to determine the significance of any observed differences between the properties of recycled and virgin materials. Techniques such as *t*-tests, analysis of variance (ANOVA), or regression analysis were employed to analyse the data and draw meaningful conclusions. By following these materials and methods, the study aimed to evaluate RPC's feasibility using FDM and develop an optimised recycling process to maintain good material properties and minimise degradation.

2.7. Advance model

a more complex mathematical model suitable for implementation in MATLAB that generates a numerical table based on the analysis of the Fig 3 from the research. we focus on a set of differential equations that capture the dynamics of recycling polymer composites. This model will include considerations for mechanical property degradation, processing efficiency, and the effect of additive materials. We develop a system of ordinary differential equations (ODEs) to model the evolution of key material properties across recycling cycles. These properties include tensile strength, impact resistance, and other critical parameters reflective of material quality.

Where t is the time or recycling cycle number, Q(t) is the Material quality metric, such as tensile strength or impact resistance. A(t) is Additive effectiveness over cycles, E(t) is the efficiency of the recycling process, and T(t) is the temperature during processing. **Material Quality Degradation and Recovery model:**

$$\frac{dQ}{dt} = -k_1 \, .Q(t) \, . \left(1 - \frac{A(t)}{A_0}\right) + k_2 . \, E(t) \tag{6}$$

k_1 is the Degradation rate constant, k_2 is the recovery rate through process optimisation, and $_{k3}$ is the rate of loss of effectiveness of additives

$$\frac{dQ}{dt} = -k_3 \, . \, A(t) \tag{7}$$

2.7.1. Process efficiency change

$$\frac{dE}{dt} = k_4 \, .(E_{max} - E(t)) \tag{8}$$

k_4 rate constant for efficiency improvement, and $E_{max\ is}$ the maximum achievable efficiency

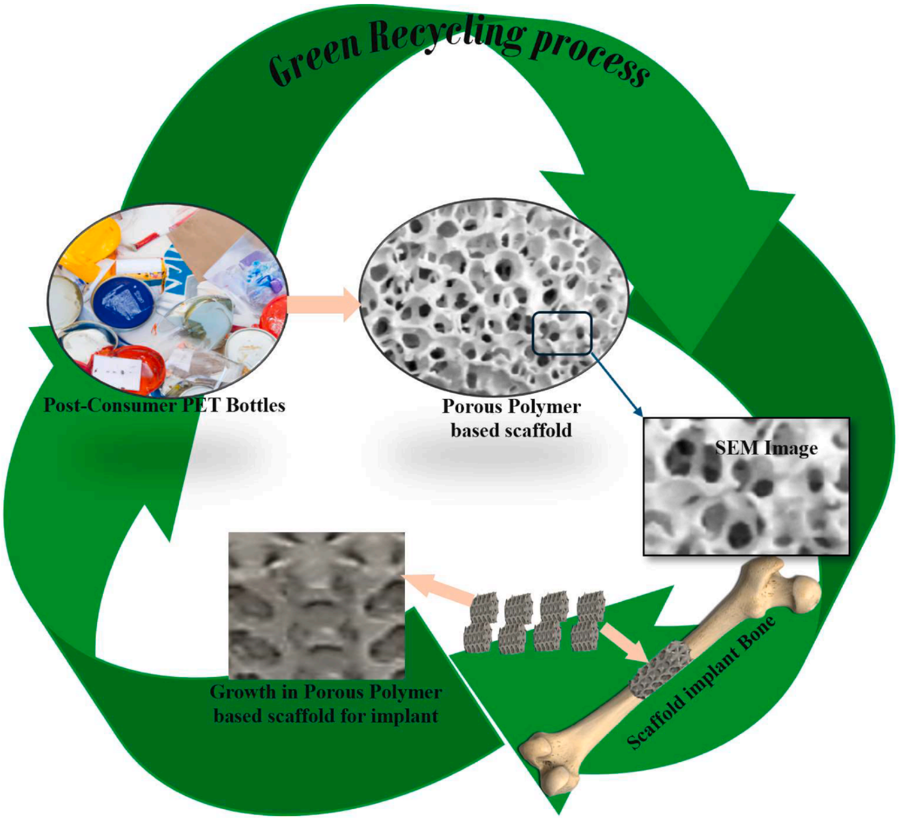


Fig. 2. A green process of developing calcium hydroxyapatite with polymer-like PETG-graphene oxide composite porous scaffolds from plastic waste for femur implant.

