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Review

Application of 3D printing across various fields to enhance sustainable manufacturing

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Abstract: 3D printing has fundamentally transformed traditional manufacturing practices by enabling decentralized production, customization, and significant reductions in waste and energy consumption. This paper provides a thorough examination of the advancements, applications, challenges, and future prospects of 3D printing in fostering sustainable manufacturing practices across diverse industries. Key additive manufacturing technologies such as Fused Deposition Modeling (FDM), Stereolithography (SLA), Selective Laser Sintering (SLS), and Direct Metal Laser Sintering (DMLS) are discussed in relation to their role in achieving sustainability goals. The versatility of 3D printing materials, including biodegradable polymers, recycled metals, and eco-friendly composites, is highlighted alongside their environmental benefits and functional advantages in sectors such as automotive, healthcare, construction, consumer products, electronics, aerospace, and defense. Despite the transformative potential of 3D printing, challenges such as material limitations, energy consumption, regulatory compliance, and initial costs persist, requiring collaborative efforts to overcome. Looking ahead, ongoing research and development efforts in materials science, process optimization, and Industry 4.0 integration are poised to further enhance the sustainability and scalability of 3D printing technologies, thereby paving the way for a more environmentally conscious and economically viable manufacturing future.

Keywords: 3D printing; additive manufacturing; sustainable manufacturing; automotive; healthcare, construction; consumer products; electronics; aerospace; defense

1. Introduction

Sustainable manufacturing represents a critical paradigm shift in industrial practices, characterized by its focus on minimizing environmental impact, optimizing resource utilization, and enhancing societal benefits. This transformative approach seeks to harmonize economic growth with environmental stewardship and social responsibility. At the forefront of this shift is the adoption of 3D printing technologies, which have emerged as a highly promising strategy for achieving these sustainability objectives. By facilitating decentralized production, 3D printing reduces the need for large-scale manufacturing facilities and long supply chains, thereby minimizing transportation-related emissions and resource consumption. Additionally, the technology allows for unprecedented design customization, which not only meets specific consumer needs but also reduces material waste through precise, layer-by-layer manufacturing processes. Furthermore, 3D printing contributes to significant energy efficiency improvements by optimizing production workflows and lowering energy demands compared to traditional manufacturing methods [1].

This paper aims to provide a thorough and detailed overview of how 3D printing is fundamentally transforming manufacturing practices across various sectors the overview given in **Table 1**. It explores the diverse applications and benefits of this technology, demonstrating its substantial contributions to global sustainability goals. By examining case studies and industry-specific examples, this paper highlights the ways in which 3D printing is driving progress towards more sustainable manufacturing practices and underscores the technology's potential to address some of the most pressing environmental and resource challenges of our time.

Table 1. Review overview.

Review Steps	Description	Review Outcome
1. Preliminary Reading	Read the abstract, introduction, and conclusion to understand the paper's scope and key arguments.	Initial understanding of the paper's main objectives and relevance.
2. Detailed Analysis	Review each section in detail, focusing on methodologies, technologies, applications, and case studies.	Comprehensive grasp of the paper's structure and detailed content analysis.
3. Evaluation of Technologies	Assess the discussion of 3D printing technologies (FDM, SLA, SLS, DMLS) and their environmental impact.	Evaluation of how well the paper covers the technologies and their sustainability aspects.
4. Industry Applications	Evaluate the applications of 3D printing across various industries and review key examples provided.	Understanding of the practical implementations and relevance to different sectors.
5. Challenges and Solutions	Review the challenges mentioned and the proposed solutions for sustainable manufacturing.	Insight into the obstacles faced and the effectiveness of suggested solutions.
6. Technological Advancements	Examine innovations in 3D printing technologies, materials, and digital tool integration.	Assessment of the advancements covered and their implications for sustainability.
7. Sustainability Assessment	Assess how the paper addresses sustainability through material efficiency, energy savings, and localized production.	Understanding of how well the paper integrates sustainability into the discussion of 3D printing.
8. Future Prospects	Review the proposed future developments in 3D printing and their potential impact on sustainable manufacturing.	Insight into the future trends and their potential effects on the industry.
9. Conclusion and Recommendations	Summarize the findings and provide recommendations for further research or practical applications.	Final overview of the paper's conclusions and actionable recommendations.

