Innovating Green: Effect of Additive Manufacturing on Environmental Sustainability

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Abstract. Additive manufacturing (AM) produces intricate products with minimal material wastage while offering environmental benefits such as use of smart materials and reduced raw material usage. Focus on sustainability in AM is growing, encouraging companies to develop strategies to minimize waste and enhance production efficiency, ultimately increasing the value of their products and services.

Keywords: Additive manufacturing, Sustainable practices, computer-aided design (CAD) model, Waste reduction, Manufacturing Eco system.

1 Introduction

Today's modern society requires a significant amount of energy, with the construction industry producing large amounts of waste and emissions. Additive manufacturing (AM) technologies, such as 3D printing and 3D scanning, offer a sustainable alternative to traditional construction methods to fight climate change and lower greenhouse gas emissions. By utilizing AM, industries can efficiently produce a wide range of products while adhering to the principles of reducing, reusing, and recycling. Additionally, AM played a crucial role during the COVID-19 pandemic by supplying hospitals with essential medical supplies. The use of generative design in AM allows for the production of single, consolidated parts using less material, simplifying the supply chain, saving time and resources, and promoting sustainability.

1.1 Research Objectives

Manufacturers are improving AM operations by integrating feedback control and in-process monitoring, enhancing repeatability. 3D printing offers sustainable materials, like plastic, but research aims to develop natural alternatives.
The suggested article's main research goals are:

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RO1: Analyzing significant developments in mitigating environmental deterioration and additive manufacturing.
RO2: To recognize and examine different innovations in additive manufacturing that enhance environmental sustainability.
RO3: To explore the key components necessary for establishing an environment for sustainable additive manufacturing.
RO4: To verify process workflows and enhance the sustainability of additive manufacturing practices.
RO5: To determine and investigate how applications of additive manufacturing contribute to environmental sustainability. The Basic Idea In this framework, communication of secret information between the sender and the receiver can be done by transmitting a series of images using constructed inverted index structure. An efficient hashing algorithm is used to prepare the indexing structure and also be used at receiver's side to decode the secret information [9].

2 Review Methodology

This study introduces a fresh sustainability approach in additive manufacturing (AM) with better practices. Research involved searching databases using specific keywords. Over 250 articles were screened based on relevance, with 130 selected for in-depth analysis. The study reviews findings from reputable journals to explore research problems and provide recommendations. The goal is to assess AM's sustainability and determine if recent developments have offered new insights

3 Sustainability in Manufacturing and the Environment

Sustainable manufacturing, or green manufacturing, aims to minimize pollution, promote environmental sustainability, and enhance productivity in industries like automotive. It not only benefits the planet but also improves safety and well-being for workers and consumers. By reducing energy consumption, waste, and processing time, companies can boost operational performance and establish leadership roles in the market. Sustainable production integrates product and process design to enhance a company's image and customer loyalty. Implementing waste reduction strategies, recycling, and utilizing technologies like additive manufacturing can help reduce the environmental footprint and contribute to sustainability goals.

4 Additive Manufacturing and its Significant Environmental Impact

Additive manufacturing (AM) involves constructing objects by layering raw materials following a computer-aided design (CAD) model. Initially used on plastics and metal powders, AM now includes materials such as latex, cement, graphite, and graphene.

This technology offers benefits like faster prototyping, increased productivity, and customized product creation. It reduces manufacturing costs, carbon dioxide emissions, and energy consumption. The development process involves multiple prototypes and iterations until the final design is optimized. Creating support structures is crucial for complex designs to prevent collapse during printing and dissipate heat. Sustainable practices in 3D printing involve using recycled materials like plastics, which help reduce waste and promote material reuse. Additive manufacturing technology has the potential to reduce plastic production's carbon footprint through techniques like generative design and topology optimization.