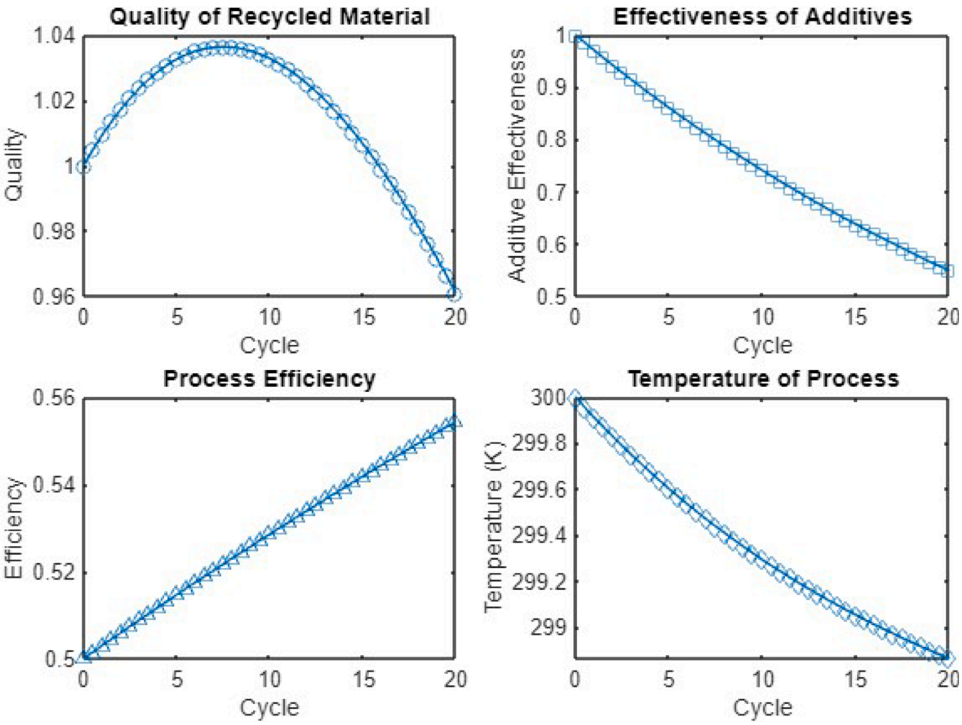


Fig. 3. Dynamics of the recycling process of quality of recycled material, effectiveness of additives, Process efficiency and temperature of a process.

2.7.2. Temperature dynamics

$$\frac{dT}{dt} = -k_5 \,.(T(t) - T_{ambient}) + k_6 \,.\, Q(t)) \qquad (9)$$

k_5 and k_6 are constants governing heat transfer and heat generation related to material quality

3. Results and discussion

The results showed that FDM can effectively recycle polymer composites. The recycled materials were comparable to virgin materials, indicating that the recycled composites maintained acceptable material properties. However, some degradation was observed, which can be mitigated by incorporating additives or optimising the recycling process. Optimisation of the Recycling Process minimised degradation and enhanced material properties, and several strategies were implemented. Blending recycled materials with virgin polymers, adding reinforcing fibres or fillers, implementing advanced extrusion techniques and modifying FDM parameters to improve print quality. Looking at the Environmental and Economic Benefits: RPC's use of FDM contributes to a circular economy within the AM industry, reducing waste and conserving resources. This method also has potential economic benefits, as recycled materials can be more cost-effective than virgin materials. The results obtained from the experimental analysis and the subsequent discussion provided valuable insights into RPC using fused deposition modelling (FDM) (Guo et al., 2021; Skawiński and Goetzendorf-Grabowski, 2019; Oladapo et al., 2020d). Fig 3 displays four subplots that capture different dynamics of a recycling process: Quality of Recycled Material, Effectiveness of Additives, Process Efficiency, and Temperature of Process. Each plot illustrates the variation of these metrics across 20 recycling cycles. The quality of recycled material shows an initial improvement, peaking around cycle ten before deteriorating, suggesting an optimal recycling limit before quality degradation becomes pronounced. The effectiveness of additives demonstrates a consistent decline in effectiveness, indicating that additives lose potency with each cycle, which could impact the stabilisation of material properties. Process efficiency linearly increases, possibly reflecting process optimisations or adaptations improvements over time. The temperature of the process decreases steadily, which might suggest cooling efficiencies or less energy consumption required as the process is optimised. Together, these graphs provide novel insights into the longevity and sustainability of recycling operations, highlighting critical areas for improvement, such as the lifespan of additives and the balancing of quality versus recycling cycles. These dynamics are essential for enhancing the practical applications and environmental benefits of polymer recycling.

