

Review

Printing the Future Layer by Layer: A Comprehensive Exploration of Additive Manufacturing in the Era of Industry 4.0

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Abstract: In the era of Industry 4.0, 3D printing, or additive manufacturing (AM), has revolutionized product design and manufacturing across various sectors. This review explores the evolution of 3D printing technology and its impact on industrial innovation, highlighting advancements in aeronautics, the automotive industry, and biomedicine. Various AM processes, such as binder jetting, direct energy deposition, and powder bed fusion, and materials like metals, polymers, ceramics, and composites, are discussed. Innovations like high-speed sintering, continuous liquid interface production, and bioprinting demonstrate ongoing advancements. The potential of 3D printing in personalized medical applications is emphasized due to its flexibility in geometry and materials. Despite progress, challenges like standardization, material quality, recycling, sustainability, and economic feasibility hinder widespread adoption. Overcoming these challenges is crucial for optimizing 3D printing technologies, ensuring high-quality, efficient, and affordable production. The review also addresses the future prospects of 4D and 5D printing technologies and their potential applications in various industries. This overview underscores 3D printing's role in shaping the future of manufacturing within the context of Industry 5.0, emphasizing human–machine collaboration and sustainability.

Keywords: Industry 4.0; 3D printing; additive manufacturing; Industry 5.0; innovations; challenges



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1. Introduction

In the era of Industry 4.0, driven by rapid technological progress, 3D printing has become a key player, transforming product design, manufacturing, and application across different industrial sectors. The article titled “Printing the Future Layer by Layer: A Comprehensive Exploration of 3D Printing in the Era of Industry 4.0” delves into the development of 3D printing technology and its impact on industrial innovation from a scientific and technical standpoint.

During the development of additive manufacturing technology, there have been numerous different terms in use, such as: additive fabrication (AF), additive processes (APs), additive techniques (ATs), additive layer manufacturing (ALF), layer manufacturing (LM), solid freeform fabrication (SFF), freeform fabrication (FF), rapid prototyping (RP), and rapid manufacturing (RM) [1–3].

Recent research advances have highlighted the significant contributions of 3D printing in industrial sectors such as aeronautics, the automotive industry, and biomedicine, with significant growth in the medical field transforming traditional ways of manufacturing into more flexible and efficient methods [4]. The technology, originally perceived as a prototype manufacturing alternative, has evolved considerably, becoming a revolutionary paradigm for custom manufacturing and small- and medium-scale production [5–7].

In a world characterized by rapid change and continuous innovation, 3D printing is distinguished by its ability to turn complex designs into reality, offering flexibility in geometry and materials. The advantages of these technologies also extend to the medical field, where personalization of products such as implants and medical devices is becoming a tangible reality [8,9]. Beyond its medical applications, this adaptable technology is utilized to manufacture a broad spectrum of goods in virtually every industry imaginable, from creating fashion accessories and food items to crafting toys, intricate airplane parts, and even entire rockets and their engines [8,10].

However, a close look at the current scientific literature reveals the technological and economic challenges still present to a widespread implementation of 3D printing in industry [4,7]. Despite notable progress, there is uncertainty regarding standardization, the quality of emerging materials, and technology issues. Important factors to consider involve recycling, minimizing risks, ensuring sustainability and manufacturability, choosing the right materials, ensuring durability, simplifying assembly, managing costs, and maintaining the products, among other aspects. The biggest challenge for 3D printing technologies is making high-quality parts that meet the needed shape, work well, and are affordable, all while keeping the 3D printing system working smoothly and efficiently [4,11].

This study attempts to provide an in-depth study of the current status of 3D printing and its potential to change manufacturing in the Industry 5.0 era by extensively examining the most recent advancements in 3D printing technology and emphasizing significant scientific breakthroughs. In order to increase productivity, Industry 5.0 places a strong emphasis on reintegrating people into the manufacturing process and encouraging human-machine cooperation. In the production process, this method aims to integrate human intelligence and creativity with the abilities of intelligent systems [12]. By adding new features, Industry 5.0 seeks to improve the interconnectivity of network sensor data, serving as an upgraded version of Industry 4.0 [13,14].

Section 2 of this paper addresses the basic principles of additive manufacturing, detailing the various processes and techniques involved. Section 3 provides a thorough examination of the current state of 3D printing within Industry 4.0, highlighting the latest developments and applications of this technology. Section 4 offers a critical analysis of the advantages and limitations of 3D printing, presenting a balanced view of its strengths and challenges.

Section 5 explores innovations in additive manufacturing, showcasing recent advancements and breakthroughs that have advanced the field. The focus of this section is on novel materials and developing technologies that are enhancing 3D printing's potential. Section 6 discusses the current challenges faced by additive manufacturing technologies and outlines prospects for the industry. It covers technical and operational difficulties as well as broader issues and anticipates future advancements and research directions. This section also considers the crucial role of 3D printing in the future of manufacturing. The paper's main conclusions are finally outlined in Section 7, which also addresses the implications for manufacturing's future.

2. The Basics of Additive Manufacturing

2.1. Overview of Additive Manufacturing Processes

This subsection provides a review of the basic principles of additive manufacturing, exploring the key concepts, methodologies, and overall framework that underpin this process.

In the International Standard Organization/American Society for Testing and Materials Standards (ISO/ASTM 52900:2021), additive manufacturing is defined as the “process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies” [1]. This method allows for the making of complex-shaped parts, cutting down on the need for a lot of extra finishing work and greatly lowering the amount of material that goes to waste [4,15].

The way 3D printing techniques are categorized can vary in different texts, which can cause confusion and make it difficult to grasp the overall picture of additive manufacturing (AM) [16]. Nonetheless, the classification most commonly accepted comes from the ISO/ASTM 52900:2021 standard, which outlines seven primary types of additive manufacturing/three-dimensional printing (AM/3DP) technologies: (1) binder jetting (BJT); (2) direct energy deposition (DED); (3) material extrusion (MEX); (4) material jetting (MJT); (5) powder bed fusion (PBF); (6) sheet lamination (SHL); and (7) vat photopolymerization (VPP) [1].

The ASTM definition for each process is defined in Table 1.

Table 1. Definitions of 3DP technologies according to ASTM 52900:2021.

No	Process	Definition According to ASTM 52900:2021
1.	Binder jetting (BJT)	Process in which a liquid bonding agent is selectively deposited to join powder materials.
2.	Direct energy deposition (DED)	Process in which focused thermal energy is used to fuse materials by melting as they are being deposited.
3.	Material extrusion (MEX)	Process in which material is selectively dispensed through a nozzle or orifice.
4.	Material jetting (MJT)	Process in which droplets of feedstock material are selectively deposited.
5.	Powder bed fusion (PBF)	Process in which thermal energy selectively fuses regions of a powder bed.
6.	Sheet lamination (SHL)	Process in which sheets of material are bonded to form a part.
7.	Vat photopolymerization (VPP)	Process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization.

Debates over the superiority of machines or technologies are nonexistent as each is designed for specific applications. These days, 3D printing technologies are utilized to create a wide range of products, going beyond prototyping [1].

2.2. Materials Used in the Printing Processes

3D printing (3DP) emerges as one of the most creative approaches to produce a broad spectrum of components across various industries, including automotive, aerospace, medical, construction, electronics, and food industries. To fabricate fully functional objects using 3DP technology, the process involves utilizing high-quality materials from several categories, such as metals, ceramics, composites, polymers, and combinations thereof in hybrid forms.

This section classifies the printing materials used in both extrusion-based 3D printing (E3DP) and selective laser sintering (SLS) into three main categories. The first category encompasses neat polymers, which refer to virgin or recycled polymers printed without additional materials. These often require fine-tuning of processing and printing parameters due to their high melting points and viscoelastic properties, but they offer excellent thermal stability and mechanical strength.

The second category, blends, consists of combinations of polymers or polymers with additives. Blends can overcome limitations like anisotropic properties found in neat polymers, offering enhanced dimensional stability, thermal resilience, and unique mechanical characteristics. They also enable the integration of recycled materials, contributing to sustainability. Additives such as thermoplastic elastomers (e.g., TPU) and compatibilizers (e.g., maleic anhydride grafts) further improve miscibility and tailor performance, diversifying the applications for these materials.

The final category is composites, which are composed of a distributive phase within a continuous polymer matrix. By incorporating fibers or fillers, composites yield superior mechanical properties, making them ideal for structural and load-bearing applications in various industries [17].

Additive manufacturing (AM) encompasses not only core materials, which serve as the primary substances for crafting objects, but also support materials. Core materials, often referred to as build or primary materials, form the essential part of the printed item and shape its fundamental traits such as strength, durability, and function. For example, in fused filament fabrication (FFF), the core material typically involves a thermoplastic filament that is melted and laid down layer by layer to create the object; however, nowadays FFF can print not only thermoplastic filaments but also metal composites and ceramic composites. In powder bed fusion (PBF), the core materials are metal or polymer powders that are selectively bonded using heat or a laser. Support materials, on the other hand, are used temporarily to provide stability and prevent warping during the printing of designs with overhangs or complex details. These assisting materials can differ from the core materials in properties, being water-soluble or easily breakable, to facilitate their removal after printing. The selection of these materials varies based on the additive manufacturing method and the core material in use. For instance, in material jetting (MJT), supports are often made from a material that is easy to manually remove or dissolve. When using selective laser sintering (SLS), the powder that surrounds the object acts as a support by nature.

In the context of fused filament fabrication (FFF), the process of creating filament from recycled PET serves as a prime example of how base materials are melted, extruded, and transformed into thin threads, which are then used to construct objects layer by layer in 3D printing.

The production of filament for 3D printing via the fused filament fabrication (FFF) method involves the precise melting, extrusion, and formation of base materials, such as polymers, into thin threads suitable for additive manufacturing [18]. In the case of recycled PET (rPET), the integration of this material into the material extrusion (MEX) process offers a sustainable and efficient method for producing 3D-printing filament from discarded PET bottles. PET's high recyclability makes it ideal for upcycling into complex, functional parts [19,20]. The filament creation process begins with extruding PET flakes into pellets, which are subsequently extruded into filament. A crucial aspect of this process is the thorough drying of the material before extrusion, as moisture can lead to degradation and adversely affect the quality of the filament. rPET, in particular, exhibits higher tensile strength compared to commercially available PETG, making it a robust alternative despite its moisture sensitivity [21].

For the FFF method, PET can be processed using either single-screw or twin-screw extruders. While twin-screw extruders are more effective for material mixing, they are less consistent in maintaining tightly controlled filament output. In contrast, single-screw extruders require precise temperature regulation (typically between 250 °C and 270 °C) to prevent PET degradation [21].

The production of filament from rPET involves two primary steps: first, recycled PET flakes are processed into pellets using a twin-screw extruder, and then these pellets serve as feedstock for a single-screw extruder to produce the final filament. Once the filament is extruded, it is cooled, cut, and prepared for use in 3D printing. Recycled PET offers numerous advantages, including excellent compatibility with virgin PET and superior mechanical properties, making it a viable and sustainable option for filament production in the MEX process [22].

Support materials in 3D printing are crucial for providing temporary stability during the printing process, particularly for designs with overhangs or complex geometries. Acting as scaffolding, they prevent warping and distortion during the layer-by-layer deposition of filament. In some processes, like powder bed fusion (PBF), the surrounding unbonded powder naturally serves as support, while in fused filament fabrication (FFF), separate, easily removable support materials are used. However, support material can often be minimized or avoided when using filaments reinforced with short fibers. For instance, in polypropylene (PP) and carbon fiber composites, the inclusion of short fibers enhances the rigidity and mechanical properties of the printed parts, reducing the need for external support. This reinforcement allows for better handling of overhangs and complex designs,

while also improving overall print quality. Additionally, the use of optimized filament-making processes further strengthens print integrity, offering a sustainable method by repurposing waste materials such as PP and carbon fibers [23].

It is essential to emphasize that the variety of materials utilized in additive manufacturing is continually expanding due to ongoing research and development, which makes it possible to introduce new materials with unique properties and applications.

3. Current Status of 3D Printing in Industry 4.0

3.1. Technological Evolution in the Context of Industry 4.0

Additive manufacturing, commonly referred to as 3D printing, is revolutionizing the manufacturing sector and playing a major role in the development of Industry 4.0. The combination of digital technologies, automation, and well-informed decision-making characterizes this new industrial era, building on the achievements of previous industrial revolutions. It incorporates cutting-edge technology including robots, data analysis, artificial intelligence (AI), and the Internet of Things (IoT) [14].