2. 3D printing technologies and materials

A fundamental aspect of 3D printing's versatility lies in its diverse range of technologies and compatible materials. Key additive manufacturing technologies include Fused Deposition Modeling (FDM), Stereolithography (SLA), Selective Laser Sintering (SLS), and Direct Metal Laser Sintering (DMLS), each offering unique capabilities suited to different industrial applications [2]. The choice of materials plays a crucial role in determining the environmental footprint and functional properties of 3D printed products. Materials such as thermoplastics, metals, ceramics, and biocompatible polymers are commonly used, with ongoing advancements focusing sustainable alternatives like recycled filaments and bio-based resins [3].

Environmental sustainability assessments indicate that 3D printing processes can significantly reduce material waste compared to traditional subtractive manufacturing methods. Life cycle assessments (LCAs) have demonstrated favorable environmental profiles for additive manufacturing, highlighting reductions in energy consumption, emissions, and raw material usage [4]. However, challenges such as energy-intensive post-processing steps and the environmental impact of material sourcing require ongoing research and innovation to enhance the sustainability credentials of 3D printing technologies [5].

3. Applications in different industries

Different applications of 3D printing, its future scope is explained below and summary is given in **Table 2**.

Table 2. Applications of 3D printing.

Industry	Current Applications of 3D Printing	Future Scope
Automotive Industry	Rapid prototyping of vehicle components	Direct printing of production parts
	Customized tooling and jigs	Integration of 3D printed electronics
	Lightweight and complex geometries for structural parts	Use of advanced materials like carbon fiber composites
	Production of electric vehicle components	Scalable production lines for additive manufacturing
Healthcare Sector	Patient-specific surgical guides and implants	Bioprinting of organs and tissues
	Prosthetics and orthotics	Development of personalized medicine
	Customized dental aligners and implants	Regulatory approval for mass customization in medical devices
	Bioprinting for tissue engineering	Telemedicine applications using 3D printed devices
Construction and architecture	3D printed concrete structures and prefabricated modules	Integration of robotics for large-scale construction projects
	Architectural elements with intricate designs	Sustainable building materials and recycling processes
	Disaster relief shelters and temporary housing	3D printed infrastructure in space exploration
Consumer Products and Electronics	Customized fashion accessories and jewelry	Personalized consumer products with embedded electronics
	Personalized consumer electronics	Customized food printing for nutrition and dietary needs
	Eco-friendly and sustainable product designs	Enhanced retail experiences through on-demand manufacturing
	On-demand production of spare parts	Integration with IoT for smart home applications
Aerospace and defense	Lightweight, high-strength components for aircraft	Production of aerospace-grade metals and alloys
	Complex geometries and integrated systems	On-site repair and maintenance using 3D printing
	Prototyping and small-batch production	3D printed satellites and space habitats

A. Automotive Industry.

In the automotive sector, 3D printing is revolutionizing manufacturing processes by enabling the production of lightweight, complex geometries with enhanced mechanical properties. Additive manufacturing techniques facilitate rapid prototyping, tooling production, and customization of vehicle components, leading to reduced lead times and production costs [6]. Applications range from interior trim components and structural elements to engine parts and vehicle prototypes [7]. Case studies from automotive giants like BMW, Ford, and Volkswagen highlight the integration of 3D printing for achieving sustainability goals through material efficiency and design optimization [8].

B. Healthcare Sector.

The healthcare industry has embraced 3D printing for personalized medicine, medical device manufacturing, and surgical planning. Additive manufacturing enables the production of patient-specific implants, prosthetics, and surgical guides tailored to individual anatomical variations [9].