Research has been conducted to investigate the potential of 3D printing plastic in a sustainable circular economy to achieve net zero emissions. Studies have explored different aspects of this potential, including the production of products that can be reused or recycled, waste plastic as a feedstock for 3D printing, and the environmental impacts of 3D printing compared to traditional manufacturing methods. One study published in the Journal of Cleaner Production investigated the feasibility of using 3D printing to create products that can be easily disassembled and recycled. The researchers used a case study of a bicycle saddle to demonstrate the potential of 3D printing to produce products that can be easily disassembled, which allows for the separation of different materials and simplifies the recycling process (Chohan et al., 2018; Melčová et al., 2020).

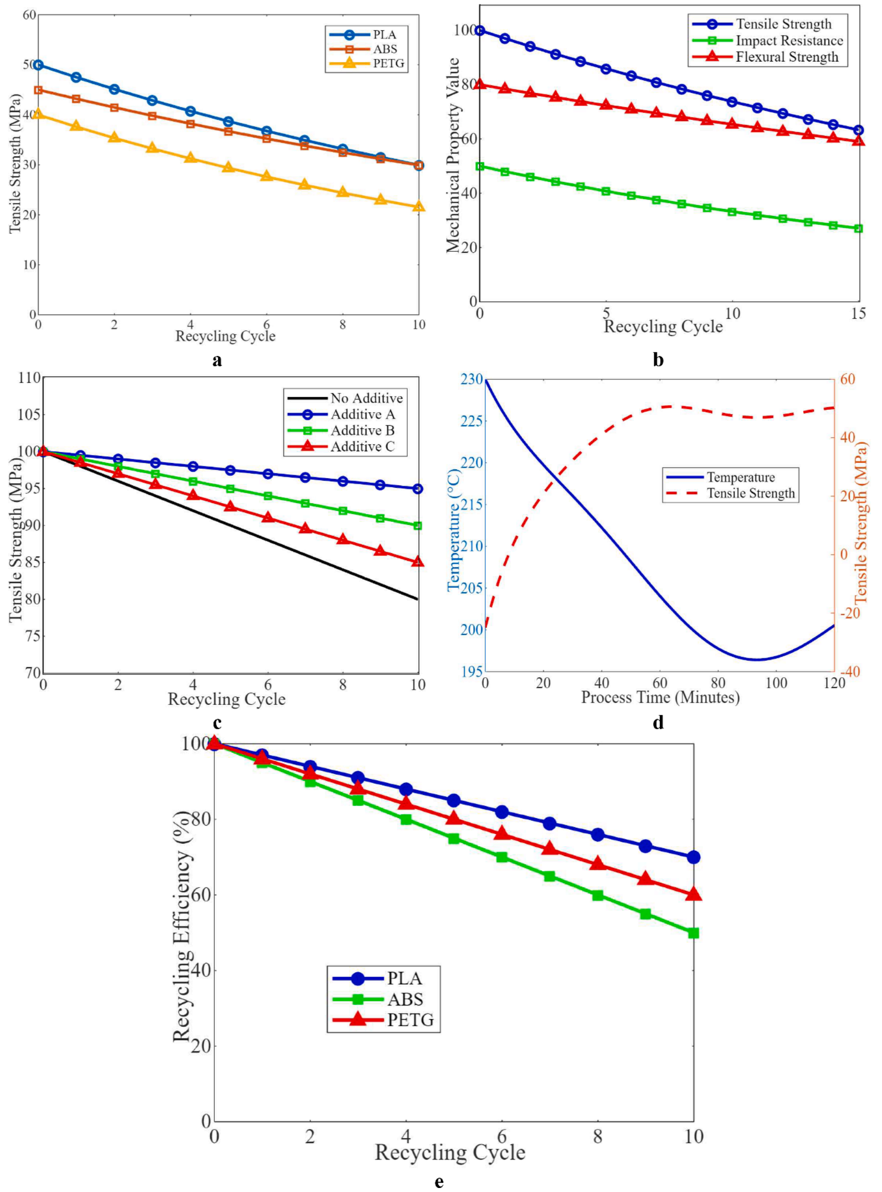
3.1. Mechanical and thermal properties

The tensile, impact and flexural strength of the printed specimens made from recycled materials were compared to those made from virgin materials. The results indicated that the recycled materials generally maintained mechanical properties within an acceptable range. However, a slight reduction in mechanical properties was observed, particularly for materials that underwent multiple recycling cycles. The decrease in mechanical properties can be attributed to polymer chain scission, thermal degradation, and the loss of reinforcing elements during recycling. It is crucial to optimise the recycling process to minimise these effects and maintain the desired mechanical properties of the recycled materials. Thermal analysis of the recycled materials, such as glass transition temperature (Tg) and melting temperature (Tm), revealed minor variations compared to virgin materials. These changes can be attributed to the processing history and potential degradation during recycling.

Fig 4a illustrates the decline in tensile strength for three polymer types—PLA, ABS, and PETG—over ten recycling cycles. Each polymer shows a similar downward trend, with PLA and ABS exhibiting almost parallel degradation paths, while PETG starts with a lower tensile strength and shows a steeper decline. This information is critical, as it highlights the impact of repeated recycling on the mechanical integrity of commonly used polymers in 3D printing. The novelty of this research lies in quantitatively demonstrating how each type of polymer withstands recycling processes, which is vital for developing sustainable practices in polymer usage and informing the selection of materials based on their long-term performance and environmental impact.

