Sustainability in 3D Printing: Embracing the Circular Economy Model for Challenges, Opportunities, and Strategies

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Abstract

This research examines how sustainability can be advanced in 3D printing by integrating circular economy principles with life cycle assessment (LCA). Although additive manufacturing is often presented as a cleaner alternative to conventional manufacturing because it reduces material waste, customization, lightweight design, and decentralized production, the study shows that its environmental profile remains mixed. Key challenges include high energy consumption in several printing processes, volatile organic compound emissions, dependence on petroleum-based materials, difficulties in recycling multi-material outputs, and limited regulatory support for sustainable practices. Through a structured literature review, the research analyses major 3D printing technologies, materials, industrial applications, supply-chain characteristics, and environmental assessment methods. Particular attention is given to the contrasting sustainability profiles of common materials such as ABS, PLA, PETG, metals, and photopolymers. The findings indicate that 3D printing can contribute to sustainability when supported by biodegradable or recyclable feedstocks, closed-loop material systems, and systematic environmental evaluation. Based on the review, the research proposes a conceptual framework that combines the 6R circular economy principles, reduce, reuse, recycle, recover, redesign, and remanufacture with LCA to improve material circularity and reduce lifecycle impacts. The framework is complemented by implementation strategies involving infrastructural investment, collaborative supply chains, innovation in materials and recycling technologies, workforce training, and policy incentives. Overall, the study concludes that 3D printing has significant potential to support sustainable manufacturing, but achieving this potential requires coordinated technological, managerial, and regulatory action across the broader production ecosystem. It also highlights future research on scalable experiments, sustainable materials, and AI-enabled process optimization strategies.

Keywords: 3D printing; sustainability; circular economy; life cycle assessment.

1 Introduction

Rapid industrialization in recent years, coupled with the ineffective utilization of capital resources and deforestation, has led to severe environmental issues and health hazards. The result of this is the need of sustainability. However, the challenges of implementing sustainability practices in the current era of digitalization are formidable [1]. In the world of manufacturing, 3D printing has emerged as a transformative technology that promises not only innovation in product development and production but also presents unique challenges and opportunities in terms of environmental sustainability [2]. And to achieve sustainable manufacturing, every activity in the supply chain must adhere to sustainability principles, from raw materials processing to the finished product [3].

3D printing also known as additive manufacturing (AM) provides many benefits, including reduced material waste, customization options, and decentralized production. However, the environmental impact of 3D printing is poorly understood, and there is a bigger need to investigate and improve the sustainability practices in 3D printing industry [4]. There are several environmental factors linked to the 3D printing industry. Some major problems as suggested by include the energy consumption during the operations of 3D printing machines which rises the trade-off between product quality and energy consumption, the emission of VOCs (Volatile Organic Compounds) [5], and the materials needed for 3D printing are inherently unsustainable because obtaining new plastic requires petroleum products for production as well as having high carbon intensity to actually produce the plastic itself [6].

This research aims to explore the concept of sustainability in 3D printing, analyze its current state, identify challenges, and propose strategies in achieving more sustainable outcomes and methodologies. By addressing these issues, this research targets to contribute to the development of environmentally responsible practices within the 3D printing industry.

According to a European Commission study, by 2050 3D printing (also referred to as '"additive manufacturing") could save up to 90% of the raw materials required for manufacturing. This is one of the greatest advantages of 3D printing because a decrease in raw material use means a proportionate decrease in extraction of natural resources, emissions generated from raw materials sourcing and processing (by as much as half!), and of course, waste. These stats come as welcome news for any enterprise weighing the economic and environmental pros of 3D printing [7].

Problem of the research

On a study conducted by Shuaib *et al.*, 2021, he presented that though 3D printing is viewed as more sustainable in terms of waste reduction than traditional manufacturing, it still presents some environmental downsides such as higher energy consumption during the production phase, VOCs emissions, freshwater usage, marine water contamination due to unmanaged disposal of waste etc. The emission of volatile organic compounds (VOCs) during 3D printing is a significant concern. The emissions caused by the heating of polymer materials can health risks to operators and contribute to air quality degradation. This research addresses the research gap in comparative environmental assessments between AM and traditional manufacturing techniques, which in some way affects the ability of stakeholder to make informed decisions about implementing 3D printing technologies in an environmentally sustainable manner.

Most of the materials currently used in 3D printing are derived from non-renewable sources, such as petroleum-based plastics and have significant environmental risks. It can be very challenging to bring these materials into circularity or to reuse and recycle. Therefore, there is a need to explore and develop more sustainable, bio-based, or recyclable materials specifically designed for 3D printing. Today, 3D printing does not commonly use "green" materials which cause few ecological impacts in their extraction or production. The possible exception is PLA bioplastic, which is commonly used, shows to lower printer energy use as well as having lower embodied impacts than ABS plastic as per the study on material choice conducted by Faludi *et al.*, 2015.

Additionally, the economics of implementing sustainable 3D printing practices can have high initial costs and specially difficult for current 3D printing industries' which are mostly Small and Medium Scale Enterprises (SMEs) [9]. This research will propose regulatory and policy recommendations to foster a supportive environment for sustainable 3D printing practices. Furthermore, this research will investigate sustainable alternatives to the commonly used unsustainable materials in 3D printing and address the urgent need for more environmentally friendly solutions in the industry.

2. Literature Review

In this research, a comprehensive literature review is performed to study the existing challenges within the 3D printing industry. The review covers an exploration of sustainability principles, life cycle assessment (LCA) methodologies, and circular economy concepts within the 3D printing world. By diving into previous scholarly works, this study intends to shed light on how these concepts might be used to reduce the environmental effect of 3D printing methods and materials. Studies examining the environmental impact of 3D printing compared to traditional manufacturing methods, with a focus on energy consumption, material usage, and waste generation. Case studies and best practices for sustainable 3D printing, emphasizing successful initiatives and novel approaches to reducing environmental footprints.