Within Industry 4.0, embedded systems merge hardware and software in industrial operations. 3D printing transforms these systems by enabling flexible design, quick prototyping, and cost-effective production of complex components, leading to more efficient and compact systems. Fast prototyping accelerates development, reducing time and cost to market. A key benefit of 3D printing is its ability to facilitate tailored, on-the-spot manufacturing, allowing for design adjustments to meet individual customer requirements without costly equipment changes. This reduces inventory needs, cuts storage expenses, and supports a sustainable supply chain [24].

In this Industry 4.0 landscape, 3D printing, or additive manufacturing, extends into 4D printing, introducing a temporal dimension to materials, allowing them to alter their shape or properties over time. This development increases the versatility and usefulness of 3D printing technologies in a number of fields, such as the aerospace, dental, regenerative medicine, and automotive industries, where it can be difficult to create complicated geometries and parts using conventional manufacturing techniques. 4D printing introduces exciting possibilities in new industries by using materials that can evolve and transform, offering considerable benefits [25].

In the future, 3D printing is poised to become a key component in the manufacturing landscape of Industry 4.0. Combining 3D printing with technologies such as AI, IoT, and robotics will drive further innovations in embedded systems. Merging 3D printing with digital twin technology enables immediate adjustments and feedback throughout the design and manufacturing stages, enhancing efficiency and minimizing waste. Furthermore, the incorporation of cutting-edge materials in 3D printing, like conductive substances and smart materials equipped with sensors, offers the potential to develop embedded systems that are more advanced and capable of self-diagnosis and self-repair [24].

In composite manufacturing, 4D printing interacts with Industry 4.0 technologies like AI and IoT, significantly improving adaptability, precision, and efficiency. Similar to its application in 3D printing, AI in 4D printing is used to develop generative designs, model and predict robotic arm movements, and ensure the quality control of printed elements [26]. AI algorithms analyze real-time data to optimize the printing process, allowing materials to adjust their shape or properties over time. Meanwhile, IoT enables connectivity between systems, where 4D-printed components with embedded sensors can monitor their own performance, communicate their status, and automatically adapt to external conditions.

In recent years, cloud-based 3D and 4D printing systems, powered by AI, have further advanced the manufacturing process by optimizing productivity, facilitating knowledge transfer, enhancing collaboration, and supporting universal software development. These AI-driven systems streamline printing operations, allowing for real-time adjustments and improving the management of complex manufacturing tasks [27]. By integrating AI and IoT, 4D printing not only enables the production of more intelligent, adaptive, and self-healing

materials but also reduces waste and enhances overall production efficiency, aligning with the goals of Industry 4.0.

The most straightforward approach to achieving 4D printing is by 3D-printing a single smart material, a method that has recently attracted considerable interest from material scientists. The most commonly utilized smart materials for shape-shifting are shape memory polymers (SMPs) and liquid crystal elastomers (LCEs). Consequently, 4D printing can be realized by printing a single SMP for one-way actuation or an LCE for two-way reversible actuation [28].

4D printing, achieved by 3D-printing smart materials like shape memory polymers (SMPs) and liquid crystal elastomers (LCEs), enables objects to change shape in response to external stimuli. SMPs are widely used for one-way actuation, while LCEs allow for two-way reversible actuation. The process typically involves programming SMPs at a specific temperature, fixing the shape, and then applying heat or light to recover the original form. Recent innovations in 3D printing techniques, such as UV-assisted direct ink writing (DIW) and magnetic field actuation, have expanded the applications of SMPs in biomedicine, flexible electronics, and soft robotics.

SMPs can also facilitate multiple or automatic shape-shifting without the need for reprogramming. Using materials like Gray 60, researchers have demonstrated sequential shape recovery by programming two temporary shapes at different temperatures. Additionally, heat-shrinkable properties allow for complex shape transformations, with examples like foldable lattices and self-folding origami structures. These developments underscore the versatility of SMPs in 4D printing for creating dynamic structures.

LCEs are another key material for 4D printing, offering reversible shape changes in response to heat. Integrating LCE films onto 3D-printed objects with conductive wires has enabled thermal actuation in devices like crawling robots. Recent advancements have focused on directly printing LCEs using high shear forces to align their molecular structures, leading to rapid and programmable shape transformations. Incorporating nanoparticles like gold and carbon nanotubes enhances LCE functionality, further expanding their use in 4D printing.

Multimaterial 4D printing allows for the creation of structures with locally controlled properties, generating eigenstrains for shape changes in response to environmental stimuli. Systems like SMP composites and multimaterial SMPs enable multiple shape-shifting and complex designs. Techniques such as bilayer SMP composites and self-folding electronics have further advanced this field, with applications ranging from aerospace to biomedicine. These innovations highlight the potential of multimaterial 4D printing for developing complex, responsive structures.

4D printing has progressed from focusing solely on shape-shifting to also including changes in functional properties. This advancement allows for the integration of shape transformation with functional devices like electronics, while properties such as optics and conductivity can evolve alongside these changes. Time-dependent functions like tissue maturation, degradability, self-healing, and color shifting are now considered part of 4D printing. Recent developments in 4D bioprinting and self-healing materials highlight the expanding potential of multifunctional 4D printing [28].

3.2. Adoption Rates and Trends

While Industry 4.0 offers significant industrial growth, it also poses challenges like increased resource consumption, environmental issues, and higher energy demands. The massive amounts of data produced by interconnected machines complicate data analysis, particularly in quality management, but are valuable for tracking product quality and optimizing supply chains [29]. In Industry 4.0, adjusting to digitalization is a significant challenge. By employing robots to complete repetitive tasks, Industry 5.0, in contrast, emphasizes human-centric approaches that combine human creativity with machine precision to increase productivity and performance and improve product quality [13,30,31].

As a reaction to Industry 4.0's shortcomings, Industry 5.0 has arisen. Industry 4.0 has not been able to meet the European goals for 2030, leading to a dominance of technology.

Industry 5.0 aims to prepare for future disruptions, like the COVID-19 pandemic, with a strong emphasis on sustainability. Unlike Industry 4.0, which has a partial focus on sustainability, Industry 5.0 centers around approaches that prioritize human values and needs [14,32,33].

Industry 5.0 addresses key challenges of Industry 4.0 by balancing technology with human involvement, particularly in supply chain management and automation. While Industry 4.0 focused on mass customization through technology, Industry 5.0 enhances this with advanced AI, cobots, and a focus on sustainability. It also improves data security by integrating blockchain and smart contracts, addressing vulnerabilities in IoT systems [34–36]. Additionally, Industry 5.0 emphasizes human-centricity, combining human creativity with machine precision, allowing cobots to handle repetitive tasks while workers focus on more valuable and safer responsibilities [13,37].

Industry 4.0, while advancing technology with innovations like 5G, robotics, cloud storage, 4D printing, and holography, presents certain limitations that Industry 5.0 addresses directly. For instance, the integration of 5G technology in Industry 4.0 has enhanced remote communication and real-time data processing, especially in healthcare through telemedicine. However, Industry 5.0 advances this by improving AI and IoT applications, allowing for even greater automation and human–machine collaboration [38]. Similarly, robotics in Industry 4.0 have been pivotal in tasks like sample collection during COVID-19, but Industry 5.0 introduces more human-centric robots, or cobots, that work alongside humans to improve efficiency and safety in industries [39].

Moreover, 4D printing, an evolution of 3D printing, adds adaptability by allowing objects to self-assemble and self-repair in response to stimuli, reducing the reliance on external maintenance, a feature enhanced in Industry 5.0 through smarter, more sustainable manufacturing processes. Finally, Industry 5.0 also improves on the cloud storage and holography innovations of Industry 4.0 by integrating these technologies into more user-friendly and interactive systems, further enhancing data processing and real-time decision-making in manufacturing and healthcare settings [14].

To provide a comprehensive view of the research landscape, we chose to search for both “3D printing” and “additive manufacturing” in the publication data. While “3D printing” is commonly used in consumer and mainstream contexts, “additive manufacturing” represents the broader, more technical term encompassing a range of advanced industrial processes. By examining both terms, the diagram in Figure 1 captures the full scope of research trends in this evolving field, reflecting its widespread application across both public and industrial domains.

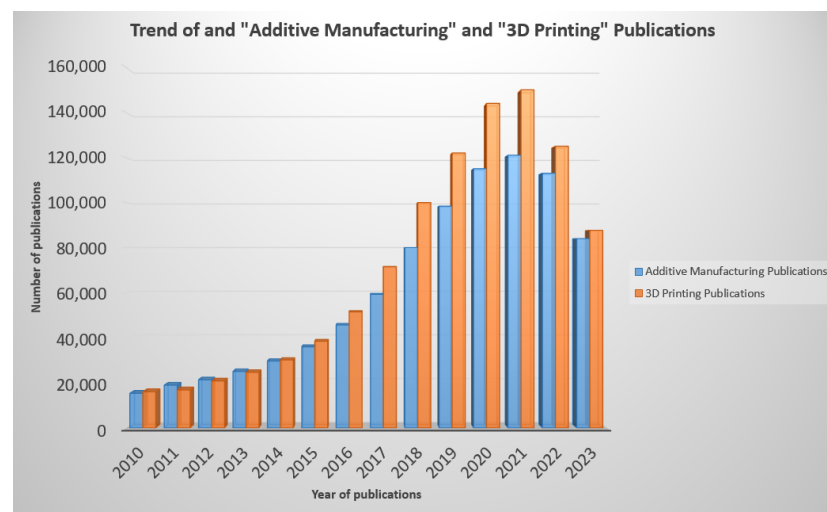


Figure 1. Trend of Additive Manufacturing and 3D Printing Publications (2010–2023). Adapted from reference [40].

The diagram illustrates the rising trend in publications for “additive manufacturing” and “3D printing” from 2010 to 2023. Both fields show significant growth in research interest over the years. Initially, “3D printing” had more publications, but from 2016 to 2019, “additive manufacturing” took the lead, reflecting its broader technical use. In recent years, “3D printing” has regained prominence, likely due to its recognition in mainstream applications. Despite a slight dip in 2022 and 2023, both terms continue to attract substantial research, underscoring their ongoing importance in industrial and academic contexts [40].

4. Advantages and Limitations

When comparing additive manufacturing technologies to traditional manufacturing processes, there are benefits and drawbacks. These are presented in Table 2:

Table 2. Advantages and limitations of 3D printing. Adapted from references [14,41–44].

AM Advantages	
✓	Customization benefits: A major strength of 3D printing lies in its capacity for customization, particularly valuable in healthcare for tailored prosthetics and implants for patients.
✓	Cost and time savings: 3D printing, particularly in the creation of molds for injection molding, offers a quicker and more economical solution compared to traditional production techniques, making it ideal for small-scale outputs and prototyping.
✓	Quick production: The technology behind 3D printing ensures a rapid production process, eliminating conventional steps like molding and casting, leading to faster completion times.
✓	Environmental advantages: 3D printing contributes to sustainability by minimizing material waste, as it uses only the necessary amount of material for each item. Additionally, by enabling local, on-demand production and reducing the transportation of finished products, carbon emissions can be decreased.
✓	Innovation and progress: Numerous industries, including the aerospace, automotive, fashion, and food sectors, might see a transformation thanks to 3D printing. This makes it possible to test and prototype new ideas quickly, which might result in the development of new products and improved manufacturing procedures.
✓	Accessibility: The growing availability and affordability of 3D printing technology make it a valuable tool for individuals and small enterprises.
✓	Medical Applications: 3D printing has brought significant advancements in medical fields, offering custom-made implants, prosthetics, and opportunities in tissue engineering.
✓	Supply Chain Efficiency: The capability for on-demand manufacturing with 3D printing reduces the reliance on large inventories, cutting down on storage expenses and leading to more streamlined supply management.
AM Disadvantages	
–	Material variety: When it comes to materials, the selection for 3D printing is more constrained than for traditional production. Although the selection is expanding, it has not yet reached the diversity found in conventional methods.
–	Production time: Printing complex or large items with 3D technology can be slow, making it less suitable for mass production.
–	Strengths and longevity: Items made through 3D printing might not be as robust or long-lasting as those produced traditionally, posing a challenge for parts that need to endure stress or impact.
–	Surface finish: The finish on 3D-printed items may not be as refined as that achieved through traditional methods and might need extra steps to improve.
–	Build size constraints: The dimensions of the 3D printer’s printing area can restrict the maximum size of the objects it can produce at once.
–	Layer visibility: The layer-by-layer construction of 3D-printed objects often results in visible lines, which can impact the item’s look and structural integrity.
–	Equipment costs: Although, more-accessible, top-tier industrial 3D printers come with a high price tag.
–	Legal issue: The ease of replicating objects with 3D printing brings up concerns regarding intellectual property and copyright laws.
–	Health risks: The printing process might release harmful particles, posing risks to those operating the machine, especially when using certain materials.
–	Expertise and equipment needs: Operating 3D printers and handling the outcomes require specialized skills and equipment, which can be costly to acquire and maintain.
–	Post-processing requirements: Printed items often need additional work like sanding, painting, or curing to meet specific standards, depending on their use.

