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Innovative and sustainable advances in polymer composites for additive manufacturing: processing, microstructure, and mechanical properties.

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Editorial

Innovative and Sustainable Advances in Polymer Composites for Additive Manufacturing: Processing, Microstructure, and Mechanical Properties

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Abstract: Additive manufacturing (AM) has revolutionised the production of customised components across industries such as the aerospace, automotive, healthcare, electronics, and renewable energy industries. Offering unmatched design freedom, reduced time-to-market, and minimised material waste, AM enables the fabrication of high-quality, customised products with greater sustainability compared to traditional methods like machining and injection moulding. Additionally, AM reduces energy consumption, resource requirements, and CO_2 emissions throughout a material's lifecycle, aligning with global sustainability goals. This paper highlights insights into the sustainability of AM polymers, comparing bio-based and traditional polymers. Bio-based polymers exhibit lower carbon footprints during production but may face challenges in durability and mechanical performance. Conversely, traditional polymers, while more robust, require higher energy inputs and contribute to greater carbon emissions. Polymer composites tailored for AM further enhance material properties and support the development of innovative, eco-friendly solutions. This Special Issue brings together cutting-edge research on polymer composites in AM, focusing on processing techniques, microstructure–property relationships, mechanical performance, and sustainable manufacturing practices. These advancements underscore AM's transformative potential to deliver versatile, high-performance solutions across diverse industries.

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1. Introduction

Additive manufacturing (AM) has revolutionised production processes in industries such as the aerospace, automotive, healthcare, electronics, and renewable energy industries, enabling the rapid fabrication of complex shapes and parts [1]. Over the past 30 years, AM has evolved into a technology at the forefront of Industry 4.0 [2]. This layer-by-layer fabrication technique, based on computer-aided design (CAD) models, offers unmatched advantages, including reduced time-to-market, customisation, and minimised material waste [3]. Recent advances in AM technology have introduced nanomaterials into polymer matrices, significantly enhancing the mechanical, thermal, and structural properties of AM products [4,5]. Materials such as carbon nanotubes and graphene are being integrated into resins and powders, enabling applications in high-performance sectors like aerospace and medical devices [6]. These innovations underscore AM's potential to fabricate complex geometries and structures that were previously unattainable with conventional manufacturing methods. This Special Issue, "Innovative and Sustainable Advances in Polymer

Composites for Additive Manufacturing", explores recent breakthroughs in AM. Topics include processing techniques, microstructure–property relationships, mechanical performance, and sustainable manufacturing practices. By addressing these themes, this Special Issue aims to bridge the gaps in the research and foster innovation in polymer composites tailored for AM applications.

Figure 1 highlights the growing research interest in AM from 2015 to 2024, as evidenced by a steady increase in publications. This trend reflects the broadening adoption of AM technologies across industries, driven by demands for lightweight, sustainable, and customised solutions [7]. The steady increase in publication numbers highlights the pivotal role of additive manufacturing in shaping the future of manufacturing.