5 Additive Manufacturing's Development for Environmental Improvement

Digital technologies such as computer-assisted modelling, machine learning processes, and additive manufacturing (AM) are transforming the manufacturing industry. AM reduces errors, minimizes material usage, and enhances production efficiency. Mass customization enables tailored goods for consumers, while AM benefits industries like aerospace and medicine. Advanced information technologies automate production supervision. AM is also used for creating complex structures and architecturally sustainable 3D-printed houses. Powdered-metal additive technologies improve material efficiency and mechanical properties. Continuous research is needed to make these technologies cost-effective and sustainable. Recycling materials through powder-bed 3D printing promotes sustainability and addresses inventory challenges in production processes.

5.1 Additive Manufacturing for Minimizing Resource Demands

AM technology reducing manufacturing costs by requiring fewer resources and a smaller workforce. It cuts distribution expenses, saves time, and improves project planning by applying design enhancements based on CAD plans and customer needs.

5.2 Using Additive Manufacturing to Reduce Supply Chain Cost

Flexible infrastructure in supply chains is enhanced by additive manufacturing (AM), which reduces costs by enabling direct product delivery to customers. AM produces lightweight parts, cutting transportation expenses, and eliminates assembly needs, shortening the supply chain. 3D printing allows for easy modifications during the development phase, reducing customization expenses and overall production costs. Various industries like healthcare, defense, and electronics benefit from AM in their supply chains. Environmentally, Industry 4. 0 technologies such as AM help reduce waste, improve recycling, and collect data for enhancing product performance. AM also aids in cost reduction, optimization of supply chains, and creating sustainable manufacturing practices through waste reduction.

5.3 Additive Manufacturing to Reduce Waste

There is ongoing debate about whether additive manufacturing (AM) is a more sustainable option compared to traditional methods. AM can reduce plastic waste by using only necessary materials, with technologies like binder jetting and powder bed fusion further minimizing waste by enabling powder recycling. AM is widely used in various industries for prototyping and reverse engineering. Beyond prototyping, AM allows for the creation of intricate and efficient products without the need for tooling or assembly lines, catering to individual demands. Sustainability, recyclability, and efficient energy consumption are key advantages of AM, contributing to a reduced environmental footprint despite the lack of universal material standards.

5.4 Scrape Reducing

Manufacturing businesses are prioritizing environmentally sustainable raw materials, with 3D printing playing an important role. Some methods are used to recycle single-use plastics into raw materials. 3D printing enables rapid prototype creation and quick production of new products, but support structures are often needed. Additive manufacturing reduces scrap waste compared to traditional methods by building up material layer by layer. Multi-material 3D printing integrates various functions into a single product, leading to a more efficient production process.

5.5 Recycling Material/Renewable Raw Materials

Recycling initiatives are progressing, with industries focusing on waste management benefits. Addressing plastics' slow degradation requires promoting circular economies and innovative solutions. Additive manufacturing (AM) supports sustainability by creating new materials and enhancing market outcomes. AM reduces waste from traditional processes, allowing for on-demand production and streamlined supply chains. It also improves manufacturing productivity without major investments. 3D printing minimizes overproduction, reduces storage needs, and creates opportunities in various fields like medical equipment and patient-specific implants, showing versatile industrial applications.

5.6 The Beneficial Effect of Additive Manufacturing on Pollution Control

3D printing in manufacturing produces fewer toxic substances compared to traditional methods, offering economic advantages and reducing environmental impact. The technology minimizes energy consumption, transportation emissions, and air pollution associated with conventional manufacturing processes. It enables on-demand production of components locally, reducing the need for specialized facilities in distant locations. 3D printing eliminates millions of shipping trips for components, minimizes waste, and avoids harmful by-products, safeguarding air and water quality. The carbon footprint of 3D printing is smaller than mass production, allowing for intricate internal geometries without waste.

6 Establishing A Sustainable Additives Manufacturing Ecosystem : Key Components

To create a sustainable environment in the additive manufacturing (AM) sector, a strategic approach involving several key elements is essential. These foundational components include process safety, economic viability, environmental friendliness, and societal impact, all of which are crucial for enhancing existing AM technologies with sustainable practices. Important considerations for sustainability within AM include health-related issues, scrap material generated during production, and operator safety. Additionally, aspects such as market growth, process efficiency, and cost-effectiveness are integral to the economic features of AM.