Introduction to 3D printing and processes involved.

3D printing or additive manufacturing is a process of making a three-dimensional solid object of virtually any shape from a digital model [10]. Unlike traditional subtractive methods like cutting or drilling, which remove material, additive manufacturing efficiently uses materials, creating objects by adding successive layers [11]. 3D printing technology allows users to build highly complex products from a large variety of materials (e.g. plastic, metal, ceramic, sandstone, resin, bio material and food substances) [12]. The process consists of printing successive layers of materials that are formed on top of each other. This technology has been developed by Charles Hull in 1986 in a process known as stereolithography (SLA), which was followed by subsequent developments such as powder bed fusion, fused deposition modelling (FDM), inkjet printing and contour crafting (CC) 3D printing constructs solid objects from digital files by depositing material layer by layer [13], [14].

Processes and Materials Involved

There are several types of 3D printing technologies depending on the processes they adopt for material deposition in order to create a desired 3D model. Some of them melt the material while others solidify powders or liquidize materials. The basic processes are Material Extrusion, Powder bed Fusion, Vat Photopolymerization and Sheet Lamination [15].

Material extrusion is an AM process which creates layers by mechanically extruding molten thermoplastic material on a build platform. In Powder bed Fusion process, an electron beam is used to melt the spread material on a powder bed, while in Vat Photopolymerization process an ultraviolet laser is used to polymerize the UV resins and create a layer of solid material. Finally in Sheet Lamination a controlled laser is used to cut the coated material on a building platform [15], [16].

There are several 3D printing technologies that are based on these processes. The most common method of 3D printing that mainly uses polymer filaments is known as fused deposition modelling (FDM). In addition, additive manufacturing of powders by selective laser sintering (SLS), selective laser melting (SLM) or liquid binding in three-dimensional printing (3DP), as well as inkjet printing, contour crafting, stereolithography, direct energy deposition (DED) and laminated object manufacturing (LOM) are the main methods of AM [13]. These methods are shortly described below along with the materials involved and the impacts of these methods.

Fused Deposition modelling (FDM)

Also known as Fused Filament Fabrication (FFF), this technology is considered the most popular and cheapest form of 3D production methods [17]. This method uses a continuous filament of a thermoplastic material such as ABS or PLA [16] and builds a part by heating and extruding this thermoplastic filament through a moving, heated extrusion print head one layer each time[15]. Commonly seen in both commercial and consumer use, FDM printers are relatively inexpensive, and may be fed using a wide range of thermoplastic and organic material blends, including ABS (acrylonitrile butadiene styrene), PLA (poly-lactic acid), and polycarbonate [18]. Some major field that use these technology include manufacturing industries to creating prototypes, automotive industries to critical custom parts and prototypes to reduce development time and cost, aerospace for non-load bearing components that benefit from the lightweight properties of FDM materials, healthcare for bespoke prosthetics, orthotics, and surgical planning models that need to be tailored to individual patients and educational institutions for enhancing learning through practical models and hands-on experience with technology.

Stereolithography (SLA)

SLA is traditionally the first 3D printing system in the world. Chuck Hull devised stereolithography in 1986, which filed a technology patent and founded 3D printers to commercialize the technology [17]. Also referred as optical fabrication, this technology uses an ultraviolet (UV) laser or similar power source to cure photo-reactive resins layer by layer [15]. An SLA system uses galvanometers, with one located in the X-axis and one in the Y-axis. Such galvos rapidly aim at a laser beam through a resin vat that selectively cures and solidifies the cross-section within this construction area and creates it layer by layer. SLA printing generally produces models with a high level of detail. SLA prints high-quality parts at a fine resolution as low as 10 μm. On the other hand, it is relatively slow, expensive and the range of materials for printing is very limited[13]. The strength of the product means that it can often be machined or used as a master for injection molding and metal casting. The drawback of this method tends to be expense, as resin often costs more than USD 100 per liter. Industrial SLA printers can cost hundreds of thousands of dollars [18].

Selective Laser Sintering (SLS), Selective Laser Melting (SLM), Selective Heat Sintering (SHS)

Selective Laser Sintering (SLS) uses a high-power laser to sinter small parts of powdered material aiming at specific points across a powder bed. In **Selective Laser Melting (SLM)** the powdered material is spread over the fabrication bed and melted or sintered by a high powdered optic laser. In this process the metal material can be fully melted [19]. In **Selective Heat Sintering (SHS)** the material is fed from the powder deposition tanks, heated to just below its melting point , spread out into a thin layer over the movable building platform and flattened using a roller [20]. These are the are industrial processes capable of producing highly accurate models with excellent mechanical properties [18].

Electron Beam Melting (EBM)

Electron Beam Melting (EBM) is an additive manufacturing process that uses a focused electron beam to melt metal powder, building parts layer by layer in a vacuum. This technology is particularly used with materials such as titanium alloys, nickel-based superalloys, cobalt-based superalloys, and stainless steels due to their high performance in demanding environments [21]. The process is mainly based on a melting process which uses a metal powder and an electron beam. The material is spread on the building platform and heated by an electron beam [15].

Other Processes

There exist some other less common AM processes, such as Digital light processing (DLP), Continuous Liquid Interface Production (CLIP) and so on. Digital Light Processing (DLP) uses a digital projector screen to flash a single image of each layer across the entire platform at once [22]. In Continuous Liquid Interface Production (CLIP) technology a beam of ultraviolet light is projected through an oxygen-permeable window into the vat of liquid resin, illuminating the precise cross-section of the object [23]. Table 1 illustrates the 3D printing technology processes and Table 2 discusses their advantage and disadvantages.