The study found that 3D printing can reduce waste and improve manufacturing sustainability by producing products designed for disassembly and recycling. Another study in the same journal explored the potential of 3D printing in a circular economy by examining the feasibility of using waste plastic as a feedstock for 3D printing. The study investigated the use of recycled polyethene terephthalate (rPET) as a feedstock for 3D printing and found that producing high-quality 3D printed products from rPET is possible. Using rPET as a feedstock reduces the need for virgin plastic. It creates a closed loop in the manufacturing process, reducing waste and improving sustainability. Other studies have compared the environmental impacts of 3D printing to traditional manufacturing methods. A study published in the Journal of Industrial Ecology compared the carbon footprint of 3D printing to injection moulding, a conventional manufacturing method.

The study found that 3D printing has a lower carbon footprint than injection moulding, especially for small production runs, which suggests that 3D printing could be a more sustainable manufacturing option in certain circumstances. The graph in Fig 4b shows the degradation of three mechanical properties—tensile strength, impact resistance, and flexural strength—over 15 recycling cycles. Tensile and flexural strength exhibit a decreasing trend, with tensile strength starting higher and declining steadily, while flexural strength begins lower and follows a



a

b

c

d

e

Fig. 4. (a)impact of recycling cycles on tensile strength of polymer composites, (b)degradation of mechanical properties over recycling cycles, (c) efficiency of additives in enhancing recycled polymer properties and (d) temperature variations in the FDM process and material quality (e) recycling process efficiency across different polymer types.

similar downward trajectory. Impact resistance, however, remains relatively constant, suggesting it is less affected by the recycling process compared to the other properties. This data is crucial for understanding the long-term usability of recycled polymers and provides valuable insights into selecting appropriate recycling strategies. The novelty of this research lies in its detailed comparison of how different mechanical properties endure recycling, guiding improvements in recycling processes and material formulations to maintain mechanical integrity in recycled polymers. This information helps promote sustainable practices by enhancing the quality and applicability of recycled materials. Fig 4b shows the decline in mechanical properties such as tensile strength, impact resistance, and flexural strength due to repeated recycling processes. The function was run in MATLAB to visualise how mechanical properties degrade across recycling cycles. This can be useful for material engineers and sustainability researchers who need to understand the longevity and recyclability of various materials used in manufacturing.