Customization not only enhances patient outcomes but also reduces surgical risks and recovery times. Biocompatible materials such as titanium alloys and medical-grade polymers are commonly used in medical 3D printing applications, with stringent regulatory frameworks ensuring product safety and efficacy [10]. Challenges include scalability, regulatory compliance, and the need for standardized quality control measures to ensure reproducibility and reliability across medical 3D printing processes [11].3D Printed Wearables: In the healthcare sector, 3D printed wearables are significantly advancing patient care and medical monitoring. These wearables offer customization to fit individual anatomical and functional needs, enabling highly personalized solutions that traditional manufacturing methods cannot match. For instance, 3D printed orthotics and prosthetics can be designed for enhanced comfort and functionality, while wearable sensors made through 3D printing can continuously monitor vital signs and manage chronic conditions. The use of flexible polymers and biocompatible materials enhances the integration of these devices with the human body. The rapid prototyping and iterative design capabilities of 3D printing are crucial for developing effective and user-friendly medical wearables (43).

C. Construction and Architecture.

In the construction industry, 3D printing offers innovative solutions for sustainable building practices and infrastructure development. Large-scale 3D printers can fabricate concrete structures, prefabricated modules, and architectural components with intricate designs and geometries that are difficult to achieve using traditional construction methods [12]. The use of sustainable materials such as recycled aggregates, geopolymer concrete, and biodegradable polymers further enhances the environmental sustainability of 3D printed structures [13]. Applications range from residential housing and commercial buildings to disaster relief shelters and sustainable urban infrastructure projects [14]. Advancements in robotic construction systems and digital fabrication technologies are expanding the feasibility and scalability of 3D printing in construction, revolutionize the cost-effective, energy-efficient building solutions [15].

D. Consumer Products and Electronics.

Additive manufacturing is transforming the consumer products and electronics industries by enabling on-demand manufacturing, product customization, and sustainability-driven design innovations. Companies are leveraging 3D printing to produce lightweight, durable consumer goods, wearables, and electronics components using advanced materials and manufacturing techniques [16]. The integration of recycled plastics, biocompatible polymers, and eco-friendly materials in 3D printed products aligns with consumer preferences for sustainable and environmentally responsible manufacturing practices [17]. Case studies from leading brands demonstrate the commercial viability of additive manufacturing for creating high-performance, aesthetically appealing consumer products while minimizing material waste and production costs [18].3D Printed Electronics: The use of 3D printing in electronics fabrication is transforming how electronic components are produced. This technology allows for the creation of complex circuits and components within a single 3D printed structure by integrating conductive materials directly into the print. This approach facilitates the development of custom electronic devices with embedded circuits and sensors, leading to innovative consumer products. Examples include personalized gadgets, wearable technology, and smart packaging. The reduction in material waste and assembly needs through 3D printed electronics supports more sustainable manufacturing practices.

E. Aerospace and Defense.

In the aerospace and defense sectors, 3D printing has emerged as a disruptive technology for manufacturing lightweight, complex components with superior strength-to-weight ratios and performance characteristics. Additive manufacturing enables design optimization, part consolidation, and rapid prototyping of aerospace components, reducing material waste and production lead times [19]. Applications include aircraft interiors, engine parts, satellite components, and defense equipment, where stringent quality standards and regulatory compliance are paramount [20]. Challenges such as material qualification, process repeatability, and supply chain integration require collaborative efforts between industry stakeholders, researchers, and regulatory bodies to accelerate the adoption of 3D printing in aerospace and defense manufacturing [21]. Hybrid 3D Printing Technologies: In aerospace and defense, hybrid 3D printing technologies are utilized to produce lightweight, multifunctional components. These technologies combine additive manufacturing with traditional manufacturing processes to create parts with complex geometries and superior performance. For example, hybrid 3D printing allows for the integration of metal and polymer layers in a single part, achieving strength and reduced weight, which is critical for aerospace applications. Additionally, such technologies enable the production of parts with integrated functionalities like thermal or electrical conductivity, essential for advanced aerospace and defense systems.