Table 1 : 3D printing process, technologies and materials used.

Processes	Technologies	Materials Used
Material Extrusion	FDM	Thermoplastic polymers, Ceramic slurries, Metal pastes, Eutectic metals
Powder Based Fusion	3DP, EBM, SLM, SHS, SLS	Polyamides, Polymer, Ceramic, Metal, Glass powders, Thermoplastics, Nylon
Vat Photopolymerization	SLA, DLP, CLIP	Photopolymers, Ceramics, Semi-flexible materials, ABS
Sheet Lamination	LOM	Polymer composites, Ceramics, Paper, and metal-filled tapes

Table 2 : Advantages and disadvantages of different 3D printing technologies

Technologies	Advantages	Disadvantages
Fused Deposition Modelling (FDM)	- Various colors, high speed Simplicity - low waste production as material is added layer by layer - Use of thermoplastic polymers which can be recycled - Low energy consumption as compared to intensive industrial methods.	- requires support for complex structures, weak mechanical properties, Poor surface finish - The lower precision can result in increased material usage for refinishing
Stereolithography (SLA)	- Less time consuming, customized coloring, high quality, fine resolution - Efficient use of material with minimum spillage	- Limited materials, Possible brittle components, Expensive support structures for parts with overhangs -Uses photopolymers that are often non-recyclable and can release VOCs. -Energy intensive due to use of laser and UV light
Selective laser Sintering (SLS)	- Large part size, variety of materials, Fast procedure, High strength and stiffness - Powder can be reused, reducing raw material consumption. - No need of support structure	- Post processing required -Expensive process - High power consumption due to laser usage - Difficult to recycle due to mixed properties
Digital light processing	-High accuracy, Fine resolution, Material variety, Fast process - This process is faster than SLA, so the process is more energy efficient -High accuracy and required very less or no processing	- Costly process, post processing required - Like SLA, the process uses resins which may not be recyclable
Laminated Object Manufacturing (LOM)	- Reduced manufacturing time	-Inferior surface quality, post processing

	- Variety of materials, larger structures, reduced tooling cost	required, Limitations for very complex shapes. -Generates considerable waste due to the cutting process, with much of the excess material not being reusable

Overview of the 3D printing industry

3D printing is an approach for fabricating objects through depositing material in specific, ordered layers from a CAD model and is widely recognized as a potent method in the modern manufacturing sector [24], [25]. Compared to traditional subtractive manufacturing processes, 3D printing has demonstrated the potential to reduce waste, energy demand, and carbon emissions. In addition, 3D printing has the ability to create lightweight materials using less material by printing hollow structures with decreased infill. This technology is becoming progressively valuable for various applications, including aircraft, automotive, food, medical, and robotics industries [26]. This section explores the industry's evolution, its current structure, and the important role of enterprises within the supply chain. Understanding these dynamics is crucial for assessing the sustainability and circular economy potential of 3D printing technologies.

3D printing Ecosystem and Supply chain

Rogers, Baricz and Pawar, 2016 predict that, with the evolution of 3D printing technology, a variety of 3d printing services are emerging, and if this trend continues, they are expected to be the major drivers of market growth over the next decade. However, widespread adoption of 3D printing is hindered by a number of decisive factors including high printer acquisition costs, lack of experience with the technology and the technical limitations of 3D printers [27].

3D printing has seen widespread adoption in sectors that predominantly produce small batches of products and/or require customization, such as medicine, aerospace, and custom-made consumer goods. Even though 3D printing could potentially make supply chains leaner, more agile, more responsive, more cost effective, more sustainable and overall, less wasteful, manufacturers are not yet convinced that it can fully replace traditional manufacturing processes, particularly at high production. For industry sectors where customization is seldom required and/or cost is a key performance measure, traditional manufacturing technologies is expected to dominate.

While the 3D printing was initially used as a prototyping tool, it has now been for wider applications including production of tools, production of goods etc [28]. And with rapid progress, 3D printing may provide new opportunities for startups and individual entrepreneurs, disrupting incumbents which are not sufficiently nimble or lacking skills in core areas necessary to compete. 3D printers have become inexpensive (the price of cheapest 3d printer can range from $150-$200) enough to be used by individuals and smaller businesses.

The barriers in the past of accessing mass-manufacturing facilities because of a lack of sufficient funds, may disappear [28]. Despite these advantages, the global adoption of 3D printing technology has been limited by the cost, availability and quality of raw materials, as well as the accuracy and strength of 3D-printed products and the process is still limited to small scale production.

Kapetaniou *et al.*, 2018 have classified the 3d printing firms into four categories [28]:

i. **Supplier-dominated firms**: These are the firms that rely heavily on their suppliers for new technologies and materials such as 3D printers and materials to produce products.
ii. **Scale-intensive firms**: These are the firms that produce on a large scale. These types of firms mostly use 3D printing to produce prototypes. An example of these firms can be BMV, where they use this technology to make prototypes of various parts or products.
iii. **Science-based firms**: Science-based firms in sectors such as aerospace, pharmaceuticals, and electronics use 3D printing for its ability to produce highly complex and lightweight structures, as well as for rapid prototyping of new technology.
iv. **Specialized suppliers**: In the 3D printing ecosystem, specialized suppliers are crucial as they provide innovative 3D printing materials, sophisticated software, and specialized printing technologies that enable other firms to enhance their manufacturing processes.

In the 3D printing service supply chain, the customers first select the type of 3d printing service they require followed by the transfer of the 3D model to the printing facilities. The transfer is then managed by the 3D printing service provider, who coordinates between the source of the model, such as local scanning facilities, and the production facilities where the model will be printed [29], [30]. Production can occur internally within enterprise 3D printing providers or externally through third-party subcontractors commonly used by consumer-focused providers. The final stage involves distribution, where the manufacturing facility handles packaging and outsources transportation to third-party services like DHL or TNT. Products are then delivered directly to customers or made available for pickup at retail locations.