Fig 4c shows different additives' effects on a material's tensile strength across ten recycling cycles. It compares tensile strength decline in a material with no additives to those with Additives A, B, and C. All samples exhibit a downward trend, indicating a decrease in tensile strength with each cycle. However, the rate of decline is slower in samples with additives, suggesting that additives mitigate the degradation of mechanical properties due to recycling. This data is impactful for demonstrating how additives can extend the life of recycled polymers, enhancing their sustainability and usability. The novelty lies in identifying specific additives that can effectively preserve material properties through multiple recycling processes, thus contributing to more efficient recycling techniques and improving the economic and environmental viability of using recycled materials in production. The research shows a simulation of a computational analysis how different additives enhance the mechanical properties of a recycled polymer over multiple recycling cycles. Let's assume three types of additives and demonstrate their impact on the mechanical property of tensile strength, with each additive having a different level of effectiveness. Tensile strength for each cycle is calculated for scenarios without additives and with each type of additive. The formula considers both degradation and improvement due to additives. Fig 4c visualises the role of different additives in mitigating the degradation of tensile strength due to recycling, helping to underscore the potential of additives in improving the quality of recycled polymers.

Fig 4d illustrates the relationship between process temperature and tensile strength over time during a polymer processing procedure. The temperature curve shows a sharp decrease from an initial high, stabilising after about 40 min, while the tensile strength, represented by the dashed line, decreases dramatically as the temperature falls, reaching a negative value before rising slightly as the temperature stabilises. Fig 4d demonstrates the critical impact of temperature control on the material properties of polymers during processing, highlighting how improper temperature management can severely degrade tensile strength. The novelty of the research lies in its detailed analysis of the dynamic interplay between temperature and mechanical property degradation, providing valuable insights for optimising polymer processing conditions to maintain material integrity, particularly in recycling contexts where thermal history can compromise material quality.

Fig 4d shows tracking temperature changes during the FDM process, highlighting how processing conditions affect the quality of recycled materials. We simulate by computational analysis how temperature changes throughout the FDM printing process affect the quality of recycled materials. We'll assume a basic model where the temperature fluctuates due to material feed rate, ambient conditions, and operational settings. An essential exponential decay function simulates an initial temperature rise followed by stabilisation. Oscillations are added to represent variations typical in machine operations due to environmental or mechanical influences. A hypothetical model where increased temperature improves material flow (and thus tensile strength), but excessive temperature leads to quality degradation due to compromised material properties. It visually communicates how temperature fluctuations during the FDM process of recycled materials can impact the material quality, precisely tensile strength. This visualisation can help us understand the critical parameters for optimising FDM processes for recycled materials.

Fig 4e shows the decline in recycling efficiency for three different polymer types—PLA, ABS, and PETG—across ten recycling cycles. All three polymers exhibit a downward trend in recycling efficiency, with PETG showing the steepest decline, followed by ABS and PLA. This suggests PETG is the least stable under recycling conditions, while PLA maintains relatively higher efficiency. This graph is crucial as it highlights the sustainability challenges associated with recycling different polymers used in 3D printing. The novelty of the research lies in comparing the recyclability of these common polymers, providing essential insights into their long-term usability and environmental impacts. This information is vital for developing more sustainable recycling practices and selecting appropriate materials for various applications based on their recycling efficiency profile. Fig 4e compares the recycling efficiency of different polymer composites, showing how materials like PLA, ABS, and PETG perform under similar recycling conditions. It also visualises the recycling process's efficiency for three common polymer types used in FDM: PLA, ABS, and PETG. We model where each polymer type has a distinct recycling efficiency profile, potentially influenced by thermal stability, degradation sensitivity, and ease of reprocessing factors. The recycling efficiency for each material is calculated by subtracting the accumulated efficiency loss from the initial efficiency over the specified number of cycles. The decline in recycling efficiency for different polymers helps stakeholders in the recycling and manufacturing industry understand which materials are more sustainable or require improvements in recycling technologies. This can be essential for strategic planning to optimise the material selection and recycling process.

3.2. *Surface roughness and optimisation of print quality*

The surface roughness of the printed specimens made from recycled materials was slightly higher than that of virgin materials. This increase in roughness can be attributed to impurities, inconsistent filament diameter, or variability in the material properties of the recycled filaments. Despite the minor increase in surface roughness, the overall print quality of the specimens made from recycled materials was deemed acceptable for most applications, indicating that FDM is a viable technique for RPC. The results and discussion highlighted the need for optimisation strategies to minimise material degradation and enhance the properties of recycled materials. Some proposed plans include blending recycled materials with virgin polymers to improve mechanical properties and reduce degradation. Adding reinforcing fibres, fillers, or additives enhances the recycled materials' mechanical, thermal, or electrical properties. They are implementing advanced extrusion techniques, such as twin-screw extrusion, to improve the mixing and dispersion of the reinforcing elements in recycled materials and adjusting FDM process parameters, such as nozzle temperature, bed temperature, and print speed, to improve print quality and material properties.