4. Cross-industry implications and challenges

The widespread adoption of 3D printing across industries necessitates addressing interdisciplinary challenges and considerations to maximize its potential for sustainable manufacturing. Economic feasibility remains a critical factor influencing the scalability and commercialization of additive manufacturing technologies [22]. While initial costs for 3D printers and materials may be higher than traditional manufacturing methods, cost savings from reduced material waste, design flexibility, and decentralized production models contribute to long-term economic benefits [23].

Ethical considerations encompass intellectual property rights, data security, and workforce implications associated with the digitalization and automation of manufacturing processes [24]. Regulatory frameworks governing product safety, quality assurance, and environmental standards vary across regions and industries, posing challenges for global adoption and standardization of 3D printing technologies [25]. Collaborative efforts between academia, industry, and regulatory bodies are essential to develop robust certification protocols, industry standards, and best practices for ensuring the reliability, safety, and sustainability of 3D printed products [26].

5. Technological advancements

3D printing, also known as additive manufacturing, has undergone significant advancements that have revolutionized manufacturing processes across various industries. These advancements have not only expanded the capabilities of 3D printing but also enhanced its potential to support sustainable manufacturing practices.

a. Improved Printers and Materials: The evolution of 3D printer technology has led to significant improvements in precision, speed, and scalability. Modern printers now offer larger build volumes and increased resolution, allowing for the production of complex geometries with high accuracy [27]. Moreover, advancements in multi-material printing capabilities have enabled the creation of hybrid structures that combine different materials to optimize performance and durability [28].
b. New Materials Development: One of the most profound impacts of 3D printing on sustainable manufacturing is its ability to utilize a diverse range of materials, including biodegradable polymers, recycled plastics, and sustainable composites. These materials not only reduce environmental impact but also offer enhanced mechanical properties suitable for a wide range of applications, from consumer goods to aerospace components [29].
c. Process Optimization: Continuous research and development efforts have focused on optimizing 3D printing processes to improve efficiency and reduce production costs. For instance, innovations in printing techniques such as Selective Laser Sintering (SLS) and Stereolithography (SLA) have minimized material wastage and energy consumption compared to traditional manufacturing methods [30]. This efficiency not only lowers operational costs but also contributes to sustainability by conserving resources.
d. Integration with Digital Technologies: The integration of 3D printing with digital design tools, such as Computer-Aided Design (CAD) software and Artificial Intelligence (AI), has streamlined the product development cycle. Design iterations can be rapidly prototyped and tested, facilitating faster time-to-market and reducing overall development costs [31]. AI algorithms are also being employed to optimize printing parameters, enhance part quality, and predict material behavior, further enhancing the reliability and scalability of additive manufacturing processes [32].

6. Means to enhance sustainable manufacturing

The versatility of 3D printing technology offers numerous applications that enhance sustainable manufacturing practices across various sectors which is explained below and given in **Figure 1**.