This supply chain loop demonstrates the integration of 3D printing services within broader manufacturing supply chains, enabling the creation of customized products ranging from accessories and clothing to prosthetics [31]. Customers can initiate orders through various entry points in the supply chain, such as requesting scans at retail locations or directly interacting with manufacturers to customize products like car cup holders, showcasing the versatility and customer-centric nature of 3D printing services.

Life cycle Assessment (LCA) in 3D printing

Life cycle assessment (LCA) is an instrumental methodology for assessing the environmental implications of products, services, or processes across their entire lifecycle, encompassing stages from raw material acquisition to production as well as waste management [32]. In the context of growing environmental awareness and increasing request for sustainable solutions in the manufacturing industry, the assessment of environmental impacts throughout the entire life cycle of materials and related production processes plays a central role [33]. This includes extracting and processing raw materials, manufacturing, distribution, use, repair and maintenance, and final disposal or recycling. By evaluating the environmental impacts through the entire life cycle, LCA helps identify ways to improve products, so they have a lesser effect on the environment [34].

Several studies have explored the energy consumption and material efficiency of 3D printing processes compared to conventional manufacturing. For instance, research by [33] found that 3D printing can reduce material waste significantly due to its additive nature, but the energy consumption per unit of material processed can be higher than in traditional manufacturing due to high energy requirements for melting and sintering materials.

LCA Methodology and Scope

The LCA conducted in the study by [33] compares traditional composite manufacturing methods like autoclave and bag molding with an innovative 3D printing process using Thermal Laser Curing (TLC). The assessment follows the standard UNI EN ISO 14040-14044, covering:

- **Goal and Scope Definition**: Identifying the environmental assessment's boundaries and goals, focusing on the production and disposal of tensile specimens made from carbon fiber and epoxy resin.
- **Inventory Analysis (LCI)**: Collecting data on all inputs and outputs within the system's boundaries, including energy use, material consumption, and emissions.
- **Impact Assessment (LCIA)**: Quantifying the environmental impacts using indicators such as Global Warming Potential (GWP) and ReCiPe endpoints, which measure impacts on human health, ecosystems, and resource availability.

The study reveals significant environmental benefits of 3D printing over traditional methods:

Material Efficiency: 3D printing dramatically reduces waste by precisely using materials only where needed, unlike traditional methods that involve significant scrap from cutting and machining.

Energy Consumption: The innovative TLC technology used in 3D printing minimizes energy consumption by eliminating the need for high-temperature autoclaves and extensive mold use, which are energy-intensive in traditional composite manufacturing.

Findings and Environmental Impacts

Reduction in GWP: The LCA results show that 3D printing with TLC technology reduces CO2 emissions by 45.8% during the production phase compared to traditional methods. The end-of-life impacts are also reduced by 67.8%, primarily due to decreased waste and lower reliance on landfill disposal.

Resource Utilization: The study highlights improved resource efficiency in 3D printing, reducing the demand for new materials and lowering the environmental burden associated with material extraction and processing.

Thus**,** this study strongly suggested that the comprehensive LCA provides valuable insights for industries in making informed decisions about adopting eco-friendly manufacturing processes, particularly in high-tech sectors relying on long-fiber composites.

In addition to this, the other LCA study conducted by [35] found that 3D printing shows a 45.8% reduction in CO2 emissions during production and a 67.8% decrease at the end-of-life phase compared to traditional methods..

Circular Economy Concepts

A circular economy is an economic system that aims to achieve sustainability goals through more efficient and circular use of materials [36]. This system aims at drastically reducing waste through the continual repurposing of resources for sustainability. Circular systems employ recycling, reuse, remanufacturing and refurbishment to create a closed system, minimizing the use of virgin materials and the creation of waste along the producer-to-consumer continuum [37].

The concept of a circular economy represents a shift from traditional, linear economic models, where products are manufactured, used, and then disposed of, to a more sustainable model that designs out waste and minimizes environmental impact. The conceptual message of circular economy is very powerful as it is based on reducing wasteful resources through effective design and implementation of products and processes for improved resource-efficiency with circular material flow involving *recovery, reuse, recycling* and remanufacturing of products [35].

Circularity in 3D printing

The integration of 3D printing into contemporary manufacturing practices aligns with the core tenets of the circular economy. It brings forth a multitude of benefits, such as diminishing the consumption of raw materials and curbing the release of pollutants, thereby mitigating waste generation. This contributes to the objective of creating a more sustainable framework for manufacturing, recycling, and optimizing the use and reuse of resources [38].

The 3D printing industry mostly relies on variety of polymers and metals which present challenges in terms of recyclability and sustainability. Typical materials like ABS and PLA, while popular, differ greatly in their environmental impacts—ABS is oil-based and difficult to recycle, whereas PLA is plant-based and biodegradable but requires industrial composting to degrade effectively.

Circularity of Plastic materials and wastes

In recent times, polylactic acid (PLA) has emerged as a preeminent raw material employed in FDM-based 3D printing process, owing to its biodegradability and eco-friendly attributes [26]**. Plastics** are considered a significant material for 3D printing and must comply with the 6R principle to have sufficient value and utilization. The circular development of 3D printing materials can be implemented mainly from the following aspects. Both chemical and physical recycling of 3D printed waste plastics were developed so that the waste of 3D printed plastics can be degraded into useful molecules, reused, or rendered harmless [39]. The most common types of plastics used in 3d printing are:

- **PLA (Polylactic Acid)**: A biodegradable thermoplastic made from renewable resources like corn starch or sugarcane.
- **ABS (Acrylonitrile Butadiene Styrene)**: A petroleum-based non-biodegradable plastic known for its strength and durability.
- **PETG (Polyethylene Terephthalate Glycol)**: A variant of PET, commonly used for bottles, which is recyclable and offers a good balance between flexibility and strength.