Fig. 1. The ecosystem of additive manufacturing is sustainable.

A visual representation (Fig. 1) illustrates various established strategies within the additive manufacturing ecosystem that promote sustainability across these technological platforms. This framework highlights the interconnectedness of societal, economic, and environmental sustainability, with safety being a vital aspect of a comprehensive sustainable ecosystem. Environmental factors such as energy consumption, emissions, and recyclability are also critical for achieving complete sustainability in AM processes. One of the most notable advantages of using 3D printing in manufacturing is its ability to significantly reduce material waste and production costs. This technology enables the recycling of materials, providing considerable environmental benefits. Compared to conventional manufacturing methods, 3D printing has a more profound positive impact, as it reduces pollution and addresses several current issues in the manufacturing industry. Furthermore, 3D printing allows for the sustainable production of items from virtually any location, whether in a store or at home. This capability substantially decreases the need for shipping, thereby minimizing associated pollution [13,14]. Additionally, 3D-printed products can be lighter due to innovative designs and internal geometries that often differ from those achievable through traditional machining techniques. These advancements require less energy and contribute to lower pollution levels.

7. Enhancing Sustainability Through Additive Manufacturing Process: Process Flow

The process of implementing a sustainable culture within the existing additive manufacturing (AM) framework involves several key steps. It begins with an assessment phase that includes life cycle assessments, focusing on sustainability-related characteristics. Following this, attention shifts to material considerations and their overall environmental impacts, aiming to achieve targeted sustainability within the AM sector [7,8] Next, post-assessment steps are undertaken, which are further improved by enhancing the overall additive manufacturing processes. By doing so, AM can lower energy and resource costs essential for scaling production, all without significant alterations. This enables industries to enhance the speed and profitability of their business models. Additionally, the technology contributes to reducing time-to-market and localizing production [8,9]. Such advancements positively influence the environment by addressing the challenges associated with long-distance transportation. Increased automation levels foster this transition, improving productivity and enhancing worker safety. This shift not only saves lives but also boosts the profitability of mining operations. Furthermore, this transformative phase opens up new market opportunities and prompts a reevaluation of corporate practices, maximizing the use of emerging innovations. Ultimately, this could lead to significant reductions in pollution, with AM playing a crucial role in enhancing the sustainability of our economies and communities [10]

8. How additive manufacturing improves environmental sustainability.

Additive manufacturing (AM) is utilized to create a diverse range of products while prioritizing environmental impact and the welfare of workers and customers. It incorporates green and lean processing methods and includes a range of sustainability indicators. The entire product life cycle is designed around sustainable practices, extending from production through to end-of-life considerations, including remanufacturing and recycling [11,12].

Transforming a standard manufacturing facility into a smart factory involves both horizontal and vertical integration, which connects all production areas to manufacturers and customers. The seamless integration of information technology systems into Industry 4.0 enhances manufacturing processes and supply chain management. To achieve sustainable development, manufacturing engineers face a variety of industry-wide challenges [14,15]. Designers can identify significant concerns during the product design and development phases, allowing the manufacturing sector to eliminate internal waste while increasing efficiency. Plans may be changed quickly, allowing manufacturing teams to provide the necessary components while reducing waste. These revolutionary technologies encourage sustainable production by digitizing manufacturing processes [15].By leveraging smarter designs, manufacturers can enhance efficiency through lighter materials, sustainable practices, and improved component performance. Additive manufacturing helps reduce the need for additional processing and physical inventory. Recently, metal 3D printing has gained significant attention among leading companies. However, metal technologies like metal binder jetting have lagged behind