Reducing the limitations of 3D printing can be achieved by enhancing the strength and mechanical properties of the printed parts, particularly through the incorporation of short and continuous fibers into the filament. According to recent studies, such as the one conducted on continuous carbon fiber (CF)-reinforced Onyx composites, the addition

of continuous fibers significantly enhances tensile strength and flexural rigidity of the materials. For instance, in the case of Onyx composites, adding continuous carbon fibers led to a 1344% increase in tensile strength compared to the neat material, and a 316.6% increase in flexural strength. The fibers improve the material's ability to resist micro-crack propagation and fiber pull-out, which are common issues in standard 3D-printed parts [45].

Furthermore, short fibers such as glass fibers (GFs) have been shown to enhance the impact resistance and overall mechanical performance of 3D-printed composites. The addition of these reinforcements within the polymer matrix helps overcome one of the major challenges of 3D printing, which is the relatively lower strength and stiffness of printed components compared to those produced by traditional manufacturing methods. This makes fiber-reinforced 3D-printed parts more suitable for high-performance applications like aerospace, automotive, and even drone manufacturing [45].

5. Applications Across Diverse Sectors

5.1. Recent Innovations

In terms of technology, materials, and applications, additive manufacturing has seen tremendous advancements in the last several years. This section explores the most recent advancements in AM technology that could transform and expand the AM industry (see Figure 2).

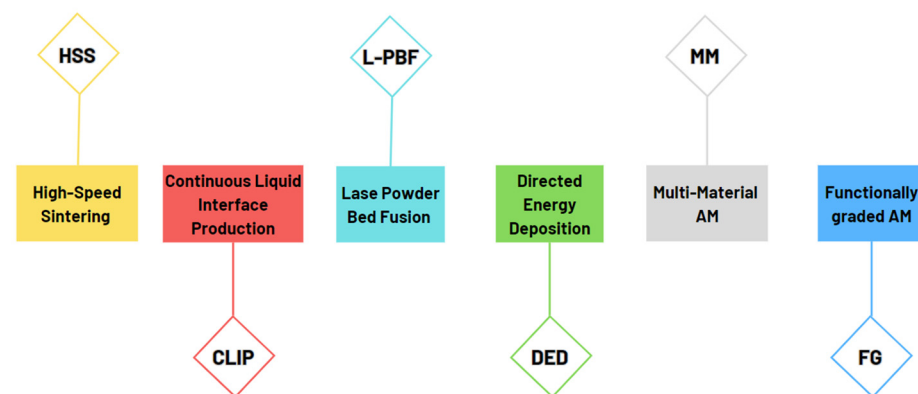


Figure 2. Recent inventions in AM processes. Adapted from reference [46].

- *High-speed sintering (HSS)*, a creation of Loughborough University, represents an innovative approach within the powder bed fusion (PBF) category, employing infrared heating to specifically sinter polymer powders. This method allows for quicker production rates and the possibility of mass-producing functional polymer parts. HSS is transforming 3D printing by making it feasible to produce complex, tailored components on a large scale affordably. Because of this, it is now a preferred method in many industries, including aerospace, the automotive industry, consumer goods, healthcare, and medicine [46–48];
- *Continuous liquid interface production (CLIP)* is a resin-based 3D printing method that expands on the ideas of SLA/DLP procedures. It produces quick printing and smooth surfaces by continually and smoothly converting liquid resin into solid objects by the use of light and oxygen [46,49];
- *Advancements in laser powder bed fusion (L-PBF)* for additive manufacture of metals place a strong emphasis on material innovation, process control, and monitoring. These developments are intended to improve part quality, decrease porosity, improve mechanical properties, and boost production efficiency. Examples of these developments include monitoring the melt pool, using optical tomography, scanning each layer as it is deposited, applying multi-laser processing, and introducing new materials [46,50];
- *Directed energy deposition (DED)* methods have developed to use both powder and wire as raw materials, broadening the range of materials to metals, ceramics, and

composites. This expansion increases the variety of designs that can be created and makes it easier to manufacture bigger parts. Additionally, integrating subtractive manufacturing with DED AM methods further enhances surface quality and dimensional accuracy, particularly for large components [46,51].

Improvements in additive manufacturing have led to techniques capable of printing structures with multiple materials or graded properties. These innovations enhance design flexibility and expand the range of applications for printed parts [46,52].

5.1.1. Multi-Material AM

Advancements in multi-material 3D printing technology have made it possible to deposit many materials simultaneously, resulting in the production of intricate objects with a variety of mechanical, electrical, and optical characteristics. This development finds applications in electronics, aircraft, and healthcare [53,54]. At the voxel level, additive manufacturing offers precise control of material composition and characteristics, providing unmatched complexity and functionality. MIT researchers have created a device that prints at a precision of 50 μm per voxel using up to eight different materials. This system uses tiny nozzles to deposit photopolymer resin drops, which are then hardened with ultraviolet light, allowing the creation of objects with varied hardness, clarity, color, and electrical conductivity in one session [55,56].

This capacity creates new opportunities in areas including electronics, Internet of Things (IoT), autonomous manufacturing, and space exploration. For instance, Nano Dimension's DragonFly system exemplifies successful multi-material additive manufacturing. This technology specializes in producing electronic devices, enabling the creation of electronic circuits and parts, like multi-layer circuit boards, by printing them layer by layer. With the DragonFly technology, complicated electrical designs, quick prototype creation, versatility in design, and the direct integration of electronic components into 3D-printed things are all made possible by printers that deposit both conductive and non-conductive inks [57]. It is utilized in research and development, aerospace, defense, and the automotive industry, showcasing the extensive applications and potential of multi-material 3D printing in high-tech electronics production [46,58].

Nano Dimension's DragonFly system supports printing with multiple materials by using various specialized inks, each designed for specific applications and the needs of different circuits [58]:

- *Conductive inks*: Conductive inks containing metallic particles like silver or copper are used for printing conductive traces and interconnects;
- *Dielectric and insulation inks*: Dielectric inks are used to form insulating layers that are essential for separating the parts of a circuit, whereas insulating inks offer the structural support and strength needed for the printed item;
- *Functional inks*: Functional inks, such as magnetic or optical variants, add specific functionalities like sensors or antennas.

This technology makes it possible to build complex electronic circuits with multiple layers and various functions, providing versatility in both design and operation tailored to the specific needs of the electronic device being created [46].

5.1.2. Beam-Based Metal AM

Because of its potential applications, beam-based metal additive manufacturing has attracted a lot of interest from a variety of sectors. However, achieving widespread adoption in industrial settings requires further development, prompting substantial investments in research and development by companies, research institutions, and universities [59]. The rise in patents related to beam-based metal additive manufacturing indicates increased activity in this field, with key players including multidisciplinary companies, AM machine producers, aerospace end users, universities, and research centers [60].

Several methods have emerged in beam-based additive manufacturing to construct structures using multiple materials or with gradually changing properties. One notable

technique involves using blended powders and advanced scanning to produce functionally, structurally, and compositionally graded structures, such as Damascus steel with unique properties [61]. Aerosint, founded in 2016, introduced “selective powder deposition” (SPD), a technology that accurately places multiple powders to form layers comprising two or more materials. Unlike blade recoaters or standard single-material rollers, Aerosint’s SPD is suitable for a range of AM processes, such as laser powder bed fusion (L-PBF), binder jetting, and pressure-assisted sintering.

Aerosint’s SPD technology significantly expands the possibilities of additive manufacturing by facilitating selective powder deposition. It makes it possible to construct intricate structures that combine several materials with unique properties all within the same layer. This innovative technique allows for the precise placement of different materials together, enabling the manufacture of parts combining properties like electrical conductivity, strength, flexibility, and corrosion resistance in a single piece [46].

5.1.3. Stereolithography and Microwave Sintering

A groundbreaking development in additive manufacturing merges stereolithography with microwave sintering, enabling the rapid fabrication of intricate objects using powdered materials. This approach significantly reduces processing time while ensuring precision, allowing for quick consolidation and densification of printed items. This invention revolutionizes the production of intricate and useful products by expanding the variety of materials that can be utilized in 3D printing [62].

Another notable advancement is continuous liquid interface production (CLIP), patented by Carbon3D in 2014. Unlike traditional stereolithography (SLA) and digital light processing (DLP), CLIP employs a continuous method to transform liquid resin into solid objects using light and oxygen. This method eliminates discrete printing steps and maintains a continuous liquid interface, enabling uninterrupted curing as the part is extracted from the resin. CLIP utilizes a digital projector and microcontrollers to optimize the printing process, resulting in a layer-less design and enhanced efficiency [46].

CLIP presents numerous advantages over conventional printing methods (see Table 3).

Table 3. Advantages of CLIP over traditional printing methods.

No	Advantage	Description
1.	Exceptional speed	CLIP prints are just as precise and smooth as DLP/SLA prints but can finish printing up to 100 times quicker.
2.	Superior surface finish	The lack of visible layers in CLIP prints improves their surface quality, making them comparable to parts made by injection molding.
3.	Exceptional properties	CLIP-printed parts are waterproof, have uniform properties in all directions, and are stronger than those printed with SLA/DLP.
4.	Versatility for prototyping and production	CLIP is appropriate for both creating functional prototypes and conducting entire production cycles.
5.	Structural integrity	CLIP can seamlessly incorporate different cellular structures within a single component to provide varied performance traits.
6.	Versatility	Printers using CLIP/DLS technology support a wide variety of materials, setting them apart from many other types of printers.

5.1.4. Bioprinting and Tissue Engineering

By altering conventional 3D printing methods, bioprinting creates complex biological structures using living cells, biomolecules, and biomaterials. Bioinks take the role of ink, while biodegradable supports take the place of paper. Bioprinting is currently only

compatible with a limited number of 3D printing techniques, including material extrusion (MEX), inkjet, and laser printing.

In order to create functioning tissues and organs for transplants or medication trials, tissue engineering has a great deal of promise with this cutting-edge manufacturing technique. Researchers at Rice University created a bio-additive manufacturing method that combines tissue engineering with bioprinting. They print tissue constructs with their own blood supply using a bioink made of stem cells, blood vessels, and hydrogel. These structures can develop into liver, cartilage, bone, and skin [46,63–65].

Bioprinting for tissue regeneration has made significant strides in replicating tissues like skin, bone, and cartilage using 3D printing techniques. Key advancements include 3D-printed skin, which shows promise for wound healing, burn treatment, and in vitro testing.

Researchers like Lee and Koch achieved high cell viability and survival rates by printing layered skin with keratinocytes and fibroblasts. Michael et al. successfully implanted bioprinted skin into mice, while Ng introduced a gelatin–chitosan hydrogel to improve printability and antimicrobial properties.

Cubo advanced the field by bioprinting human bilayered skin that mimicked the structure and function of human skin. Kim's innovative strategy combined extrusion and inkjet bioprinting for 3D skin models, creating stable dermal and epidermal layers. Xiong developed gelatin-sulfonated silk scaffolds that enhanced skin regeneration and cell proliferation in animal models, demonstrating potential for clinical use.

Bone bioprinting has emerged as a viable alternative to traditional bone grafting methods, addressing limitations such as graft availability, immunogenicity, and risk of disease transmission. Through 3D printing techniques, researchers have developed scaffolds that facilitate enhanced bone regeneration and promote cellular differentiation.