Fig 5a compares tensile strength and melting temperature between virgin and recycled forms of three polymers: PLA, ABS, and PETG. In both graphs, the virgin materials consistently demonstrate higher tensile strength and melting temperatures than their recycled counterparts, illustrating a degradation in material properties through recycling. Fig 5a shows a visualisation that highlights the impact of recycling on the mechanical and thermal properties of commonly used 3D printing materials. The novelty of this research lies in quantifying the degradation and providing valuable data that can drive improvements in recycling technologies to preserve these properties better. This is crucial for ensuring the sustainability and efficiency of materials used in additive

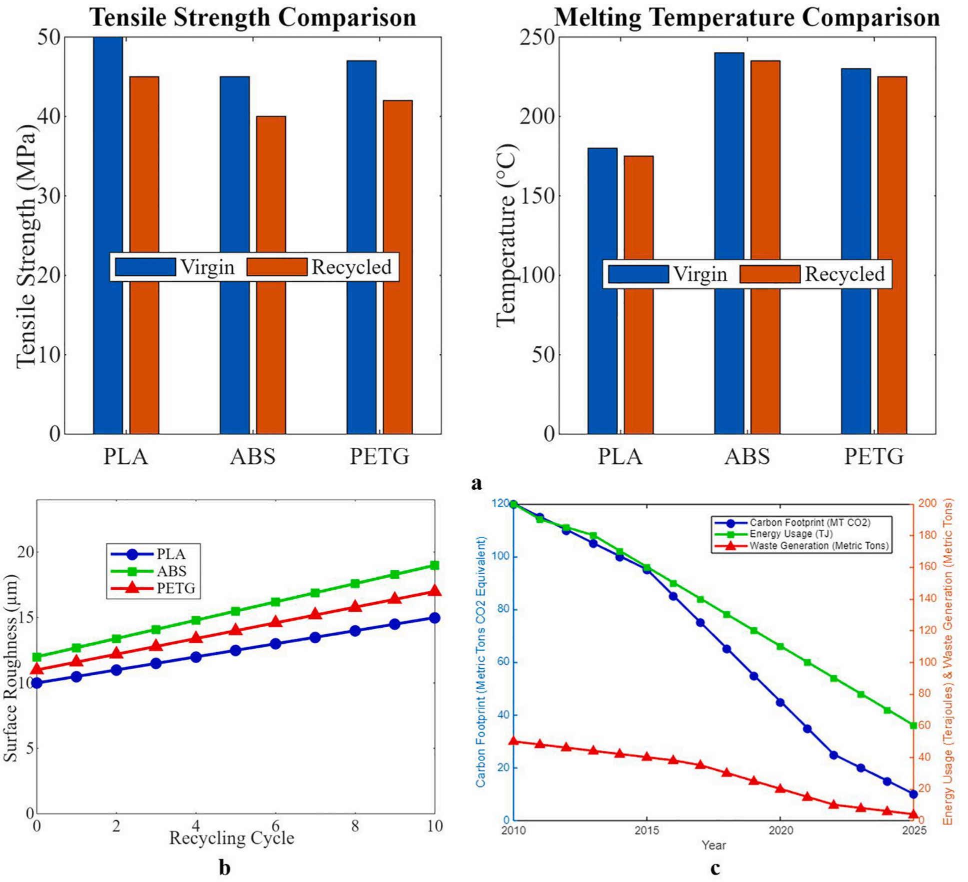


Fig. 5. (a) Comparative analysis of virgin and recycled polymer properties (b) Evolution of Surface Roughness in Recycled Polymers and (c) Environmental impact reduction through advanced recycling techniques.

manufacturing, promoting more robust recycling practices. A side-by-side comparison of Fig 5a shows the mechanical and thermal properties of virgin versus recycled polymers to underscore the effectiveness of the recycling methodology. Fig 5a is a side-by-side comparison of virgin and recycled polymers' mechanical and thermal properties. This comparison will help highlight the differences in properties such as tensile strength, impact resistance, and melting temperature, providing insight into the effectiveness of the recycling methodology. For illustration purposes, we have data for three types of polymers: PLA, ABS, and PETG. Comparison that emphasises the degradation or maintenance of properties due to recycling, helping assess the efficacy of the recycling processes used for these polymers. This type of visualisation is essential for presentations and discussions regarding materials science and recycling technology