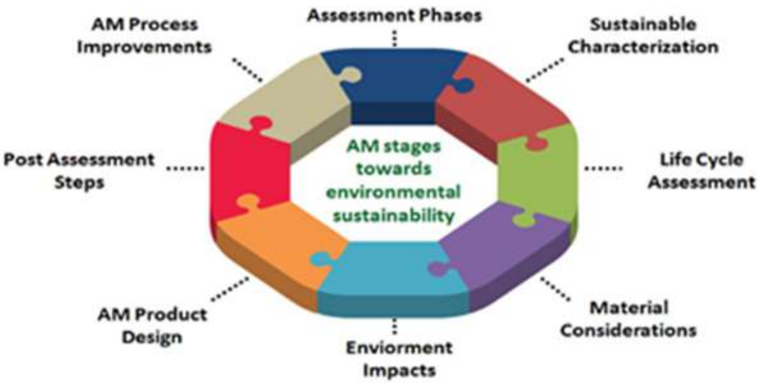

Fig.2. The process flow of AM phases is aimed at improving environmental sustainability.

Table 1. Important areas of use where environmental sustainability can be improved via additive manufacturing

S.No	Sustainable Application	Description
1	Creative sustainable design	Generative design's first and best-known applications were on reducing material consumption, which considerably reduced an assembly's or component's weight. In addition to providing immediate sustainability benefits and weight-related cost savings, this method improves overall design efficiency. For the best possible environmental impact, it supports a variety of production techniques. Furthermore, 3D printing makes it possible to manufacture prototypes with design flexibility and the required materials, encouraging innovation and advancing technology.
2	Achieving environmental goals	Generative design's first and best-known applications were on reducing material consumption, which considerably reduced an assembly's or component's weight. In addition to providing immediate sustainability benefits and weight-related cost savings, this method improves overall design efficiency. For the best possible environmental impact, it supports a variety of production techniques. Furthermore, 3D printing makes it possible to manufacture prototypes with design flexibility and the required materials, encouraging innovation and advancing technology.
3	Minimizing the potential for overproduction	Improved usability, faster printing speeds, and the flexibility to make design changes quickly all greatly reduce the chance of overproduction. Greener industrial environments and more sustainable procedures are now within the reach

		of manufacturers. In contemporary industries, this is a major technological advancement. It lessens dependency on commercial manufacturing by enabling the quick fabrication of intricate and customized goods at home.
4	Reduce material waste	It is also possible to recycle thermoplastic components made with this technology. 3D printers can be used to recycle a variety of other materials. Environmentally beneficial items can be printed with this method. Furthermore, a number of businesses have created processes for turning waste into powder that may be used in 3D printing. Metal recycling is also advancing, but the majority of recycling activities are focused on the polymer 3D printing industry. This technology will further the science of recycling in the future.
5	Reduced energy consumption	Despite improvements in metal recycling, the majority of recycling efforts are focused on the polymer 3D printing industry. The advancement of recycling science will be another goal of this technology in the future. In comparison to many conventional production methods, 3D printing uses less energy when producing critical materials. Generally speaking, 3D printing technologies require less energy than conventional machining operations. This technology provides a straightforward and creative solution. 3D printing is more energy-efficient than subtractive techniques, offering a practical means of maximizing output and inventory needs while reducing manufacturing fuel use.
6	Material recycling	One essential component of sustainability is the recycling and reusing of 3D printing materials. Given the high cost of materials and the fact that metal powder cannot be recycled, this is especially important in the 3D metal printing industry. The mechanical qualities of the materials are greatly impacted by the appropriate recycling and reuse of metal powders. This method makes powder-based operations more economical and efficient. Additionally, manufacturers are creating screening methods for metal 3D printing, which are now considered industry norms.
7	Sustainable products	Using organic and biodegradable materials, additive manufacturing (AM) has also become a popular way to produce environmentally friendly 3D items. This technology uses PLA, which is sustainable, non-toxic, biodegradable, and produces little waste. Compared to CNC machining, its low melting temperature reduces material waste and making it appropriate for a variety of applications. Compared to conventional methods like machining, casting, and welding, metal 3D printing can be simpler for low- to mid-