For instance, Lee et al. incorporated bone morphogenetic protein-2 (BMP-2) into 3D-printed poly (DL-lactic-co-glycolic acid) (PLGA) scaffolds, resulting in successful bone regeneration in rat models. Tarafder et al. fabricated mechanically robust tricalcium phosphate (TCP) scaffolds, further enhancing their osteogenic properties through the addition of strontium and magnesium, which significantly improved osteogenesis and bone formation. Similarly, Jensen et al. created polycaprolactone (PCL) scaffolds with nano-structured pores, demonstrating effective osteointegration in animal studies.

The application of 3D printing in bone tissue engineering continues to evolve, with the development of biocompatible materials such as collagen–calcium phosphate scaffolds. Moreover, the use of thermoplastics and ceramics, due to their suitability for the load-bearing and calcified nature of bone, underscores the potential of 3D printing to advance bone tissue regeneration and repair [66].

Challenges in tissue engineering with scaffold-based methods include achieving uniform cell distribution, enhancing vascularization, and improving cell attachment to scaffold materials. Addressing these issues requires incorporating living cells, bioactive molecules, and biomaterials into three-dimensional scaffolds [67]. The significant expansion of 3D bioprinting is driven by its application in medical fields such as the cosmetic and pharmaceutical industries. This expansion is fueled by the critical need for organ transplants, especially given the limited availability of organs and the growing demand from an aging global population [46,68].

5.1.5. Two-Photon Polymerization

In the world of additive manufacturing, two-photon polymerization (TPP) is used for a variety of purposes. It allows for the crafting of complex microstructures found in microelectronics, such as photonic crystals and microelectromechanical systems (MEMS), which are crucial for small devices and sensors. Furthermore, TPP is employed in optics to create top-notch micro-optical components, such as lenses and waveguides. These components offer meticulous management of light passage, improving systems used in optical communication and imaging.

TPP plays a vital role in tissue engineering by creating intricate scaffolds for cell growth and organization in regenerative medicine. Additionally, it enables precise fluid manipulation in microfluidics by producing microchannels, valves, and pumps. Its versatility extends to various fields, especially those requiring intricate microstructures and nanostructures for advanced applications [46,69].

5.1.6. Hybrid Technologies

Hybrid additive manufacturing started by mixing traditional manufacturing with AM to fix their separate issues. This new method is great for making complex parts of medium to large sizes very accurately and efficiently. Recent trends, shown in Figure 3, indicate a growing adoption of hybrid AM practices, with notable advancements in steel-based materials through powder bed fusion (PBF) and directed energy deposition (DED) techniques [70]. Moreover, combining directed energy deposition (DED) methods with standard CNC machining offers more versatility for uses in hybrid manufacturing, applying protective layers, and fixing parts.

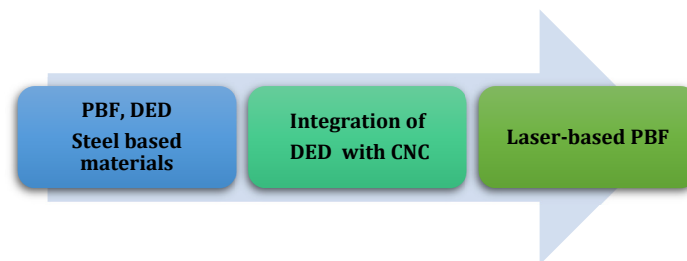


Figure 3. Hybrid AM processes.

Laser-based PBF further facilitates hybrid AM by enabling the conventional manufacturing of simple-shaped substrate components, while directly printing complex-shaped parts onto them, such as integrating conformal cooling into existing bulk molds [46].

Recent developments in hybrid additive manufacturing include merging various manufacturing processes to create 3D objects. A key strategy in hybrid AM involves blending additive practices with subtractive methods, like milling or machining. This method efficiently produces complex components by utilizing the strengths of both additive and subtractive technologies. Consequently, production speed is enhanced, and surface quality is refined [71].

The combination of binder jetting printing and standard heat-based finishing represents a form of hybrid manufacturing. In this approach, additive manufacturing is used to create initial models, and then traditional powder metallurgy techniques like sintering and liquid metal infiltration are applied to solidify and refine these models, achieving the necessary density and characteristics [72–76]. Merging AM with follow-up processing techniques is beneficial for producing functional components and composites, making it possible to craft parts with specific properties and detailed designs. Integrating binder jetting with conventional heat treatments facilitates the development of new materials and effective components. Continuous research is being conducted to improve this hybrid technique for broader application in various industrial fields [46,75,76].

5.2. Inventions in 3D Printing Technologies

In additive manufacturing, new technologies are changing many industries. AM enables the creation of intricate components in robotics, enhances the design and maintenance of complex systems through digital twins, augments the immersive experience in virtual reality (VR), and streamlines automation processes. These advancements demonstrate the enormous potential of new additive manufacturing technologies to impact robotics, automation, digital twins, and virtual reality (VR) in the future [46].

5.2.1. Robotics

In the robotics sector, additive manufacturing has contributed to significant innovations and advancements. Here are a few important inventions and advances made by applying AM to robotics [46]:

(1) *Multi-material and functionally graded robots*: AM allows for the creation of robots featuring complex designs and built-in parts from various materials. Robots can now possess a range of characteristics, such as different levels of hardness, built-in sensors, and moving parts, all in one piece. Li and colleagues used a 3D printing method called stereolithography to combine several materials with unique physical traits. This made it possible to build advanced tiny robots with specific magnetic properties for movement, offering the ability to craft detailed forms that can be customized [77].

(2) *Soft robotics*: Soft robotics utilizes flexible materials to design robots capable of safe interaction with humans and delicate object manipulation. AM techniques, such as selective deposition, allow for the fabrication of intricate structures in soft robots. These structures can include embedded features like pneumatic networks, sensors, and actuators. Howard's research concentrated on grippers utilizing granular jamming, which is difficult to model. He introduced an innovative "one-shot" method that employs multi-material 3D printing to create complete grippers, encompassing both the membranes and grains, in just one printing session [78].

(3) *Hybrid robots*: A new class of robots called soft and stiff hybrid robots has emerged as a result of advancements in hybrid robotics made possible by additive manufacturing. Integrating soft and hard elements, these robots manage to combine adaptability with structural support, making them capable of executing detailed tasks precisely and interacting safely with humans. Researchers at Harvard have succeeded in developing a hybrid robot that incorporates hard elements within a soft exterior, illustrating the capabilities of this approach [79].

(4) *Modular and reconfigurable robots*: Additive manufacturing enables the fabrication of modular components, facilitating the assembly and reconfiguration of robotic systems for swift customization to different tasks and environments. Scientists are using 3D printing to create hybrid robots with swappable parts, increasing their flexibility and allowing for easy adaptation to different tasks. Saab et al. developed GHEFT, a universal connecting system for modular robots that can change their shape, making it reliable, safe, even if parts fail, and able to connect well even when not perfectly aligned, which helps the robots rearrange themselves [80].

5.2.2. Digital Twins

Lately, progress in additive manufacturing has converged with digital twin technology, which digitally replicates physical assets or systems for immediate tracking and improvement. Matulis and colleagues presented a case study that focused on developing and training a digital twin of a robot arm. This involved training with artificial intelligence (AI) in a virtual environment and then applying what was learned to real-world settings [81]. This method combined a digital environment with a real one by using a 3D-printed copy of the virtual robot arm. The digital twin concept enhances AM processes by optimizing parameters, detecting defects, monitoring machine health, and managing big data. This emerging research area has the potential to unlock AM's full capabilities for demanding applications, necessitating further developments in modeling, databases, machine learning, equipment integration, and predictive algorithms [46,82–84].

5.2.3. Virtual Reality

3D printing (3DP) combined with virtual reality (VR) technology has revolutionized design, development, and user experiences. Recent advancements include the following [46]:

(1) *Haptic feedback devices*: Additive manufacturing has made it possible to create devices that provide haptic feedback, improving the experience of virtual reality by adding

touch sensations with parts made by 3D printing. Degraen et al. examined the potential of 3D-printed hair-like structures as flexible haptic components for virtual reality settings [85].

(2) *Customized VR accessories*: 3D printing allows for the creation of custom accessories for VR setups, including controllers, mounts, and ergonomic improvements. Lee et al. developed customized electronic glasses with multiple functions to improve interaction between users and machines in VR and digital health settings [86].

5.2.4. Automation

Additive manufacturing has transformed automation, making it possible to produce intricate shapes, tailor-made designs, and quick prototype development. Recent innovations include the following [46]:

(1) *Mobile 3DP platform*: Equipped with omnidirectional wheels, this mobile platform can move freely in both the x and y directions, supporting material experimentation and use across various sectors [87].

(2) *Grippers and robotic hands*: Custom grippers and robotic hands that are strong, light, and able to perform complex grasping and handling tasks may be produced thanks to additive manufacturing, expanding the potential for automation [78].

(3) *Jigs and fixtures*: In automated manufacturing processes, custom jigs and fixtures help with accurate positioning, alignment, and assembly activities, increasing efficiency and accuracy [46].

(4) *Electronics and sensors integration*: Additive manufacturing methods facilitate the embedding of electronic elements and sensors within printed components, leading to intelligent robotic systems equipped for immediate data gathering and enhanced automation functionality [46].

5.2.5. AI-Assisted AM

AI integration in additive manufacturing enhances design capabilities, optimizes part performance, and refines process monitoring [88]. MIT researchers developed a system combining AI and computer vision to improve 3D printing by making real-time adjustments to printing parameters, which enhances accuracy and allows seamless incorporation of new materials [89]. Machine learning also expedites design optimization, with Yao et al. using CNN to replace heavy parts with lightweight components, achieving results 20 times faster than conventional methods [90].

AI methods are set to transform the development of complex metal mixtures like high-entropy alloys (HEAs). Machine learning and data-based models quickly identify and refine alloy compositions, enabling the exploration of new alloys with outstanding features [46]. AI enhances the understanding of material structure–property relationships, identifying key components that improve performance. Overall, AI accelerates the development of new materials and advancements in materials science for aerospace, energy, and medical industries [46,91,92].

AI holds significant potential in advancing materials science, particularly for complex alloys like high-entropy alloys (HEAs), where traditional trial-and-error methods are impractical due to the vast number of possible compositions [93,94]. AI techniques use data-based models and machine learning to identify optimal mixtures and understand the relationship between structure and properties in HEAs, speeding up the discovery of new alloys with specific features [46,95].

In additive manufacturing, AI is promising for process monitoring and control. Scime and Beuth utilized neural networks to classify powder bed images into seven defect types during laser powder bed fusion (L-PBF) processes, enabling real-time problem correction and improved manufacturing quality [96]. AI leverages extensive data from materials databases and research papers to systematically develop complex alloys, accelerating the creation and refinement of HEAs with exceptional properties [46,95].

5.3. New Materials

In this chapter, we will explore the various materials used in 3D printing, with a particular focus on advanced and novel filaments. While the article primarily concentrates on these innovative filaments, it is essential to first consider some of the foundational materials that have been instrumental in the field. These include widely used engineering thermoplastics such as acrylonitrile butadiene styrene (ABS), polyamides (PAs), and polyesters, as well as high-performance polymers like polyetherketone (PEK) and polyetheretherketone (PEEK). By examining these materials, we can better understand their role in traditional and additive manufacturing processes, setting the stage for a deeper dive into the emerging filaments driving the evolution of 3D printing.

These new filaments play a crucial role in advancing additive manufacturing. They offer improved properties and functionalities beyond what traditional manufacturing methods can achieve. These filaments come in various compositions, including advanced polymers, composite materials, and specialty filaments with unique features like flexibility, conductivity, and heat resistance. By focusing on these innovative filaments, the article aims to delve into the forefront of materials science in 3D printing, appealing to readers interested in the latest developments and applications driving the evolution of additive manufacturing technology.

Based on a vast experience in plastic processing and profile extrusion, Fiberlogy stands out for the production of new filaments that have unique properties and parameters for FFF/FDM printers. A selection of these materials is presented in Table 4.

The development of new materials that now encompass a larger spectrum of materials that may be used to build top-notch components and goods has been a huge achievement in 3D printing. These include wood, paper, sandstone, as well as an extensive selection of plastics, metals, minerals, and organic substances.