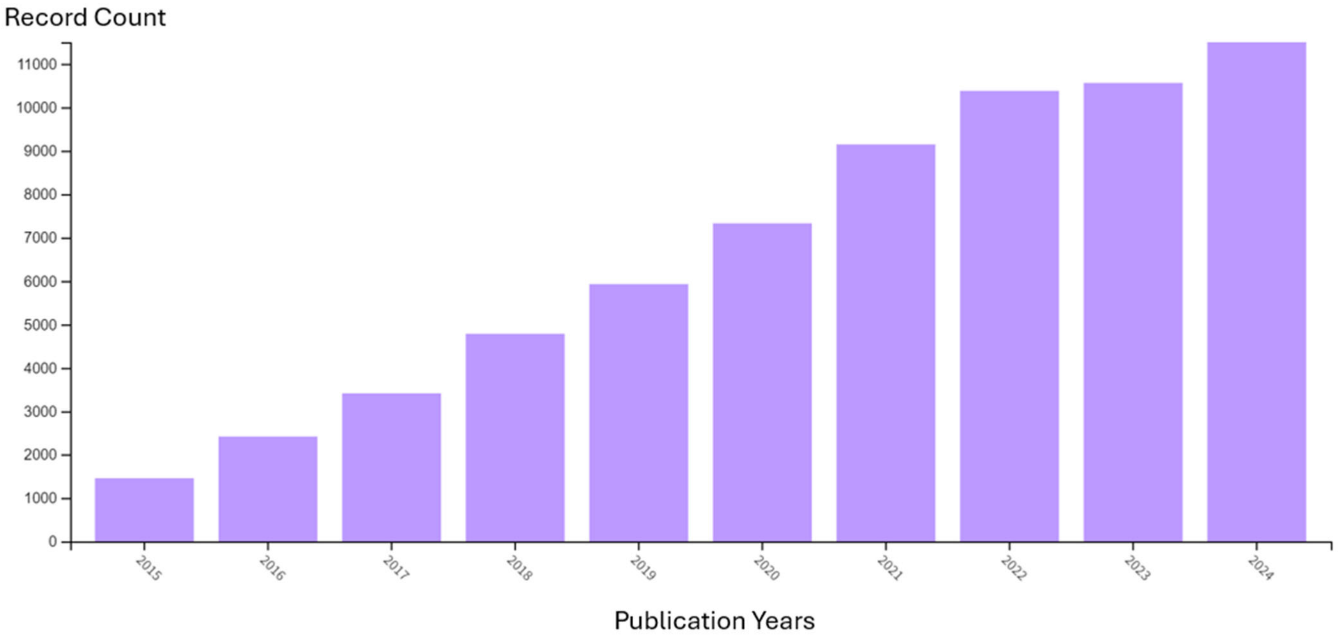

Figure 1. Publication years and record counts from 2015 to 2024, obtained from Web of Science.

2. Advantages of Additive Manufacturing (AM)

Additive manufacturing (AM) techniques offer several significant advantages. These include unmatched design freedom; minimal tool requirements; and the ability to produce high-quality, customised products [8]. AM is also a sustainable manufacturing method, reducing material waste, energy consumption, resource usage, and CO_2 emissions across the material lifecycle [9]. Additionally, AM supports the transition to a digitalised supply chain, streamlining workflows and reducing reliance on traditional labour-intensive processes. Industries such as the aerospace, healthcare, and automotive industries have adopted AM to create prototypes, custom implants, and lightweight components at lower costs without compromising quality [10]. These capabilities position AM as a transformative technology for modern manufacturing, as shown in Figure 2.

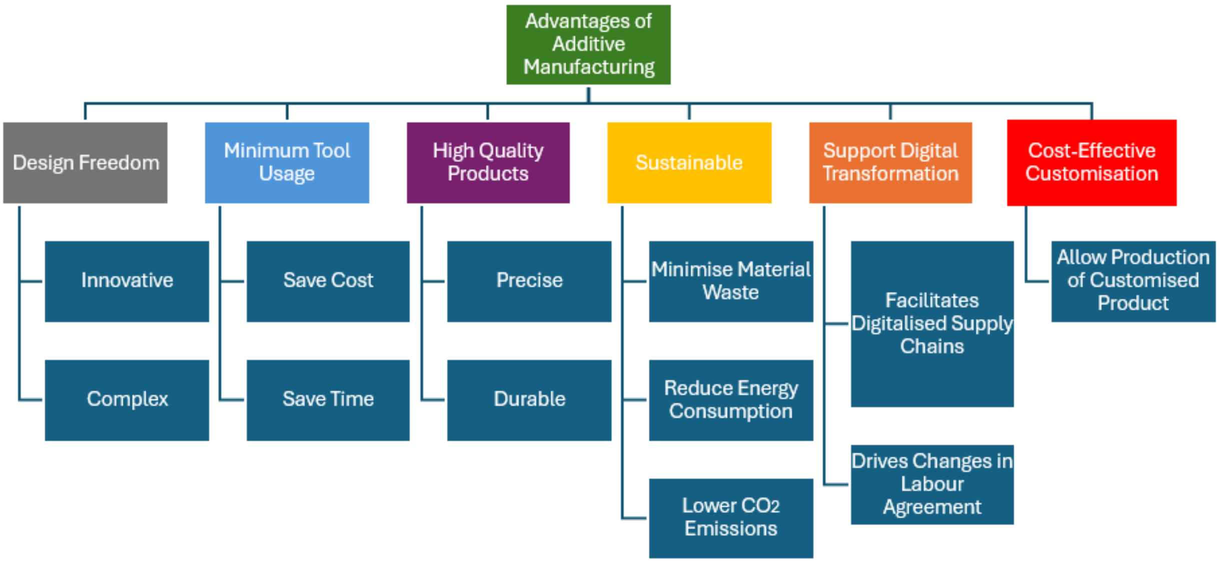

Figure 2. Advantages of additive manufacturing (AM) [8–10].

3. Additive Manufacturing (AM) Techniques

Additive manufacturing (AM) encompasses a variety of techniques, each offering distinct capabilities and advantages. The general workflow of AM begins with 3D modelling in CAD software such as SolidWorks 2025 [11]. The model is saved as an .STL file, which is then processed to generate layer slices and toolpaths. These data are sent to a 3D printer, where the object is built layer by layer, as illustrated in Figure 3. While all AM techniques follow this layered approach, the mechanisms for forming layers differ significantly across methods.