The 3D printing methodology can not only be used to recycle the waste from the 3D printing process but also can be used to recycle the plastic wastes from other sources. This approach highlights the closed-loop cycle for plastic products and various recycling pathways. The processes involved are discussed below:

Collection and Sorting: Collect and sort plastic waste from various sources, including household waste, industrial by-products, and discarded 3D printed objects.

Mechanical Recycling: Grind and melt sorted plastics to reprocess them into filaments for 3D printing, converting waste into usable raw materials.

Chemical Recycling: For plastics unsuitable for mechanical recycling, break them down into monomers or basic chemicals to create new polymers or materials.

Additive Manufacturing (3D Printing): Use recycled polymers and materials as feedstock for 3D printing to create new, functional parts, reducing reliance on virgin materials.

Usage and Maintenance: Use the 3D printed parts in various applications, maintaining, repairing, or upgrading them to extend their life.

End-of-Life Management: Collect end-of-life 3D printed parts for recycling, feeding them back into the mechanical or chemical recycling processes.

Mechanical recycling converts plastic products into polymers, aligning with 3D printing by using recycled filaments. Chemical recycling breaks down plastics into new materials, complementing 3D printing by providing alternative recycling pathways. Upcycling enhances the value and functionality of recycled materials, similar to 3D printing which creates high-value, customized parts. The closed-loop cycle promotes continuous recycling and reuse of materials, supported by integrating 3D printing with both mechanical and chemical recycling methods [40].

Circularity of Metal wastes and other materials

Besides plastics raw materials and wastes, metals like titanium, stainless steel, and aluminium are also widely used in 3D printing for industries such as aerospace, automotive, and healthcare because of their properties like high strength and corrosion resistance.

Along with plastic polymers, the 6R methodologies can also be used to bring the metal wastes and other wastes like ceramics into circular economy. In the 6R methodology, *reduce* mainly focuses on the first three stages of the product life cycle, and refers to the reduced use of resources in pre-manufacturing, reduced use of energy, materials and other resources during manufacturing, and the reduction of emissions and waste during the use stage. *Reuse* refers to the reuse of the product as a whole, or its components, after its first life cycle, for subsequent life cycles, to reduce the usage of virgin materials to produce newer products and components. *Recycle* involves the process of converting material that would otherwise be considered waste, into new materials or products. The process of collecting products at the end of the use stage, disassembling, sorting and cleaning for utilization in subsequent life cycles of the product is referred to as *Recover*. The *Redesign* activity involves the act of redesigning of next generation products, which would use components, materials and resources recovered from the previous life cycle, or previous generation of products, while *Remanufacture* involves the re-processing of already used products for restoration to their original state or a like-new form through the reuse of as many parts as possible without loss of functionality [35]. This method of 6R can be used to achieve circularity of all types of materials and wastes from 3D printing.

3. Key findings

In the literature review section, we have successfully studied the concept of 3D printing, processes involved, and material used in 3D printing, the LCA methodologies, the overview of industries involved in 3D printing, the circular economy principles, and the possibility of implementing circular economy principles in 3D printing materials and wastes. Now, we will summarize the trends, challenges, and opportunities that we have found based on the reviews specific to each of the topics above and propose are framework in achieving sustainability in 3D printing raw materials and wastes by implementing circular economy principles and LCA methodologies.

Trends and challenges in 3D printing, materials, and their implications

The 3D printing industry is not just an additive manufacturing process but also a technology that offers possibility of reducing materials wastes in manufacturing as well as recycling of some types of the existing industrial wastes such as plastics and other polymers. Despite the advantages, the 3D printing environment isn't completely green because several 3D printing processes release VOCs and consume significant amount of energy during manufacturing.

Similarly, the trend of materials in 3D printing are not the best in terms of environment. The major raw materials used in 3D printing are polymers (plastics), metals, ceramics etc that have high environmental impacts. However, the recent trend of materials has highlighted the increasing use of biodegradable materials like PLA that have lower environmental impacts as compared to traditional plastics materials like ABS.

Circular economy and industries/firms in 3d printing

Despite the recent developments in 3D printing technology, the capability of this technology to handle large scale production is still developing. Though the recent trend is gradually shifting towards more sustainable and biodegradable materials such as PLA, the current 3D printing process heavily relies on plastics which are not easy to recycle or sustainable. So, implications of circular economy principles to achieve sustainability is not easy in 3D printing. Moreover, the firms involved in this technology are mostly SMEs. These types of firms face challenges such as high initial cost including setup cost and operation cost. When the firms are already facing financial problems, it is very difficult to bear cost related to achieving circularity. Additionally, there aren't of specific regulations that encourage the recycling and reuse of 3D printing materials. This makes sustainable practices difficult to implement and standardize across the 3D printing industry.

Framework for realization of Sustainability in 3D printing raw materials using Circular Economy principles and LCA methodologies.

Based on the literature reviews and references of studies conducted by Jawahir and Bradley, 2016 [35], I have come up with a proposal that can be implemented to achieve sustainability in 3D printing. This method combines the circular economy principles with the LCA methodologies to achieve the sustainability.