		volume production and does not require tools. Because near-net shapes can be printed fast in a single piece, additive manufacturing (AM) is very useful for reducing material loss, which saves money and time overall.
8	Reduced tooling requirements	Producers will be able to better satisfy market demands thanks to the development. Additive manufacturing is one of the emerging technologies being used to increase involvement in a variety of industries. Products can be produced via additive manufacturing without the use of any equipment, fixtures, or assembling parts. Additive manufacturing is being used by a number of sectors to create components for their R&D procedures.
9	Novel products	It is currently used to produce tiny quantities, customized pieces, and novel products, and its uses are always changing to become more sophisticated and economical. Despite all of this technology's advantages, one thing to keep in mind is how much energy it uses. Nevertheless, compared to conventional processing techniques, 3D printers use less material. Only the minimal quantity of plastic, metal, or ceramic needed to create a component can be melted, bound, or sintered by them. This approach is different from traditional subtractive processing, which frequently requires removing extra material instead of just adding the necessary quantity.
10	Sustainable manufacturing	It uses less energy to produce this extra material. One popular green technology used to create 3D printed parts is powder metallurgy. By reducing trash and energy use, this technology promotes a better environment. In addition, it is a far more environmentally friendly processing approach than conventional manufacturing methods like machining. Additionally, weight can be decreased by using lightweight materials in additive manufacturing. Additive manufacturing provides a number of additional sustainability benefits in addition to reducing fuel usage.
11	Eco-friendly solutions	Additionally, it uses a lot less material than conventional manufacturing techniques. By using digital input to enable sustainable prototype and final products, additive manufacturing (AM) opens up new design options without the constraints of subtractive production. A variety of materials, such as common, clever, and unusual ones, can be used successfully. The most widely utilized materials are metals and polymers, which are especially useful for waste reduction and low-volume production. Furthermore, materials like glass, chocolate, and biochemical and medicinal chemicals can be used. Components with complex designs or

		those that profit from lightweight conditions, including parts for trucks, cars, airplanes, or medical purposes, can be efficiently made for metal additive goods.
12	Eco-friendly supply chain	A digital transformation's architecture should protect the company and supply chain as a whole. Information digitization can assist in addressing quality concerns and improve comprehension of additive manufacturing material performance. Although the economic benefits of additive manufacturing are the main consideration, it also has implications for product and quality assurance procedures. Even while modern manufacturers have started implementing shop floor digitization, more work needs to be done.

metal powder bed fusion, impacting the advancement of manufacturing industries. The energy content of their products varies considerably due to the differences in size between a 3D printer that produces a single item at a time and traditional manufacturing systems that generate hundreds or thousands of products continuously [8].This technology is evolving to become more cost-effective while simultaneously decreasing its environmental impact. It aids the environment by reducing plastic consumption and lightweighting components without sacrificing strength, resulting in products that are better suited for specific applications. Traditional subtractive manufacturing methods cannot achieve such complex geometries. The concept of By creating digital warehouses where parts are made as needed rather than being stockpiled, Design for Additive Manufacturing helps to drastically cut down on the amount of needless plastic waste that ends up in landfills. Additionally, these automated warehouses save emissions associated with transportation because parts can be manufactured locally, effectively eliminating transportation-related pollution. Additionally, 3D printing enables the creation of lighter, more intricate, and curved cement surfaces that disperse wave energy in multiple ways, minimizing erosion and environmental intrusion [9]