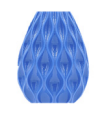
Acrylonitrile butadiene styrene (ABS) is a widely utilized engineering thermoplastic in 3D printing, renowned for its balanced properties of rigidity and lightweight design. Its versatility makes it suitable for various applications, including in biomedical, industrial, and electronics sectors. Extensive research has focused on optimizing printing parameters and enhancing the mechanical properties of ABS, particularly in fused filament fabrication (FFF). Techniques such as photoinduced graft polymerization have been employed to improve biocompatibility for medical uses, while dynamic chemical processing has facilitated the production of conductive components for automotive applications. In selective laser sintering (SLS), optimizing factors like laser power and scan speed is essential for achieving high-quality prints, particularly for non-structural automotive parts.

To further enhance ABS's performance, blending with thermoplastic elastomers such as TPU has emerged as an effective strategy. This approach not only improves viscoelastic properties but also allows for room-temperature printing, reducing energy consumption and production costs. Additionally, fiber-reinforced ABS composites, particularly those containing continuous carbon fibers (CFs), can be customized for load-bearing applications in automotive and aerospace industries, although higher CF content may present extrusion challenges. Sustainable alternatives, including natural fillers like rice straw and macadamia nut shells, have been investigated to create eco-friendly composites. While these natural fillers may reduce mechanical properties and increase water absorption, macadamia shells offer a cost-effective solution that supports circular economy initiatives.

Moreover, nanocomposites integrating fillers such as lignin-coated cellulose nanocrystals and organically modified montmorillonite provide benefits like reduced weight and increased stiffness. These materials can enhance tensile strength and thermal stability, although issues related to porosity and layer adhesion can affect overall performance. In SLS applications, ABS composites combined with thermoplastic starch have shown high thermal stability and reduced volatile organic compound (VOC) emissions, making them suitable for industrial and automotive use. However, conducting cost comparisons with existing materials is vital for evaluating their commercial viability and ensuring the economic feasibility and sustainability necessary for market adoption.

Polyamides (PAs) are formed through condensation reactions between acids and amines. While traditionally synthesized from petroleum, there is a growing trend toward producing polyamides from biological sources, such as bio-succinic acid derived from microorganisms. The diverse structures of polyamides—ranging from crystalline to amorphous—make them suitable for various applications, particularly in prosthetics, where toughness and durability are essential. Notable examples include PA 6,6, PA 6, PA 12, and PA 11. PA 6,6, the first commercialized polyamide, is commonly used in products like toothbrush bristles, while PA 11, derived from castor beans, is frequently used in additive manufacturing, especially through selective laser sintering (SLS).

Table 4. Latest 3D printing materials. Adapted from Fiberlogy.

Material	Picture	Characteristics
ESD		ESD Fiberlogy filament protects sensitive electronic components from electrostatic discharges, reducing the risk of damage.
CPE ANTIBAC		This innovative antibacterial filament boasts high mechanical strength, temperature resistance, and antimicrobial properties, making it ideal for various applications.
PCTG		PCTG filament, a variant of PET-G, offers enhanced impact strength, temperature resistance, and clarity without needing a heated chamber. Its low shrinkage ensures high dimensional stability, making it ideal for novice 3D printing enthusiasts.
CPE HT		CPE HT filament, a modern copolyester, stands out for its high mechanical and temperature resistance. Unlike its counterparts like PETG and PCTG filaments, it excels in withstanding high temperatures, reaching up to 110 °C. Additionally, it exhibits ongoing high resistance to chemicals and lipids.
FIBERFLEX		Flexible-filament 3D-printed items have the following characteristics: excellent resistance to chemicals and abrasions, low temperature resistance, and high impact resistance.
FIBERSATIN		FiberSatin filament offers a solution to the visible layer boundaries common in 3D printing, providing a high layer bondability and a semi-matte finish that gives models a refined appearance. It serves as an alternative to silk filaments, offering a distinctive matte finish with a touch of glossiness.
FIBERSILK		FiberSilk filament produces 3D printouts with a distinctive metallic shine, highlighting intricate details and enhancing aesthetic appeal. It has a low visibility of layer boundaries and high impact strength.
FIBERSMOOTH		FiberSmooth, a type of PVB filament, offers easy post-processing by smoothing it with isopropyl alcohol (IPA). This process partially dissolves the model, improving layer adhesion and hiding layer boundaries, leading to a glossy, porcelain-like surface.
FIBERWOOD		Available for over a decade, it combines wood particles with resin, creating beautiful prints that smell like real wood.

Engineering thermoplastic polyesters are synthesized through the condensation reaction of acids with alkanediols, with some precursors now sourced sustainably to improve their biocontent. Polybutylene terephthalate (PBT) is a notable example, recognized for its excellent electrical properties, chemical resistance, and high strength, particularly in automotive applications. Polyethylene terephthalate (PET) is another commonly used polyester, known for its thermal and chemical stability, making it suitable for automotive parts and packaging materials. Poly(trimethylene terephthalate) (PTT), made from 1,3-propanediol and terephthalic acid, exhibits high thermal stability and elastic recovery, with a renewable content of 37% from bio-sourced PDO.

Polyether-derived polymers, including polyetherketone (PEK), polyetheretherketone (PEEK), and polyetherimide (PEI), are known for their exceptional mechanical performance and thermal stability. PEI is an amorphous engineering thermoplastic with excellent dimensional stability and heat resistance, making it suitable for injection-molded products and 3D printing applications. PEK, the first polyketone produced, offers high impact resistance and flame retardancy, although its initial production faced environmental challenges. PEEK is increasingly favored in chemical processing, aerospace, and biomedical applications due to its high melting point (335 °C) and biocompatibility.

Polycarbonate (PC) is another important engineering thermoplastic derived from carbonic acid and polyhydroxy compounds. Known for its toughness, amorphous structure, and heat deflection temperature of 130 °C, PC also exhibits excellent resistance to scratches, ultraviolet radiation, and flame retardancy.

The blending of engineering thermoplastics creates materials with enhanced mechanical properties and thermal stability. These blends allow for the development of diverse feedstock options suitable for a wide range of applications across medical, automotive, and consumer product sectors. Compatibilizing agents are often used to improve the compatibility of immiscible polymers, which is vital for maintaining mechanical performance. The blending strategies established in injection molding are now being adapted for additive manufacturing, facilitating the production of customized materials tailored to specific application needs.

Fibers and fillers are often added to composites to enhance properties, increase renewability, reduce costs, and improve mechanical performance. Additionally, hybrid materials combining polymers with metal powders show potential in both biomedical implants and the electronics industry [17].

Additive manufacturing (AM) of composites offers significant advantages by streamlining the fabrication process and increasing automation, similar to traditional composite layering techniques. One of the key strengths of AM lies in its ability to precisely position fibers, which enables greater design flexibility and optimization within individual layers of a composite structure. The process typically begins with a client's design file, followed by data verification and production planning, where parameters like layer thickness and laser power are selected. This ensures that the final AM product is customized to meet specific requirements.

AM without reinforcement involves the use of polymers, particularly thermoplastics, which behave uniquely during the printing process. These materials liquefy at high temperatures and solidify upon cooling. However, this process presents challenges such as shrinkage due to repeated heating and cooling cycles, and degradation risks at temperatures near the melting point. As a result, polymer-based AM materials are primarily suited for applications that require high strength, rigidity, and resistance to elevated temperatures.

AM with reinforcement focuses on ceramic matrix composites (CMCs) and metal matrix composites (MMCs), which are widely used in industries like aerospace, biomedicine, and electronics. These composites offer high wear resistance and perform well at elevated temperatures. Selective laser melting (SLM) has proven effective in producing composite parts with enhanced mechanical properties, including improved hardness, fracture toughness, and wear resistance. Additionally, SLM-fabricated composites have demonstrated

good biocompatibility, making them highly suitable for advanced applications in fields such as biomedical implants and high-performance electronics.

In conclusion, composites provide significant advantages in 3D printing for load-bearing applications across industries such as automotive and biomedicine. The addition of fibers and fillers improves sustainability, reduces costs, and enhances mechanical performance. AM technologies, particularly with ceramic and metal reinforcements, expand their potential for high-performance uses in sectors such as aerospace and medicine [97].

6. Current Challenges and Future Prospects

6.1. Technical and Operational Challenges

The performance of printed components in real-world situations will determine the effectiveness of additive manufacturing technology in larger applications within Industry 4.0. Additionally, the conversion of intricate designs into functional end-products is pivotal for its widespread adoption. Cost competitiveness throughout the entire lifecycle of printed objects is also critical.

Initially, AM was primarily used for creating functional prototypes, concept models, and visualization tools. However, it has evolved significantly. Today, AM encompasses not only factory tooling but also end-use products and spare parts. This expansion is driven by advancements in material technology and printer capabilities. While small-scale production currently dominates, there is a gradual shift toward integrating AM into the entire production process.

A recent report indicates that 63% of industries employ AM for prototyping, while 21% utilize it for manufacturing products that pose challenges for other manufacturing methods [42].

These statistics highlight a hesitation among industries to fully integrate emerging AM technology into their production processes. Consequently, several challenges must be addressed before AM can become a cornerstone of Industry 4.0 production [42]. In Figure 4, the opportunities and challenges faced by additive manufacturing are presented.



Figure 4. Challenges and opportunities of AM in Industry 4.0.

Challenges:

Technical challenges: Broader adoption of AM is hindered by material-related issues, including standardization, qualification, and limited availability. A database for material properties, along with solutions for recyclability and sustainability, is needed. Reliability and stability issues affect quality and surface finish consistency, requiring proper tools and methodologies to achieve desired results [42,98].

IT integration challenges: The largely manual AM process, from CAD design to file transfer, complicates integration into software solutions. Industry 4.0 emphasizes mass production and cost-saving measures, necessitating standardized integration methods.

Lack of standardization increases complexity and costs, despite some vendors offering APIs for direct printer connectivity [42].

Design challenges: Despite attempts to adopt new approaches, design engineers often apply traditional constraints to AM. AM revolutionizes design by emphasizing performance, but it lacks standardized design procedures, with each manufacturer offering different recommendations. The absence of a standardized framework for AM design poses hurdles for widespread adoption in Industry 4.0 [42,98].

Capability challenges: Transitioning to AM requires new skills in management and engineering, but a significant skill gap exists. Many graduates have limited understanding of AM capabilities, and skilled workers often lack familiarity with AM materials and design processes. Addressing this gap requires novel education initiatives to cultivate a skilled workforce adept in collaborative teamwork, modeling software, and scanning systems [42].

Financial challenges: Industrial AM systems and materials are expensive, posing challenges for large-scale production. Although costs have dropped compared to previous years, the expense remains significant. The pricing structure for AM is divided into phases with distinct cost elements differing from conventional manufacturing techniques [42,99].

Opportunities:

Mass customization: By removing the requirement for tooling and lowering the number of manufacturing steps, AM dramatically reduces production costs. It reduces the need for assembly by streamlining design iteration and prototyping and enabling the manufacturing of complex pieces in a single step. Additionally, it digitizes inventory and logistics processes, reducing expenses, and enhances customer interactions by allowing feature selection and real-time tracking of preferences [100,101].

Lightweighting: AM focuses on lightweighting through topology optimization and advanced simulation tools, enabling the creation of intricate shapes and features not possible with traditional methods. This improves the performance-to-weight ratio in industries such as the automotive, cycling, aerospace, and medical industries. AM's precision allows for complex inner shapes and lattices, saving materials and potentially enhancing part strength and heat management [100,101].

AM and IoT optimization: In Industry 4.0, IoT integration allows connected devices to process information and adapt operations, enhancing production quality. Quick wireless technologies like Bluetooth, WiFi, and 5G enable real-time system adaptation from design to end-user feedback. This process involves customers at every step, improving product development, reducing expenses and waste, and optimizing the supply chain [100,101].

Bionic and generative design opportunities: Additive manufacturing expands the possibilities for generative design by integrating design and production processes. This combined approach improves quality and reduces production time for essential structural components, such as joints that connect elements and transfer loads in structural systems. Using this methodology, generative design powered by machine learning algorithms can rapidly produce multiple optimized configurations of a component based on design objectives and cost constraints. Selected models undergo analysis for structural performance before being produced via 3D printing, ensuring precision and high product quality. Therefore, integrating generative design with 3D printing enables the creation of innovative and efficient solutions for complex structures.