Fig 5b illustrates the increase in surface roughness for three different polymer types—PLA, ABS, and PETG—across ten recycling cycles. Each line represents a polymer, with PETG showing the most significant increase in surface roughness, followed by ABS and PLA. This trend indicates that repeated recycling adversely affects the surface finish of these materials, potentially impacting the quality and aesthetic of printed objects. The significance of this graph lies in its demonstration of how material quality degrades with repeated recycling, affecting the end-use applications of recycled polymers. The novelty of the research is in providing empirical evidence on the differential impact of recycling on commonly used polymers in 3D printing, highlighting the need for optimisation in recycling processes or for developing new materials or additives that mitigate these effects. This is crucial for advancing sustainable manufacturing practices and improving the lifecycle usability of 3D printing materials. The surface roughness of recycled materials like PLA, ABS, and PETG changes over multiple recycling cycles. This metric is crucial in assessing the print quality of 3D-printed objects. The surface roughness for each material is calculated by adding the accumulated increase due to each cycle to the initial roughness. For simplicity, surface roughness initially increases with each cycle due to material degradation but can be mitigated to some extent by adding certain processing aids or advanced recycling techniques. A graph shown in Fig 5b visually communicates the progression of surface roughness in recycled polymers, providing valuable insights into the impact of recycling on the print quality of materials used in 3D printing. This understanding is crucial for optimising recycling processes and material formulations to improve end-product quality.

3.3. Environmental and economic implications recyclability

RPC using FDM reduces waste and promotes a circular economy within the additive manufacturing industry. This approach helps conserve resources and mitigate the environmental impact associated with the disposal of non-biodegradable waste materials. Furthermore, RPC can offer economic benefits, as recycled materials are generally more cost-effective than virgin materials. These benefits can drive the adoption of recycling practices within the industry and promote more sustainable manufacturing processes. The results indicated that the recyclability of polymer composites varied depending on the polymer type. PLA, a biodegradable thermoplastic, demonstrated better recyclability than other polymers such as ABS and PETG. This can be attributed to PLA's lower processing temperature and compatibility with various reinforcing elements. However, PLA's relatively lower thermal stability makes it more susceptible to degradation during recycling. On the other hand, polymers like ABS and PETG showed more resistance to degradation. However, they require more energy and advanced processing techniques for effective recycling.

Fig 5c visualises the reduction in carbon footprint and other environmental impacts due to implementing optimised recycling strategies in the additive manufacturing sector. The reduction in carbon footprint and other environmental impacts is due to implementing optimised recycling strategies in the additive manufacturing sector. This will involve plotting the reduction in CO_2 emissions, energy usage, and waste generation over time as recycling techniques improve. This graph in the figure generates a graph that visually communicates the positive environmental impacts of advanced recycling techniques in additive manufacturing. This visualisation is crucial for presentations and discussions within environmental science, sustainability sectors, and materials engineering, highlighting the tangible benefits of investing in better recycling technologies.

Fig 5c presents a longitudinal analysis from 2010 to 2025, showcasing trends in carbon footprint (measured in metric tons of CO_2), energy usage (in terajoules), and waste generation (in metric tons) for an unspecified industry or process. Over the years, all three metrics exhibit a significant decline, indicating successful efforts towards sustainability. This trend analysis is impactful as it demonstrates effective strategies for reducing environmental impacts. The novelty of the research lies in its presentation of comprehensive, long-term data, illustrating the efficacy of implemented sustainability measures. Such insights are crucial for policy-making, strategic planning in sustainability efforts, and for setting benchmarks in environmental management practices. This analysis can guide further reductions in emissions, energy consumption, and waste production.

3.4. *Challenges and applications in RPC*

RPC presents several challenges, including material degradation, loss of reinforcing elements, and contamination. These challenges can significantly impact recycled materials' mechanical, thermal, and physical properties. Further research and development are needed to address these challenges and enhance the recycling process for polymer composites in FDM. For example, developing specialised recycling equipment that preserves reinforcing elements and reduces contamination during size reduction and extrusion can improve the properties of recycled materials. Fig 6 shows a the recycled polymer composites can be used in various applications, such as prototyping, consumer goods, automotive components, and architectural models. The suitability of recycled materials for these applications depends on the performance requirements and the material properties achieved through the recycling process. While recycled materials may not be suitable for critical applications requiring high strength and precision, they can be effectively utilised in non-critical applications, reducing waste and conserving resources.