9. Key Discoveries and Discussions

Additive manufacturing (AM) enables virtual teams worldwide to collaborate on new ideas, significantly streamlining the prototype manufacturing process and the production of various components. This technology accelerates the launch of new products, allowing for quicker adjustments in response to shifting market demands. AM adapts the output rates of new products to align with consumer needs and is instrumental in creating practical 3D-printed prototypes. By significantly reducing the time from concept to production, AM facilitates the rapid development of innovative products. In comparison to traditional manufacturing methods, AM lowers the costs associated with customized products, decreases inventory control expenses, and simplifies supply chains. It minimizes the necessity for different equipment for manufacturing various components, thereby reducing both logistics costs and manufacturing. Applications of additive manufacturing that foster an eco-friendly environment include innovative sus-

tainable design and achieving environmental goals reducing the potential for overproduction, minimizing material waste, lowering energy consumption, recycling materials, and promoting green manufacturing practices. The adoption of additive manufacturing can also lead to sustainable solutions and an environmentally friendly supply chain.
The widespread use of AM fosters transformative innovations. Materials utilized in 3D printing often include new and recycled substances, presenting numerous potential advantages across various countries. A significant benefit of AM is that it requires less capital investment compared to traditional mold production, making it easier and more accessible for businesses to diversify their product offerings with smaller sizes. Additionally, AM opens up new design possibilities that are unattainable with subtractive manufacturing methods. It allows for the effective use of conventional, smart, and non-traditional materials. Frequently utilized materials include polymers and metals, which are especially advantageous for minimizing waste and low-volume production. This technology can also accommodate a variety of materials, including biochemical and medical substances, glass, and even food items like chocolate. Components with complex designs or lightweight requirements, such as those for trucks, cars, airplanes, and medical devices, can be effectively manufactured utilizing metal additive manufacturing (AM). Furthermore, the framework for digital transformation in supply chains should encompass the entire business operation. Digitizing information can address quality issues and improve comprehension of the performance of AM materials. Although additive manufacturing is frequently assessed based on its economic advantages, it also plays a role in product quality assurance processes. Contemporary factories are progressively moving toward digitization on the shop floor, which can enhance overall efficiency [5,3].By eliminating the need for imports, AM encourages countries to strengthen their supply chains and tailor products to better fit local consumer preferences. This technology presents an opportunity for countries to enhance their industrial competitiveness. Moreover, 3D-printed items can be made from renewable and recyclable polymers, allowing products to be repurposed at the end of their lifecycle.

10. Future Scope

In the future, additive manufacturing (AM) is poised to enhance energy efficiency and enable innovative designs that will lead to reduced production costs. This technology is expected to become more environmentally friendly, safer, and more sustainable compared to conventional manufacturing methods. Engineers and designers will leverage new ideas to meet customer demands effectively. AM will focus on minimizing resource usage and providing opportunities for lightweight components through techniques such as generative modelling, assembly reinforcement, and the exploration of novel materials and design options. These advancements will yield significant economic benefits while meeting consumer expectations. In the coming years, the significant environmental benefits of additive manufacturing, including reduced waste and the capacity to produce multiple components at once without requiring extensive equipment, will become more apparent. This technology will provide greater design flexibility, enabling better mechanical integration and part consolidation, which will ultimately result in lower energy consumption during processing and assembly

11. Conclusion

Components created through additive manufacturing (AM) are generally lighter, leading to reduced material usage during production and lower energy consumption during their lifecycle. This technology contributes to longer product lifespans by enabling the rapid production of replacement parts, enhancing reliability, and allowing for modular designs that facilitate upgrades. AM simplifies and shortens value chains by promoting flexibility within the production process.

The large-scale adoption of AM has the potential to transform sustainability across value chains, emphasizing the importance of localized manufacturing and significantly minimizing the environmental impact of logistics. Additionally, recycled materials can effectively serve as inputs for AM, and the ability to print on demand further reduces inventory waste. By redesigning products and processes to suit AM, manufacturers can optimize performance throughout both development and use.

Industrial sustainability has been a key focus for many years, with manufacturers increasingly exploring ways to produce goods more efficiently and sustainably. Sustainable development in manufacturing aims to minimize environmental impact, which benefits public health. The food industry is another sector actively seeking to enhance its environmental performance through AM, leading to innovative manufacturing and packaging solutions. Looking ahead, it is likely that many major industries will embrace a greener approach to development through the implementation of additive manufacturing.

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