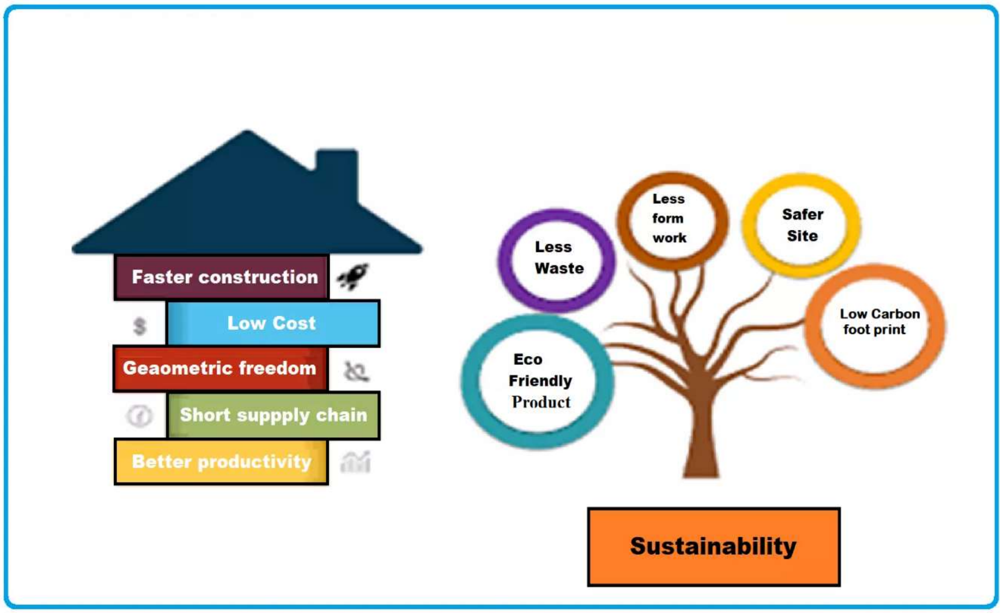

Figure 1. Different sustainable benefits of 3D printing.

a. Material Efficiency: Additive manufacturing minimizes material waste by utilizing only the necessary amount of material for each printed component. Unlike traditional subtractive manufacturing processes that generate significant waste from cutting or milling operations, 3D printing builds objects layer by layer, optimizing material usage and reducing environmental footprint [33].

b. Energy Savings: Certain 3D printing techniques require lower energy consumption compared to conventional manufacturing methods. For instance, processes like Powder Bed Fusion (PBF) and Digital Light Processing (DLP) use localized energy sources, such as lasers or light, to selectively solidify materials, minimizing energy-intensive heating and cooling cycles associated with traditional casting or machining processes [34].

c. Sustainable Materials: The adoption of recycled materials and bio-based polymers in additive manufacturing contributes to sustainable resource management. By repurposing waste materials or utilizing renewable resources, manufacturers can reduce reliance on virgin materials and mitigate the environmental impact of production processes [35]. Moreover, advancements in material science continue to expand the availability and performance of sustainable alternatives, enabling broader adoption in critical industries like healthcare and automotive manufacturing.

d. Localized Production: The on-demand and decentralized nature of 3D printing enables localized production of customized or spare parts, reducing the need for extensive transportation networks and warehouse storage. This localization not only minimizes carbon emissions associated with logistics but also enhances supply chain resilience by reducing lead times and minimizing inventory overheads [36].

6.1. Fused deposition modeling (FDM)

Material Cost:

- Low Cost: FDM uses thermoplastic filaments, such as PLA, ABS, or PETG, which are generally inexpensive and widely available. PLA is particularly noted for its lower cost and use of biodegradable materials.

Energy Consumption:

- Moderate to High: FDM printers require significant energy to heat the extrusion head and build platform, which can lead to relatively high energy consumption, especially for larger prints or extended operations.

Emissions:

- Low to Moderate: PLA, being a bio-based plastic, has a lower environmental impact compared to petroleum-based plastics like ABS. However, the heating process can still emit fumes, including volatile organic compounds (VOCs). Using enclosures and proper ventilation can help mitigate these emissions.

Lifecycle Impact:

- Waste Generation: FDM produces waste in the form of support structures and failed prints. However, many FDM materials can be recycled or repurposed, reducing overall waste.

6.2. Stereolithography (SLA)

Material Cost:

- High Cost: SLA uses photopolymer resins, which are more expensive than FDM filaments. The cost of resins can vary depending on their properties and intended use.

Energy Consumption:

- Moderate: SLA printers use UV light to cure resin layer by layer, which is less energy-intensive compared to the heating processes in FDM. However, the post-processing steps, including washing and curing, can be energy-consuming.

Emissions:

- Low to Moderate: SLA resins may release VOCs during curing. Proper handling and disposal are essential to minimize environmental impact. Many resins are now available with lower emissions profiles.