6.2. Present Obstacles Faced by AM Technologies

Even with some hurdles, the outlook for future developments in additive manufacturing is bright. Ongoing research and development are working to broaden the types of materials that can be printed, making it possible to create parts that are more complex and useful. Increased industry adoption of AM is anticipated as a result of these growing capabilities, including consumer items, the automotive industry, aerospace, and healthcare.

Progress in printing with multiple materials and combining different printing methods will improve what AM can do, allowing for the making of items with various materials and uses. Combining AM with AI and robotics could lead to manufacturing processes that

are both automated and tailored to specific needs, transforming how things are made [102]. While issues like the variety of materials, the capacity for mass production, and the speed of making things still exist, continuous improvements in technology are setting additive manufacturing up to transform various sectors and open up new opportunities in both design and production [46,103].

Current challenges in AM technologies: However, despite its potential, AM technologies still face several notable obstacles. One key challenge is the limited variety of materials that can currently be used in the process. Although advancements are being made, many industries still struggle with the restricted range of compatible materials, particularly in comparison to traditional manufacturing methods [104]. Additionally, AM production speeds remain slower than those of conventional methods like injection molding or CNC machining, making it difficult to scale up for mass production [105].

Another significant hurdle is ensuring consistent quality, especially when it comes to the dimensional accuracy and surface finishing required by industries like aerospace and healthcare. The post-processing steps needed for surface refinement add complexity and cost to the AM process, further limiting its appeal. High costs associated with AM machines and materials also present a barrier to widespread adoption across industries [105,106].

Solutions and future research directions: To address these challenges, research is increasingly focusing on innovative approaches, such as multi-material printing and hybrid manufacturing processes. By integrating AM with traditional methods, like CNC machining, manufacturers can leverage the strengths of both techniques to improve precision and production efficiency. This combination has the potential to overcome limitations related to production speed and accuracy [104,107].

The development of new materials specifically designed for AM processes is another area receiving significant attention. Innovations in high-performance polymers, biomaterials, and conductive materials are expanding the range of applications for AM, allowing it to meet the needs of industries that require advanced material properties [104,107].

Artificial intelligence (AI) and machine learning are also being explored as potential solutions for optimizing AM processes. AI-driven algorithms can fine-tune design and manufacturing parameters, leading to more efficient production, improved quality control, and reduced material waste. Additionally, integrating robotics with AM could enable fully automated manufacturing systems, which would lower labor costs and facilitate mass customization [108].

Conclusions: While challenges such as limited material diversity, slow production speeds, and high costs persist, continuous improvements in technology are positioning AM to revolutionize various industries. Future research in areas like material development, hybrid manufacturing, multi-material printing, and AI integration will be crucial in overcoming these obstacles, paving the way for AM to unlock new opportunities in design and production.

6.2.1. Bioprinting

Bioprinting merges 3D printing with biology to craft living tissue and organs using bioink [109,110]. This process, made possible by specialized bioprinters, has enormous ramifications for drug testing [111], tissue engineering [112] and organ transplantation [113], changing regenerative medicine and healthcare. With precise cell and material placement [114], bioprinting holds potential for personalized medicine [115], better patient outcomes [116], and innovative therapies [117], driving scientific research forward.

Bioprinting is held back by several issues that prevent it from becoming widely used. These include maintaining the health and usefulness of printed tissues [118], the limited supply and complicated nature of the necessary biomaterials [119], the need to produce larger quantities, and ethical concerns that need to be addressed. Overcoming these obstacles is essential to unlock bioprinting's full potential in healthcare and regenerative medicine [120].

Despite all of this, the future of bioprinting is bright, poised to transform healthcare and regenerative medicine. Progress in this field could result in organs, tissues, and implants tailored to individual patients, potentially shortening the wait for transplants and enhancing patient recovery and results [121]. Bioprinting also enhances drug testing and personalized medicine through realistic organ models. Continued progress in biomaterials and techniques could enable printing of complex structures like blood vessels, addressing organ shortages and revolutionizing regenerative medicine [122–124].

Currently, there is increasing enthusiasm for developing highly durable, eco-friendly, biodegradable, and easily manufacturable products using various AM technologies. It is crucial to understand the environmental regulations associated with the utilization of bioprinting technologies for each manufacturing process [46,125,126].

This segment explores advanced additive manufacturing techniques known as 4D and 5D printing. 4D printing incorporates the dimension of time, enabling objects to transform and develop over time, while 5D printing combines complex movements and both additive and subtractive processes. These technologies create objects and materials that can change their form, traits, or capabilities in response to environmental changes [127,128]. By using intelligent materials and innovative designs, 4D/5D printing opens new opportunities in aerospace, healthcare, robotics, and consumer products. These advancements could revolutionize manufacturing with self-building structures, adaptable gadgets, programmable textiles, and smart systems, marking a new era of innovation [46].

Despite the promise of 4D/5D printing, several challenges must be addressed for widespread adoption. Key issues include developing and integrating smart materials that respond predictably to stimuli while maintaining structural integrity, as well as ensuring their availability and scalability [129]. Improvements are needed in design, manufacturing processes, and materials understanding to precisely manage shape changes [130]. Additionally, resolving complexity and cost issues is essential to enhance accessibility and affordability. Standardization and regulatory considerations are critical for ensuring safety, reliability, and compatibility across industries. In order to fully utilize 4D/5D printing as a revolutionary manufacturing technique, certain obstacles must be overcome [46,131–134].

The prospects of 4D/5D printing technologies are poised to revolutionize various industries and enable innovative applications. These developments may lead to the creation of complex things with environmental adaptability and customization capabilities [135]. Intelligent implants in healthcare might improve patient outcomes by adjusting to physiological changes. Shape-shifting structures in aircraft might improve fuel economy. The consumer products industry might see self-assembling products and programmable textiles, while robotics could benefit from smart systems that self-repair and adapt to new situations. Addressing material characteristics, process management, scalability, and cost through ongoing research and development is vital. With continued advancements, 4D/5D printing could transform industries, lead to new inventions, and create adaptive, responsive, and intelligent objects [46,136,137].

To fully capitalize on these innovative prospects, attention must now shift toward refining 4D printing technologies to ensure efficiency and sustainability in real-world applications.

The concept of 4D printing, initially introduced by Prof. Tibbits in 2013, incorporates smart materials into 3D-printed structures, allowing them to undergo controlled changes over time in response to environmental stimuli such as pH, temperature, or moisture. This dynamic evolution of shape, structure, or functionality sets 4D printing apart from conventional 3D printing. In tissue engineering, 4D bioprinting offers substantial advantages, particularly by enabling bio-structures to adapt their functional properties, a feature critical for applications such as bone tissue regeneration.

Hwangbo and colleagues applied 4D printing techniques to develop bone tissue scaffolds that replicate the hierarchically porous structure of bone, enhancing both osteogenesis and angiogenesis. By utilizing type I collagen and hydroxyapatite (HA), they created a biocompatible scaffold that supported bone tissue regeneration. Additionally, 4D-printed polylactide (PLA) scaffolds infused with hydroxyapatite demonstrated self-

fitting properties due to their shape-memory capabilities, furthering their applicability in tissue engineering.

In the context of spinal fusion, 4D-printed scaffolds have shown significant potential. A layered scaffold composed of type I collagen for flexibility and hydroxyapatite for bone stiffness was designed to match the curvature of the spine after hydration. This scaffold successfully supported the growth of bone marrow stem cells and the formation of a new bone matrix *in vitro*, and it promoted bone tissue formation *in vivo*, highlighting its potential as an effective approach for spinal fusion surgery.

Building on the advancements in 4D printing for bone tissue engineering, a key area of focus is the development of materials for constructing scaffolds that support bone regeneration. Hydroxyapatite (HA), known for its bioactivity, is often combined with polymers to enhance both mechanical strength and biological functionality. The following section explores the materials used in 3D and 4D printing of HA-based scaffolds, highlighting innovations in creating biocompatible and mechanically robust structures for tissue engineering.

Hydroxyapatite (HA) is a ceramic material recognized for its bioactivity, making it highly suitable for skeletal regeneration applications. However, due to its brittleness, HA is often combined with polymers to enhance its mechanical properties while maintaining bioactivity. These HA-based composites are extensively used in orthopedic and dental implants, promoting tissue growth through their excellent biocompatibility and osteoinductive properties.

Incorporating polymers such as hydrogels with HA creates composite scaffolds that closely mimic the extracellular matrix, providing a conducive environment for cell proliferation and drug delivery. These scaffolds demonstrate potential in bone tissue engineering due to their structural and mechanical improvements.

Natural polymers like collagen, chitosan, alginate, and hyaluronic acid have also been used in HA-based composites for bone regeneration. Collagen–HA composites enhance mechanical strength and promote osteoblast differentiation, while chitosan–HA scaffolds improve cell viability and osteogenic activity. Alginate–HA scaffolds, when crosslinked with calcium ions, show enhanced mechanical properties and are used in bone regeneration without adverse effects on liver or kidney functions.

Hyaluronic acid (HyA) plays a vital role in bone regeneration, particularly in craniofacial and dental applications. HyA-based scaffolds, especially when combined with nano-hydroxyapatite (nHA), promote cellular adhesion and proliferation, offering stability and biocompatibility in tissue engineering.

Ceramic materials like HA and tricalcium phosphate (TCP) are widely used in 3D-printed scaffolds due to their robust mechanical properties and ability to support cellular proliferation and bone formation. These materials are suitable for both load-bearing and non-load-bearing applications.

Poly (lactic-co-glycolic acid) (PLGA) combined with HA forms a composite scaffold that resembles human bone in structure and function, enhancing mechanical strength and supporting controlled drug release. Chitosan–HA composites are also widely used in bone tissue engineering for their biocompatibility and ability to promote osteoblast cell proliferation.

Polyethylene glycol (PEG) and polycaprolactone (PCL) combined with HA form biocompatible scaffolds that show promise in bone regeneration. Gelatin, derived from collagen, has been combined with HA to create scaffolds that support natural regenerative processes, offering significant potential in bone tissue engineering [138].

As 4D printing emerges as a key player in the manufacturing landscape, there is a growing emphasis on making it a robust and energy-efficient process. Groundbreaking applications such as wind turbine blades and smart solar concentrators showcase the transformative potential of 4D printing in real-world settings [139]. These advancements highlight the ability of 4D printing to revolutionize industries by creating smart, adaptive structures that respond to environmental stimuli, making it particularly relevant in the renewable energy sector.

In the context of large composite structure manufacturing, specifically for wind turbine blades, 4D printing, when combined with large-scale additive manufacturing (LSAM) processes, enables the creation of complex and massive components more efficiently than traditional methods. LSAM integrates multiple additive manufacturing techniques, such as fused deposition modeling (FDM), continuous fiber reinforcement (CFR), and stereolithography (SLA), which are tailored for creating intricate and large-scale wind turbine structures [140]. These processes allow for rapid production of blade cores, molds, and tail sections, while also improving strength and performance through the incorporation of advanced materials like carbon fiber. Additionally, 4D printing's ability to create adaptive materials that adjust to varying wind conditions can further optimize the performance of wind turbine blades, reducing maintenance needs and enhancing energy efficiency.

This convergence of adaptive materials and cutting-edge manufacturing processes offers new possibilities for wind turbine design, making 4D printing a key innovation in the future of sustainable energy. The integration of conductive polymers, for instance, enables structures to exhibit electrical conductivity in response to stimuli, enhancing both safety and operational efficiency by enabling self-monitoring capabilities [141].

6.2.2. Micro–Nano-Scale Fabrication

Micro–nano-scale fabrication involves creating and shaping materials and structures from a few micrometers to nanometers in size using additive manufacturing techniques. This interdisciplinary discipline combines biology, chemistry, physics, and engineering to create devices with exact control over their composition and size [142]. Key methods include lithography, etching, deposition, and self-assembly, enabling the creation of tiny systems with unique features and applications.

Micro–nano-scale fabrication is advancing science and technology by developing innovative devices at micro and nano levels, manipulating matter at its most fundamental scales [143].

This technology faces challenges in achieving precision, consistency, material integration, affordability, and scalability. Advances in lithography, nanomaterials, and precise instruments are needed, along with solutions for material compatibility and large-scale manufacturing consistency [144–146]. Overcoming these challenges will unlock the potential of micro–nano-scale fabrication in various fields [147,148].