The method includes the use of the 6R principles of circular economy—Reduce, Reuse, Recycle, Recover, Redesign, and Remanufacture—into the 3D printing process.:

i. Reduce: This includes minimizing the use of materials and energy in the 3D printing processes.
ii. Reuse: After minimizing the use of materials, me move on to reusing. This strategy allows 3D printed objects or components to be reused in new applications.
iii. Recycle: Then there is a need to develop a system to recycle waste materials from 3D printing.

iv. Recover: This step involves the extraction of valuable materials and components from end-of-life 3D printed products.

v. Redesign: The designing of 3D printed products should be done in such way that considers the future life cycles and focuses on making them easier to disassemble and recycle.

vi. Remanufacture: The used materials can be checked for possibility of refurbishment. This can make the like-new condition of the 3D printed.

Integration of Life Cycle Assessment (LCA)

Life Cycle Assessment methodologies are used to identify the environmental impacts of products at each stage of their lifecycle: from material extraction through manufacturing, use, and disposal. This section helps to find where improvements can be made to ensure the effectiveness of the 6R strategies mentioned above:

LCA can be used to analyze the environmental impacts associated with raw materials, energy use, emissions, and waste generation. This will give the quantitative information about various steps involved in the 6R strategies. Using the analysis from LCA, the product design and processes in 3D manufacturing can be established in a sustainable manner.

Circular Economy Framework Implementation

The implementation of the proposed framework starts with the shift from linear to circular economy system where waste is minimized, and the life cycle of the product is considered during the designing phase. The first step to implementing is the designing of **material loop** that focuses on feeding the materials from used products back into the cycle of production.

The business models in 3D printing can also be established as **PaaS (Product as a service)** where products are leased rather than sold. This will promote waste reduction by encouraging manufacturers to design the products focusing on durability and recyclability.

From the social and legal perspective, it is very essential to raise the context of technological advancements that support sustainable manufacturing practices. This can include educating consumers, and other stakeholders of society.

Implementation Strategy

To effectively implement this proposed methodology, collaboration across various sectors including industry stakeholders, policymakers, and educational institutions is essential. Some sectors and factors that play crucial role are discussed below.

Infrastructural investments: Despite the abundance of SMEs with low financial flexibility in the 3D printing ecosystem, the SME firms can collaborate to develop new technologies and invest in establishing facilities that specialize in recycling of 3D printed products and materials. This will not only promote circularity but also contribute to sustainability by reducing waste because of single part damages (there are several cases where people throw a whole product because of minor or damage because of not having available resources and services to refurbish them).

Innovation and Research: There is a greater need to promote continuous innovation in materials science and 3D printing technologies to support the 6R strategies. The government and large-scale organizations can be supporting funding to research on methods to recycle the materials involved in 3D printing, finding alternatives to the non-recyclable materials and unsustainable process. Additionally, the companies can also adopt emerging technologies such as use of AI and machine learning to optimize the process and material usage in production.

Regulations and Policy Incentives: The companies involved in 3D printing can collaborate with government and other organization to create standards in 3D printing practices. The policy makers should develop policies that promote sustainability in manufacturing. For example, the companies can be rewarded for using recycled materials or penalized for not complying with environmental regulations.

Education and Training: The companies also need to focus on improving the skills and knowledge of the workforce. This can be done through targeted educational programs that focus on sustainability and circular economy practices, trainings, and workshop on the sustainable methods.

Supply chain and Production: As discussed above, the 3D printing firms can develop partnership with other firms and suppliers of recycled materials. This will help the companies share research and innovation and at the same time creates a positive supply chain that supports circularity. Moreover, this will provide a **shared logistic platform** for the companies. This will mean the reduced need of multiple warehouses, efficient use of transportation, cost saving, and feasibility for reverse logistics.

4. Discussion

This proposed method is based on circular economy principles and LCA methodologies. The method presents an approach to integrating sustainability into the 3D printing industry by using the circular economy principles and LCA methodologies. By taking the designing, manufacturing, and disposal of products and processes, the 3D printing firms can reduce their environmental impact while promoting economic and social benefits. This framework not only addresses the immediate environmental concerns associated with 3D printing but also sets a foundation for sustainable growth and innovation in the industry.

Future Directions

The future of 3D printing holds great possibility. In order to achieve the goals of 3D printing, the future research should focus on developing sustainable materials that can replace current 3D printing materials with lower environmental impacts. The investments should also be diverted to recycling technologies specific to 3D printing materials to attain circularity in the materials and products. Moreover, taking benefits of AI and machine learning tools to optimize printing processes and material use, reducing waste, and improving the sustainability is crucially important.

Finally, as suggested by the framework in section 3: the implementations of rules, regulations, and the system of giving incentives for sustainability in 3D printing, including subsidies for sustainable practices and penalties for unsustainable waste management can encourage and force industries to follow sustainable practices.

5. Conclusion

As this research has shown, there are still a lot of obstacles to overcome before 3D printing can truly improve sustainability by reducing material waste and enabling the use of recovered resources. These include the absence of complete legislative frameworks that fully support the concepts of the circular economy, high prices, and limits in technology.

When combined with strong circular economy principles, 3D printing is a powerful instrument for achieving manufacturing sustainability. But to fully realize this potential, industry-wide acceptance of best practices, regulatory backing, and coordinated efforts in technical innovation are needed. The road ahead for the 3D printing sector to become truly sustainable is long but bright, with great potential to improve economic viability, environmental sustainability, and societal advantages.

References

[1] K. Sankar M.S, S. Gupta, S. Luthra, A. Kumar, S. Jagtap, and A. Samadhiya, “Empowering sustainable manufacturing: Unleashing digital innovation in spool fabrication industries,” *Heliyon*, vol. 10, no. 9, p. e29994, May 2024, doi: 10.1016/j.heliyon.2024.e29994.

[2] M. R. Rezaei, Houshmand ,Mahmoud, and O. and Fatahi Valilai, “An autonomous intelligent framework for optimal orientation detection in 3D printing,” *Int. J. Comput. Integr. Manuf.*, vol. 36, no. 6, pp. 908–946, Jun. 2023, doi: 10.1080/0951192X.2022.2162587.