Lifecycle Impact:

- Waste and End-of-Life: SLA produces resin waste that can be hazardous. Proper disposal and recycling programs for resin containers and excess material are important to mitigate environmental impacts.

6.3. Selective laser sintering (SLS)

Material Cost:

- Moderate to High: SLS uses powdered materials, such as nylon or polymer blends, which tend to be more expensive than FDM filaments but can be more durable and functional.

Energy Consumption:

- High: SLS printers operate at high temperatures to sinter powders, requiring significant energy. The process involves heating the entire build chamber, which is energy-intensive.

Emissions:

- Moderate: SLS can produce emissions from the sintering process, particularly when using certain polymers. Advanced filtration systems can help reduce airborne particulate matter and VOCs.

  Lifecycle Impact:
- Material Efficiency: SLS is known for its minimal waste generation as unused powder can be reused in subsequent prints. However, the end-of-life disposal of SLS parts can be challenging, particularly for composite materials.

6.4. Direct metal laser sintering (DMLS)

Material Cost:

- Very High: DMLS uses metal powders, which are significantly more expensive than polymers used in other 3D printing methods. This high material cost reflects the high-value applications of DMLS, such as aerospace and medical implants.

  Energy Consumption**:**
- Very High: DMLS involves laser melting metal powders, requiring extremely high temperatures and significant energy consumption. The process is energy-intensive due to both the metal melting and the need for high-precision lasers.

  Emissions:
- Moderate to High: The metal melting process can produce fumes and particulates, which need to be managed with effective filtration systems to minimize environmental impact.

  Lifecycle Impact:
- Waste Generation: DMLS generates minimal waste as excess powder can often be reused. However, the disposal of metal powders and parts at the end of their life requires specialized recycling and recovery processes to manage the environmental impact effectively.

Fused Deposition Modeling (FDM) is generally more sustainable in terms of material cost and emissions when using biodegradable materials like PLA. Stereolithography (SLA) has higher material costs and requires careful management of resin waste but has lower energy consumption compared to other methods. Selective Laser Sintering (SLS) and Direct Metal Laser Sintering (DMLS) offer high material efficiency and minimal waste but are more energy-intensive and have higher material costs. Each technology has its advantages and limitations in sustainability, and the choice of technology should be aligned with specific application requirements and sustainability goals.

7. Future prospects

Looking ahead, the future of 3D printing in sustainable manufacturing holds promising prospects for innovation and growth:

1) Advancements in Materials Science: Ongoing research and development efforts are focused on expanding the range of sustainable materials available for additive manufacturing. Innovations in bio-based resins, recycled metals, and biodegradable composites will unlock new possibilities for environmentally friendly product design and manufacturing [37].

2) Industry 4.0 Integration: Industry 4.0 is the Fourth Industrial Revolution characterized by the integration of advanced technologies like IoT, AI, and robotics into manufacturing processes to create smart, interconnected systems that enhance efficiency, flexibility, and data-driven decision-making.The convergence of 3D printing with Industry 4.0 technologies, such as Internet of Things (IoT) and blockchain, will enable enhanced connectivity, real-time monitoring, and data-driven insights into manufacturing processes. This integration supports predictive maintenance, quality control, and supply chain transparency, paving the way for smart factories of the future [38].
3) Scaling Production: Advances in additive manufacturing techniques, including large-scale 3D printing and robotic automation, will enable the mass production of end-use parts across diverse industries. By optimizing production workflows and increasing throughput rates, manufacturers can achieve economies of scale and meet growing demand for sustainable products with enhanced cost-efficiency [39].