Micro–nano-scale manufacturing has a bright future, with potential breakthroughs in electronics, photonics, medicine, and energy. This technology could lead to smaller, faster, and more efficient devices, transformative optical communication and quantum computing, personalized healthcare solutions, and advanced sustainable energy systems. Continuous advancements and interdisciplinary collaborations are essential to fully realize these potentials [149–152].

6.2.3. Additively Manufactured Electronics

Additively Manufactured Electronics (AME) is a developing field that blends 3D printing techniques with the making of electronics, allowing for the direct construction of working electronic devices and circuits through additive approaches [153,154]. By using conductive and non-conductive materials in the 3D printing process, AME makes it possible to create detailed 3D shapes while also adding electronic parts, connections [155], and circuits [156] at the same time. Benefits from this innovative method include customized designs, less material waste, and expedited production. Numerous industries, including consumer electronics, the automotive industry, healthcare, and aerospace, can benefit from it. As AME technology gets better, it could completely change how electronic devices are designed and made, leading to a future with flexible, connected, and intelligent electronics [157].

AME's widespread use is held back by several major challenges. Ensuring printed electronics are conductive, reliable, and high-performing, along with high-resolution printing of detailed parts and connections, is crucial. Additionally, it is important to mix different

materials, make large-scale production more affordable, and meet standards and certification requirements [42,158–160]. Solving these problems is key to fully realizing AME's capabilities and smoothly incorporating it into the making of electronics [161].

The future potential of Additive Manufacturing Electronics in electronics manufacturing is vast. As technology progresses, increased adoption of AME is expected across industries such as the automotive industry, defense, and consumer electronics [162]. AME speeds up time-to-market, lowers waste, and increases design flexibility by enabling quick prototyping and tailored manufacturing [163]. Flexible electronics for curved surfaces and multifunctional devices with enhanced performance are made possible by integration with 3D-printed structures. New advancements in the manufacturing and utilization of electronic devices will be fueled by AME applications that will be expanded by improvements in printable materials, high-detail printing capabilities, and production capacity [46].

6.2.4. Wire Arc Additive Manufacturing

Using electric arc welding, wire arc additive manufacturing (WAAM) is a high-tech process that builds 3D objects one layer at a time [164]. It provides benefits such as fast build-up rates [165], affordability [166], and the capacity to create large components [167]. The accurate placement of metal wire in WAAM allows for the making of intricate parts that have strong mechanical features. It is used in fields like aerospace, car making, shipping, and energy, changing how things are made by offering more design options, faster production times, and greener processes.

In order to maintain uniform layer creation, WAAM must overcome challenges with arc voltage, wire feed rate, and movement speed control [168]. Achieving consistent bead shapes on complex forms and angles is difficult. Managing residual stresses and distortion from thermal cycling and rapid solidification is crucial to prevent dimensional inaccuracies and structural issues. Ensuring material quality by addressing issues like holes, unwanted particles, and impurities is necessary to meet performance standards. Additional steps like cutting can complicate and increase costs. For consistent manufacturing across industries, effective control and monitoring systems, standardization, and certification are necessary [169].

As WAAM technology progresses, its use in sectors like aerospace, the automotive industry, and energy is expected to grow. WAAM is appropriate for structural components, tools, and repairs due to its capacity to create massive, robust, and reasonably priced parts. Future improvements will focus on better process control and automation for increased accuracy, addressing residual stress and warping, and expanding material options. Developments in multi-material deposition may result in components with different characteristics. Rapid prototyping and on-demand manufacturing find WAAM appealing because of its scalability and cost benefits, which minimize production delays and material waste [145,170,171].

6.3. Anticipated Advancements and Research Directions

One of the main factors influencing economic growth is the industrial sector. However, technological improvements and the rising complexity of products and their manufacturing processes have a significant effect on industrial companies and their employees.

Critics argue that Industry 4.0 places too much emphasis on new technologies and digital tools, prioritizing machinery over human workers. This critique gave rise to Industry 5.0, which highlights the critical role of employees in manufacturing processes. This emphasis on human involvement gained importance during the COVID-19 pandemic, highlighting the crucial role of workers in maintaining productivity and resilience in industrial operations [14,32].

Industry 4.0 has led to numerous technological advancements, such as artificial intelligence (AI), cybersecurity, blockchain, additive manufacturing (AM), cyber-physical systems (CPSs), augmented reality (AR), and more, as indicated in Figure 5.

Industry 4.0 reduces the need for human decision-making by merging computers, materials, and artificial intelligence to handle issues like demand fluctuations and market volatility [14,172,173]. It aims to transform traditional machines into self-learning entities for enhanced performance and management. With digital traceability, the Internet of Things (IoT) prevents food fraud and promotes efficiency by enabling cyber-physical communication among networked devices [174].

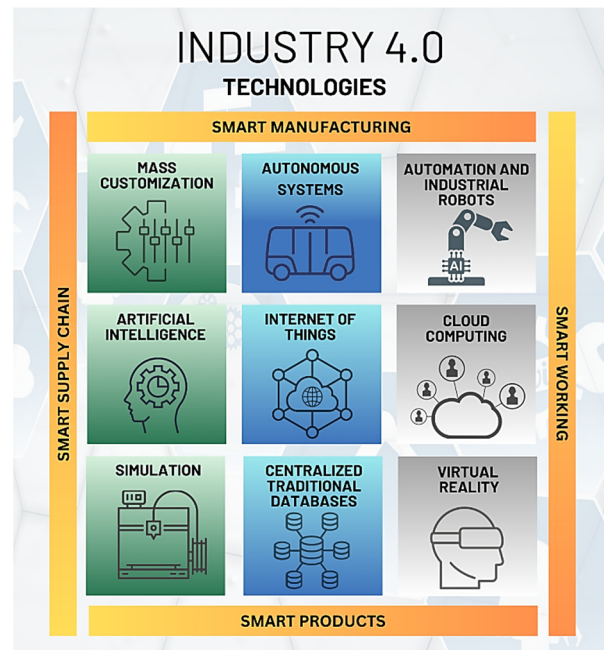


Figure 5. Technologies of Industry 4.0.

Despite the fact that Industry 4.0 has enormous potential for industrial growth, it comes with challenges such as difficulties in combining technologies. This could lead to the creation of poor-quality products if the technologies are not compatible with digitalization. Security concerns arise with IoT implementation, leading to vulnerabilities and cyber-attacks, particularly in sectors like oil, gas, power, and healthcare [175]. Data privacy continues to be a major challenge across multiple industries, particularly in cargo systems and IoT-based applications [176]. Human resource management is crucial, requiring adequate training and good management practices for employees to adapt to smart factory environments [177]. Supply chain management faces challenges in data privacy, integration, and increased system complexity, affecting product safety and quality [178].

Industry 4.0 centers on the idea of smart factories, which are places where smart products, machines, storage setups, and data all come together to create cyber-physical systems for production [179]. Although Industry 4.0 has technically improved how humans and machines work together, it is also important to consider social sustainability and acknowledge the key role that people play [180]. The COVID-19 pandemic highlighted the importance of workers and led to a rethink of the Industry 4.0 model. This led to the development of Industry 5.0, which adds social and environmental considerations [32,181–183].

Industry 5.0 focuses on re-engaging human workers in the factory environment. It promotes teamwork between people and machines, aiming to boost efficiency by combining human intelligence and creativity with smart systems that are already in place [12,14]. Improving waste management through the use of industrial upcycling techniques is one of Industry 5.0's primary objectives. It builds on Industry 4.0 by adding more features, like using data from network sensors. New developments include smarter 3D printing techniques, foreseeing maintenance needs, highly customized industrial methods, systems

that combine cyber and physical elements with cognitive abilities, and the use of robots that work alongside humans, as shown in Figure 6 [13,14,32,184].

The technologies highlighted as enablers in Industry 5.0 may seem like slight enhancements or upgraded iterations of Industry 4.0 technologies. While this perspective holds some truth, a deeper examination of each technology reveals a significant emphasis on human inclusion, environmental awareness, and social responsibility [13,185].

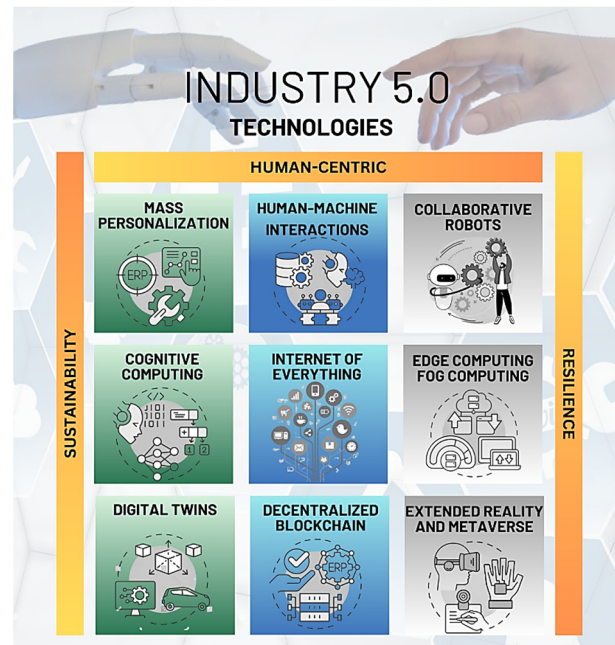


Figure 6. Technologies of Industry 5.0.

The European Commission's document emphasizes three central drivers of the new industrial paradigm, Industry 5.0 [32,183]:

1. *Human-centric approach*: This approach puts human needs at the forefront of the production process, focusing on how technology can support and benefit workers.
2. *Sustainability*: This approach highlights the importance of reusing, repurposing, and recycling materials, in addition to cutting down on waste and lowering environmental harm.
3. *Resilience*: This involves bolstering industrial production with robustness, which ensures flexibility in processes and adaptability in production capacities, particularly during times of crisis.

The main idea behind Industry 4.0 and Industry 5.0 is using technology to gather, process, and analyze data from different sources to improve how things are done in industries. This includes making decisions based on these data and learning from it. Various technologies like computing and digital tools work together to achieve this goal [185]. Table 5 summarizes the basic concepts underlying Industry 4.0 and Industry 5.0.

Table 5. Common concepts of Industry 4.0 and Industry 5.0 adapted from references [14,32,185].

Concept	Definition
Internet of Things (IoT)	IoT links computing power and network connections to sensors and objects, using different ways of communication such as between devices or from a device to a gateway. To fully tap into what IoT can do, it is important to deal with issues related to security and privacy [186,187].
Artificial intelligence (AI)	Artificial intelligence is about computers copying smart actions with minimal help from humans, commonly seen as the science of making machines that can decide things on their own without people telling them what to do [188,189].

Table 5. Cont.

Concept	Definition
Cloud computing	Cloud computing is a new technology that can save industries from managing their own computer hardware. By sharing resources virtually, clouds can serve many users with different needs using a single set of physical resources. This can save costs and offer an alternative to owning hardware for both industries and scientists [190,191].
Cyber-physical systems	Cyber-physical systems (CPSs) are a new kind of system that combine computing with physical actions, creating new ways for people to interact with them. By leveraging computation and communication, CPSs extend the capabilities of the physical world, emphasizing the significance of communication and control in driving future technological progress [192,193].
Augmented reality	Augmented reality (AR) merges virtual and real environments by enriching real-world objects with computer-generated information or objects through various technologies. By harnessing human capabilities, AR offers effective and complementary tools to aid in manufacturing tasks [172,194].
Simulation	Simulation serves as a potent tool for decision-making. As digitalization advances, simulation methods become more relevant, offering comprehensive, efficient, embedded, and cost-effective solutions [195].
Autonomus robots	Autonomous robots have the capability to identify issues and adapt their tasks independently to maintain smooth operation of processes. However, the level of a robot's independence, from being controlled by humans to operating entirely on its own, influences how humans and robots interact [196].

6.4. Industry 5.0 as a Way to Overcome the Challenges of Industry 4.0

Industry 5.0 not only expands upon Industry 4.0's base but also more successfully addresses its problems. Some of these challenges include the following:

Supply chain issue: Supply Chain 4.0 is technology-driven, focusing on strategies, disruptive technologies, and enhancing supply chain performance through mass customization and efficiency improvements. In contrast, Supply Chain 5.0 emphasizes a balanced integration of human involvement and technology, seeking to maintain and enhance Supply Chain 4.0's advantages while placing a greater emphasis on sustainability. Industry 5.0 leverages cutting-edge capabilities of AI and cobots, with a major emphasis on supply chain management sustainability [14,197].