[3] A. J. de Ron, “Sustainable production: The ultimate result of a continuous improvement,” *Int. J. Prod. Econ.*, vol. 56–57, pp. 99–110, Sep. 1998, doi: 10.1016/S0925-5273(98)00005-X.

[4] M. Shuaib, A. Haleem, S. Kumar, and M. Javaid, “Impact of 3D Printing on the environment: A literature-based study,” *Sustain. Oper. Comput.*, vol. 2, pp. 57–63, Jan. 2021, doi: 10.1016/j.susoc.2021.04.001.

[5] M. C. DOAN, “VOCs emissions in 3D Printing: All You Need to Know,” Alveo3D. Accessed: May 27, 2024. [Online]. Available: https://www.alveo3d.com/en/vocs-emissions-3d-printing-all-need-to-know/

[6] N. Giani, L. Mazzocchetti, T. Benelli, F. Picchioni, and L. Giorgini, “Towards sustainability in 3D printing of thermoplastic composites: Evaluation of recycled carbon fibers as reinforcing agent for FDM filament production and 3D printing,” *Compos. Part Appl. Sci. Manuf.*, vol. 159, p. 107002, Aug. 2022, doi: 10.1016/j.compositesa.2022.107002.

[7] “The Impact of 3D Printing Sustainability.” Accessed: May 27, 2024. [Online]. Available: https://sustainly.com/3d-printing-sustainability/

[8] J. Faludi, Z. Hu, S. Alrashed, C. Braunholz, S. Kaul, and L. Kassaye, “Does Material Choice Drive Sustainability of 3D Printing?,” *Int. J. Mech. Aerosp. Ind. Mechatron. Eng.*, Feb. 2015, [Online]. Available: https://digitalcommons.dartmouth.edu/facoa/2111

[9] A. Dhir, S. Talwar, N. Islam, R. Alghafes, and S. Badghish, “Different strokes for different folks: Comparative analysis of 3D printing in large, medium and small firms,” *Technovation*, vol. 125, p. 102792, Jul. 2023, doi: 10.1016/j.technovation.2023.102792.

[10] T. P. Mpofu, C. Mawere, and M. Mukosera, “The Impact and Application of 3D Printing Technology,” vol. 3, no. 6, 2012.

[11] A. Pandian and C. Belavek, “A review of recent trends and challenges in 3D printing,” 2016.

[12] H. Rogers, N. Baricz, and K. S. Pawar, “3D printing services: classification, supply chain implications and research agenda,” *Int. J. Phys. Distrib. Logist. Manag.*, vol. 46, no. 10, pp. 886–907, Jan. 2016, doi: 10.1108/IJPDLM-07-2016-0210.

[13] T. D. Ngo, A. Kashani, G. Imbalzano, K. T. Q. Nguyen, and D. Hui, “Additive manufacturing (3D printing): A review of materials, methods, applications and challenges,” *Compos. Part B Eng.*, vol. 143, pp. 172–196, Jun. 2018, doi: 10.1016/j.compositesb.2018.02.012.

[14] M. reza Rezaei, M. Houshmand, and O. F. Valilai, “An autonomous framework for interpretation of 3D objects geometric data using 2D images for application in additive manufacturing,” *PeerJ Comput. Sci.*, vol. 7, p. e629, Aug. 2021, doi: 10.7717/peerj-cs.629.
[15] M. Ntousia and I. Fudos, “3D Printing Technologies & Applications: An Overview,” in *Proceedings of CAD’19*, CAD Solutions LLC, Jun. 2019, pp. 243–248. doi: 10.14733/cadconfP.2019.243-248.
[16] W. Gao *et al.*, “The status, challenges, and future of additive manufacturing in engineering,” *Comput.-Aided Des.*, vol. 69, pp. 65–89, Dec. 2015, doi: 10.1016/j.cad.2015.04.001.
[17] M. Manoj Prabhakar, A. K. Saravanan, A. Haiter Lenin, I. Jerin leno, K. Mayandi, and P. Sethu Ramalingam, “A short review on 3D printing methods, process parameters and materials,” *Mater. Today Proc.*, vol. 45, pp. 6108–6114, Jan. 2021, doi: 10.1016/j.matpr.2020.10.225.
[18] N. R. Jenzen-Jones, “Small arms and additive manufacturing: An assessment of 3D-printed firearms, components, and accessories,” Small Arms Survey, 2015. Accessed: May 13, 2024. [Online]. Available: https://www.jstor.org/stable/resrep10742.10
[19] H. N. Chia and B. M. Wu, “Recent advances in 3D printing of biomaterials,” *J. Biol. Eng.*, vol. 9, no. 1, p. 4, Mar. 2015, doi: 10.1186/s13036-015-0001-4.
[20] W. J. Sames, F. A. List, S. Pannala, R. R. Dehoff, and S. S. Babu, “The metallurgy and processing science of metal additive manufacturing,” *Int. Mater. Rev.*, vol. 61, no. 5, pp. 315–360, Jul. 2016, doi: 10.1080/09506608.2015.1116649.
[21] L. E. Murr *et al.*, “Metal Fabrication by Additive Manufacturing Using Laser and Electron Beam Melting Technologies,” *J. Mater. Sci. Technol.*, vol. 28, no. 1, pp. 1–14, Jan. 2012, doi: 10.1016/S1005-0302(12)60016-4.
[22] Zongheng3d, “3D Printing Process - What is DLP? (Digital Light Processing) | THRE3D.” Accessed: May 13, 2024. [Online]. Available: https://www.zongheng3d.com/dlp-3d-printing-comprehensive-guide/
[23] J. R. Tumbleston *et al.*, “Continuous liquid interface production of 3D objects,” *Science*, vol. 347, no. 6228, pp. 1349–1352, Mar. 2015, doi: 10.1126/science.aaa2397.
[24] N. T. Tuli, S. Khatun, and A. B. Rashid, “Unlocking the future of precision manufacturing: A comprehensive exploration of 3D printing with fiber-reinforced composites in aerospace, automotive, medical, and consumer industries,” *Heliyon*, vol. 10, no. 5, p. e27328, Mar. 2024, doi: 10.1016/j.heliyon.2024.e27328.
[25] E. Shahab, A. Kazemisaboor, S. Khaleghparast, and O. Fatahi Valilai, “A production bounce-back approach in the Cloud manufacturing network: case study of COVID-19 pandemic,” *Int. J. Manag. Sci. Eng. Manag.*, vol. 18, no. 4, pp. 305–317, Aug. 2022, doi: 10.1080/17509653.2022.2112781.
[26] M. R. Hasan, I. J. Davies, A. Pramanik, M. John, and W. K. Biswas, “Potential of recycled PLA in 3D printing: A review,” *Sustain. Manuf. Serv. Econ.*, vol. 3, p. 100020, Jan. 2024, doi: 10.1016/j.smse.2024.100020.
[27] H. Rogers, N. Baricz, and K. S. Pawar, “3D printing services: classification, supply chain implications and research agenda,” *Int. J. Phys. Distrib. Logist. Manag.*, vol. 46, no. 10, pp. 886–907, Jan. 2016, doi: 10.1108/IJPDLM-07-2016-0210.
[28] C. Kapetaniou, A. Rieple, A. Pilkington, T. Frandsen, and P. Pisano, “Building the layers of a new manufacturing taxonomy: How 3D printing is creating a new landscape of production eco-systems and competitive dynamics,” *Technol. Forecast. Soc. Change*, vol. 128, pp. 22–35, Mar. 2018, doi: 10.1016/j.techfore.2017.10.011.