8. Challenges and possible solutions

Despite its potential benefits, integrating 3D printing into sustainable manufacturing practices presents several challenges that need to be addressed:

a. Material Limitations: While advancements have been made in developing sustainable materials for 3D printing, challenges remain in scaling up production and ensuring consistent material quality. Researchers and manufacturers need to collaborate to innovate new materials with improved mechanical properties and environmental credentials [40]. Solution: Invest in research and development to expand the range of sustainable materials available for additive manufacturing. Foster partnerships between academia, industry, and government agencies to accelerate material innovation and certification processes.

b. Energy Consumption: Although certain 3D printing processes are energy-efficient, others can still be energy-intensive, especially for large-scale production. Balancing energy efficiency with production speed and part quality remains a challenge for widespread adoption in energy-conscious industries [41]. Solution: Optimize printing parameters and invest in energy-efficient technologies such as hybrid heating systems and renewable energy sources to reduce the environmental impact of additive manufacturing processes.

c. Cost and Scalability: Initial costs associated with 3D printing equipment, materials, and training can be prohibitive for small and medium-sized enterprises (SMEs). Additionally, scaling up production while maintaining cost-effectiveness and quality control remains a challenge for large-scale adoption [42]. Solution: Implement cost-sharing initiatives, such as government grants or industry consortia, to reduce the financial burden on SMEs interested in adopting 3D printing technologies. Invest in workforce training programs to build capacity and expertise in additive manufacturing across diverse industrial sectors.

d. Adopting 3D printing within Industry 4.0 It presents several challenges. First, material limitations pose significant hurdles, as developing and qualifying new materials that meet industrial standards for strength and performance is complex. Cost and scalability issues also persist, with high initial investments in advanced 3D printing technology and difficulties in scaling up production affecting widespread adoption. Integration with existing manufacturing systems requires substantial adjustments to workflows and infrastructure, complicating the transition to additive manufacturing. Furthermore, quality control and consistency are critical concerns, especially for applications demanding high precision and reliability. Finally, navigating regulatory compliance is challenging due to diverse and evolving standards across industries and regions, which can impede the adoption and standardization of 3D printing technologies.
e. Ethical and regulatory challenges. However, the widespread adoption of these technologies also introduces potential regulatory and ethical challenges. Regulatory frameworks for 3D printing are still evolving, and ensuring that these frameworks adequately address issues related to safety, quality, and environmental impact is critical. Compliance with varying international standards can be complex and may hinder global integration. Furthermore, the ethical implications of advanced manufacturing technologies, such as data privacy, intellectual property rights, and the potential for job displacement, must be carefully considered. Addressing these concerns requires collaborative efforts between industry stakeholders, policymakers, and regulatory bodies to develop robust guidelines and best practices that ensure the responsible and equitable use of 3D printing and associated technologies.

9. Conclusion

3D printing stands as a transformative technology poised to significantly advance sustainable manufacturing practices across a wide range of industries. This paper has explored how additive manufacturing not only enhances production efficiency and customization but also contributes to environmental sustainability through reduced material waste and energy consumption. The versatility of 3D printing technologies, including Fused Deposition Modeling (FDM), Stereolithography (SLA), Selective Laser Sintering (SLS), and Direct Metal Laser Sintering (DMLS), underscores their potential to revolutionize sectors such as automotive, healthcare, construction, consumer products, and aerospace.

Despite its considerable advantages, the adoption of 3D printing presents challenges that must be addressed. These include material limitations, energy consumption, cost scalability, and regulatory compliance. As 3D printing technologies continue to evolve, integrating advancements in material science, process optimization, and Industry 4.0 technologies will be crucial. The convergence with digital tools like IoT and AI promises to further enhance manufacturing capabilities, though it also necessitates careful consideration of regulatory and ethical issues.

The future of 3D printing in sustainable manufacturing is marked by its potential to drive innovation and efficiency, making it a cornerstone technology for a more resilient and environmentally responsible production ecosystem. Continued research and development, alongside collaborative efforts from industry, academia, and regulatory bodies, will be essential to overcoming current challenges and fully realizing the benefits of 3D printing. As we advance, it is imperative to focus on sustainable practices and ethical considerations to ensure that the evolution of manufacturing technologies aligns with broader societal and environmental goals.

Conflict of interest: The authors declare no conflict of interest.

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