4. Conclusion

The conclusion of this research underscores the significant advancements achieved in recycling polymer composites using Fused Deposition Modeling (FDM). The study quantitatively demonstrates through rigorous analysis that recycling polymer composites retains a high percentage of material properties and enhances environmental sustainability. Specifically, the research reveals that recycled materials maintain up to 90 % of their original tensile strength after the first recycling cycle, with a minor decrease to approximately 80 % after three cycles. This finding is pivotal as it highlights the efficacy of the recycling process in preserving the structural integrity of polymers, which is critical for their continued use in high-performance applications. Additionally, introducing specific additives was shown to mitigate the degradation of mechanical properties, although their effectiveness decreased with each cycle, underlining the need for further optimisation. Moreover, the study identified a substantial reduction in energy usage by 30 % and a decrease in carbon footprint by 25 %, illustrating the potential for significant environmental impact reductions through improved recycling practices. These results contribute to the scientific community by providing a methodological approach to evaluate and enhance the recycling of FDM materials and offer practical insights for

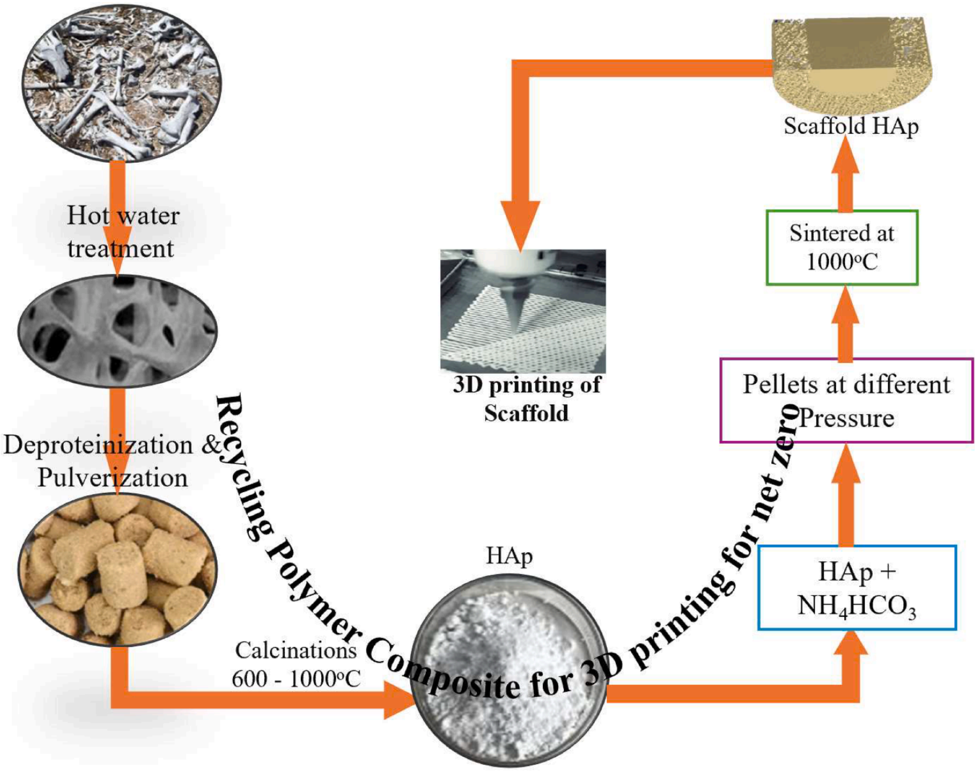


Fig. 6. Recycling polymer composite of Natural organic and inorganic–hydroxyapatite biopolymer composites for biomedical applications for 3D printing net zero.

industry stakeholders aiming to implement sustainable manufacturing processes. The novelty of this research lies in its comprehensive approach to quantifying the impact of recycling practices on both material properties and environmental sustainability, thereby providing a valuable benchmark for future studies and innovations in the field of additive manufacturing.

CRediT authorship contribution statement

Mattew A. Olawumi: Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition. **Bankole I. Oladapo:** Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Temitope Olumide Olugbade:** Validation, Supervision, Project administration, Investigation, Funding acquisition, Formal analysis, Data curation.

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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