The challenge of data security: In Industry 4.0, issues like stealing data and hacking came up with IoT, but Industry 5.0 has dealt with these. Industry 5.0 uses a special blockchain system to make the Internet of Things in industries more secure, helping to gather data better for smart manufacturing. This helps focus on certain areas of value and lowers the chance of network problems. Using smart contracts with this blockchain system makes things more self-sufficient and green, cutting down the need for outside help [36]. Resilient manufacturing strategies are crucial for data security, especially for IoT, which contains sensitive data [14,34,35].

Issue of technical integration: A notable challenge of Industry 4.0 is managing the rising digitalization. However, Industry 5.0 shifts focus towards human-centric approaches, blending human creativity with machine precision to enhance productivity and performance. Furthermore, Industry 5.0 can improve product quality by using robots to perform repetitive tasks [13,14].

Human resource issue: Industry 4.0 brought automation to traditional manufacturing, requiring thorough training for workers. Conversely, Industry 5.0 prioritizes human-centric methodologies, emphasizing the enhancement of collaborative interactions between human operators and robotic systems. Cobots play a vital role by collaborating with humans, enhancing productivity and efficiency. This collaboration allows workers to focus on value-added tasks while reducing involvement in monotonous or hazardous jobs. However, predictive maintenance is crucial to prevent breakdowns in these machines [14,37].

While Industry 4.0 is centered on digitalization, Industry 5.0 is about promoting teamwork between digital technologies and human skills in critical and creative thinking.

It prioritizes adaptability to changing market dynamics and places increased emphasis on sustainability [185].

An illustrative example of additive manufacturing within Industry 5.0 is found in the automotive sector, particularly in the production of complex, customized components for high-end or performance vehicles. Companies like BMW utilize 3D printing to create lightweight, tailor-made parts that seamlessly integrate into their vehicle designs. Additionally, Porsche has adopted 3D printing to manufacture engine pistons, demonstrating how metal 3D printing can optimize performance while reducing lead time and costs.

In the context of Industry 5.0, which emphasizes the collaboration between humans and machines, additive manufacturing enables more flexible and personalized production processes, addressing specific customer needs through advanced technology and creative human input. This approach aligns with the principles of Industry 5.0 by combining automation with human creativity to deliver consumer-centered, highly customized solutions. The impact of this technology extends beyond automotive applications; for example, Swiss aerospace company RUAG has optimized satellite bracket designs using 3D printing, highlighting the technology's potential even in space [198].

6.5. The Role of Additive Manufacturing in the Future Landscape of Manufacturing

The leading strategy for affordability in today's manufacturing sectors, which helps producers carry out their development plans while cutting down on pollution and resource use during a product's life, is known as sustainable manufacturing [199]. This approach involves additive manufacturing, which constructs product parts layer by layer, resulting in lighter yet stronger components.

Artificial intelligence (AI) algorithms and computer vision are used by smart additive manufacturing (SAM) to enhance 3D printing accuracy and visual output. The latest development in additive manufacturing is 5D printing, which allows the printing nozzle additional movement flexibility to create objects along five different axes, resembling the functionality of five-axis machining centers. Moreover, hybrid manufacturing merges the features of both additive and subtractive manufacturing in one system to make the most of both approaches [185].

Companies and researchers are increasingly adopting smart manufacturing technologies, taking advantage of developments in AI, IoT, cloud computing, big data, cyber-physical systems (CPSs), 5G, digital twins (DTs), and edge computing (EC). These advanced technologies are driving improvements in smart manufacturing, delivering gains in sustainability, profitability, and efficiency. Smart additive manufacturing has particularly gained prominence in the last decade, offering environmentally friendly production by saving energy and reducing material consumption [200].

Additive manufacturing, or 3D printing, is essential in Industry 5.0 to produce more environmentally friendly manufactured goods. Utilizing all of Industry 5.0's benefits, smart additive manufacturing (SAM) collaborates with automated systems to improve supply chain management and reduce product delivery times [13,201].

In the upcoming era of Industry 5.0, additive manufacturing, often referred to as 3D printing, is set to play a transformative and increasingly significant role in the manufacturing landscape. Table 6 contains some key aspects of its role:

Table 6. Key aspects of 3D printing in Industry 5.0.

Concept	Definition
Customization and personalization	3D printing allows for the creation of products that are highly customized and personalized, fitting the specific needs and likes of individuals. This fits well with the people-focused approach of Industry 5.0, making it possible to produce unique items that more closely match consumers' expectations.
Agile production	Unlike traditional manufacturing methods, which often require expensive tooling and long lead times for production setup, 3D printing offers greater agility. It enables businesses to quickly adapt to shifting customer needs and market demands by facilitating on-demand manufacturing and rapid prototyping.

Table 6. Cont.

Concept	Definition
Complex geometry	Complex forms and intricate structures that may not be possible to create using conventional manufacturing techniques can now be produced thanks to additive manufacturing technology. This opens up new options for design and makes it possible to make components that are light but still have good performance.
Sustainability	3D printing could cut down on material waste by using only what is necessary for making a product, thus reducing unused materials and excess stock. Moreover, by allowing for manufacturing to happen locally, 3D printing could lessen the environmental toll of transport and logistics.
Supply chain resilience	Industry 5.0 emphasizes resilience in supply chains, and 3D printing can contribute to this by decentralizing production and reducing reliance on centralized manufacturing facilities. By producing parts and products closer to the point of consumption, companies can mitigate risks associated with disruptions in global supply chains.
Design integration	3D printing technologies are increasingly being integrated with digital design and manufacturing platforms, enabling seamless collaboration between digital design tools, simulation software, and additive manufacturing hardware. This digital integration enhances efficiency, accuracy, and quality in the manufacturing process.

In the context of complex geometry, one of the methods discussed involves the numerical modeling and design of materials with controlled pore sizes. This process begins with solving the coupled Cahn–Hilliard and Swift–Hohenberg equations using a fast Fourier transform (FFT) method. The numerical solutions generate intricate patterns, which are further processed into 3D-printable formats, allowing for precise control over the microstructure of the material. These designs can then be adapted into CAD files, making it possible to print structures with customized geometries tailored to specific applications, such as bone scaffolds or other biomedical uses. These patterns exhibit diverse morphologies, including globular, lamellar, or tubular forms, depending on the model parameters.

In terms of design integration, the computational process extends beyond generating patterns; it is connected directly to the manufacturing stage. The 3D numerical solutions are translated into stl files, which can be scaled and modified for additive manufacturing processes. This workflow, termed the Mathematical Design Process and 3D Printing-Assisted Manufacturing (MDP-3DPAM), provides a streamlined approach by integrating the design, numerical analysis, and printing stages, offering a comprehensive framework for creating materials with controlled porosity and structural complexity. This methodology is highly beneficial for applications that demand precise structural properties, such as in tissue engineering [202].

Overall, 3D printing is set to be a key player in the future of manufacturing with Industry 5.0, providing unmatched levels of customization, speed, eco-friendliness, and robustness in making things. As this technology gets better and more developed, its ability to change manufacturing in many fields is expected to increase.

7. Conclusions

Additive manufacturing (AM) in Industry 4.0 presents new opportunities for design and manufacturing, allowing for on-site fabrication of customized products. AM capabilities are integral to the Fourth Industrial Revolution, enabling flexible manufacturing processes that can swiftly adapt to individualized mass production while maintaining high quality. This change in how things are made will greatly change the roles played by customers, manufacturers, and designers. Numerous industries, including aerospace, architecture, medicine, and the automobile sector, have benefited from additive manufacturing. AM stands out from conventional manufacturing techniques by enabling the creation of more complex structures, enhancing efficiency, and allowing for customized designs that are better for the environment. Consequently, AM is moving past just making prototypes to include the production of final and replacement parts. However, AM is still developing and needs more research to reduce the costs of materials and machines, improve printing

methods, and become self-reliant. The future of making things depends on technological progress, improvements in processes, and updating existing manufacturing systems [42].

The basics of additive manufacturing: The fundamentals of additive manufacturing are outlined by the ISO/ASTM 52900:2021 standard, which standardizes 3D printing techniques and offers a structured way to comprehend additive manufacturing (AM/3DP) technologies. This standard identifies seven primary categories: binder jetting, direct energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination, and vat photopolymerization, ensuring uniform language use throughout related documents. Each technology is tailored for specific applications, eliminating debates over superiority. Furthermore, the evolution of 3D printing extends beyond prototyping, with these technologies now being utilized to produce a diverse array of products.

Used in a variety of industries, including the aerospace, automotive, medical, construction, electronics, and food industries, 3D printing (3DP) is a flexible and cutting-edge production technique. It utilizes high-quality materials like metals, ceramics, composites, polymers, and hybrids to produce fully functional objects. Core materials determine the main characteristics of printed parts, while supporting materials assist in complex printing tasks. The range of materials that are accessible is always being expanded through ongoing research and development, bringing new possibilities with distinctive features that improve the adaptability and practicality of 3D printing technologies.

Current status of 3D printing in Industry 4.0: The Fourth Industrial Revolution, or Industry 4.0, is redefining manufacturing by utilizing the Internet of Things (IoT) to automate tasks and decrease human intervention, as well as technologies that allow machines to connect with one another. Consequently, 3D printing is a key part of Industry 4.0, fitting well with its goals. Moreover, 4D printing, which uses smart materials, further boosts the importance of additive manufacturing. Industry 4.0 aims for systems that work on their own and better connections. Industry 4.0 aims for self-operating systems and better connectivity, with 3D printing facilitating digital transmission of data, remote operation, minimal manual involvement, and the ability to create complex shapes and utilize smart materials. This leads to a reduction in waste and the need for additional processing steps [203].

Advantages and limitations: Additive manufacturing is transforming the manufacturing industry with benefits such as personalization, less waste, quicker turnaround times, the ability to create complex designs, and making manufacturing more accessible. It customizes products to meet precise requirements, uses materials more efficiently, accelerates the making process, enables the creation of detailed designs, and opens up manufacturing to smaller companies and individual makers. These benefits showcase additive manufacturing's transformative potential in enhancing efficiency, customization, and accessibility in manufacturing. Disadvantages of additive manufacturing include limited material options, quality control challenges, higher costs compared to traditional methods, size limitations due to printing bed constraints, and negative environmental impact stemming from non-recyclable materials and significant energy consumption.

Applications across diverse sectors: Important industries like the automotive sector, healthcare, aerospace, food, and construction have all seen revolutionary changes because of additive manufacturing. This cutting-edge technology's capacity to produce inexpensive, lightweight, and effective goods as well as intricate structures has resulted in important breakthroughs. These characteristics have been crucial in the growing application and significance of AM across numerous industries [46].

Innovations: Recent trends in additive manufacturing have revolutionized industries by offering customized, efficient, and material-efficient processes. AM techniques contribute to diverse applications, from aerospace to healthcare, with advancements in materials broadening capabilities. Multi-material printing enhances functionality, while software tools and AI streamline design and optimization. Overall, AM signifies a transformative shift in manufacturing, with ongoing advancements promising even greater efficiency, customization, and adoption across industries, driven by innovative materials and advanced technologies, including AI [46].

Current challenges and future prospects: While the industrial sector is crucial for economic growth, technological advancements and evolving production methods pose challenges for enterprises and workers alike. Industry 4.0 has faced criticism for its heavy reliance on technology, seemingly prioritizing machines over people. In response, Industry 5.0 has emerged, placing greater emphasis on the role of workers in production processes. This transition underscores the value of human contribution, which was particularly evident during the COVID-19 pandemic, where the role of workers was essential in keeping industrial operations productive and resilient. Industry 5.0 employs cutting-edge technology to address these issues, including cyber–physical cognitive systems, collaborative robotics, hyper-customization, and predictive maintenance. Although Industry 5.0 is still in its early stages of development and lacks extensive literature, it presents significant research opportunities, particularly in areas such as data security, integration, and sustainability. The era of automation and digitalization has facilitated the analysis of sensor-generated data in industries, offering opportunities to enhance productivity and efficiency by overcoming various barriers [14].

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