[29] O. Fatahi Valilai and M. Houshmand, “Depicting additive manufacturing from a global perspective; using Cloud manufacturing paradigm for integration and collaboration,” *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.*, vol. 229, no. 12, pp. 2216–2237, Dec. 2015, doi: 10.1177/0954405414546706.

[30] O. Fatahi Valilai and M. Houshmand, “A Manufacturing Ontology Model to Enable Data Integration Services in Cloud Manufacturing using Axiomatic Design Theory,” in *Cloud-Based Design and Manufacturing (CBDM): A Service-Oriented Product Development Paradigm for the 21st Century*, D. Schaefer, Ed., Cham: Springer International Publishing, 2014, pp. 179–206. doi: 10.1007/978-3-319-07398-9_7.

[31] S. Valizadeh, O. Fatahi Valilai, and M. Houshmand, “Allocation and scheduling of digital dentistry services in a dental cloud manufacturing system,” *Int. J. Comput. Integr. Manuf.*, vol. 35, no. 6, pp. 645–661, 2022, doi: 10.1080/0951192X.2021.1992668.

[32] M. Cherni, A. Sebei, B. Amor, N. Hssine, and N. Hajjaji, “Critical reviews and benchmarking Tunisian clinker and cement with life cycle assessment results,” *Case Stud. Constr. Mater.*, vol. 20, p. e03174, Jul. 2024, doi: 10.1016/j.cscm.2024.e03174.

[33] M. Andreozzi, A. Forcellese, S. Gentili, T. Mancia, and T. Verdini, “Comparative Life Cycle Assessment of molding process and 3D printing of High-Performance Long-fiber Reinforced Composites,” *Procedia CIRP*, vol. 122, pp. 909–914, Jan. 2024, doi: 10.1016/j.procir.2024.01.124.

[34] N. Mohammadian, O. Fatahi Valilai, and A. Schlüter, “Sustainable design and repair: Leveraging circular economy and machine learning for product development,” *J. Open Innov. Technol. Mark. Complex.*, vol. 11, no. 1, p. 100469, Mar. 2025, doi: 10.1016/j.joitmc.2025.100469.

[35] I. S. Jawahir and R. Bradley, “Technological Elements of Circular Economy and the Principles of 6R-Based Closed-loop Material Flow in Sustainable Manufacturing,” *Procedia CIRP*, vol. 40, pp. 103–108, Jan. 2016, doi: 10.1016/j.procir.2016.01.067.

[36] S. van Ewijk and J. Stegemann, “The Circular Economy,” in *An Introduction to Waste Management and Circular Economy*, UCL Press, 2023, pp. 306–348. doi: 10.2307/jj.4350575.17.

[37] S. E. Institute, “Transformational change through a circular economy,” Stockholm Environment Institute, 2019. Accessed: May 26, 2024. [Online]. Available: https://www.jstor.org/stable/resrep22978

[38] P. Ghabezi, O. Sam-Daliri, T. Flanagan, M. Walls, and N. M. Harrison, “Circular economy innovation: A deep investigation on 3D printing of industrial waste polypropylene and carbon fibre composites,” *Resour. Conserv. Recycl.*, vol. 206, p. 107667, Jul. 2024, doi: 10.1016/j.resconrec.2024.107667.

[39] C. Zhu *et al.*, “Realization of Circular Economy of 3D Printed Plastics: A Review,” *Polymers*, vol. 13, no. 5, Art. no. 5, Jan. 2021, doi: 10.3390/polym13050744.

[40] A. Al Rashid and M. Koç, “Additive manufacturing for sustainability and circular economy: needs, challenges, and opportunities for 3D printing of recycled polymeric waste,” *Mater. Today Sustain.*, vol. 24, p. 100529, Dec. 2023, doi: 10.1016/j.mtsust.2023.100529.