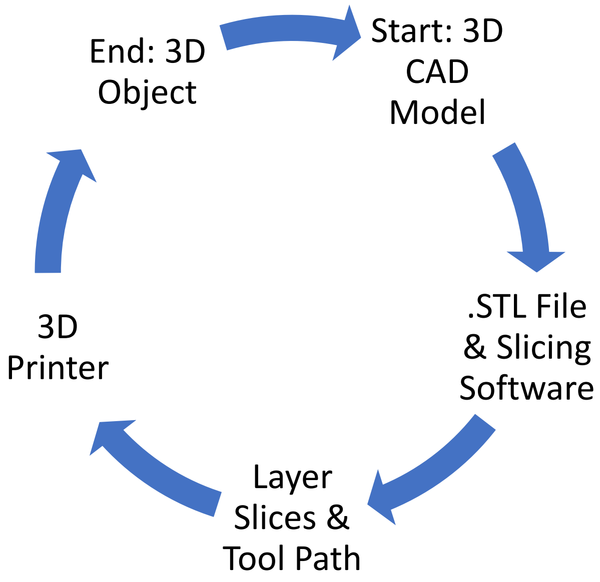

Figure 3. Layered manufacturing of a 3D-printed component.

Fused deposition modelling (FDM) is a cost-effective technique that extrudes thermoplastic material through a heated nozzle, making it ideal for applications requiring precise material properties, such as consumer goods and prototyping [12]. PolyJet 3D printing mimics inkjet printing to create intricate designs with polished surfaces, often used in healthcare and aesthetic applications. Stereolithography (SLA) employs lasers or projectors to selectively solidify liquid photopolymer resins, achieving high precision and speed, particularly with advancements like continuous liquid interface production (CLIP) technology. Selective laser sintering (SLS) fuses powdered materials using a laser, enabling the creation of intricate designs without support structures, though it requires significant post-processing to remove excess powder. Laminated object manufacturing (LOM) uses bonded sheets of material to produce 3D objects, offering simplicity and rapid prototyping capabilities [13,14].

The versatility of AM has transformed polymer synthesis, enabling the production of diverse materials with remarkable accuracy. Thermoplastic polymers like PLA and ABS are widely used for their adaptability in creating prototypes and functional parts [15,16]. Matrix composites, incorporating reinforcing agents such as carbon fibres or nanoparticles, optimise material properties for enhanced performance in demanding applications. Additionally, thermoresponsive polymers, which modify their properties with temperature changes, are tailored for aerospace [17,18], automotive [19–21], and biomedical uses [8]. These advancements illustrate the expanding influence of AM in diverse industrial sectors.

4. Evolution and Current Status of AM Technology

Several innovative methodologies have recently emerged in additive manufacturing, including liquid deposition modelling (LDM) [22] and digital light processing (DLP) [23]. In LDM, layers of volatile material are directly deposited, while DLP selectively polymerises photopolymers using a projector light. Another noteworthy technology is fiber encapsulation additive manufacturing (FEAM) [24], which enables the simultaneous deposition of both fibre and matrix materials. These advanced techniques offer greater time efficiency and increased material flexibility compared to basic 3D printing methods. However, their cost-effectiveness remains inferior to traditional approaches. Current research efforts, as highlighted by various researchers, are focused on addressing these limitations and enhancing the performance of these novel techniques.

Machine learning (ML) is expected to play a significant role in enabling intelligent, automated [25,26], and highly efficient manufacturing processes as polymer additive manufacturing (AM) continues to advance [27–30]. ML operates by using data-driven modelling to identify patterns within datasets [31], enabling algorithms to make predictions for previously unseen cases [32]. In polymer AM, the quality of the final product is influenced by numerous, highly complex material and processing parameters. While this complexity poses challenges, it also creates opportunities for ML to optimise the process. ML techniques can significantly reduce the time and resources required to understand the process–structure–property–performance relationship, compared to traditional trial-and-error experiments, numerical simulations, and analytical models. ML can drive innovation in polymer AM by facilitating the discovery of new materials, generating novel designs, accelerating defect detection, and enhancing quality control [33]. Beyond the application of established ML methodologies, research in this field also focuses on developing novel algorithms aimed at further advancing polymer AM technologies. In summary, the appropriate integration of ML techniques has the potential to accelerate advancements in polymer AM and unlock new applications, driving the field toward greater efficiency and innovation.

5. Sustainability of AM Polymers

Additive manufacturing (AM) polymers, such as polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), and advanced composites, offer unique advantages for modern manufacturing. PLA, a bio-based polymer, is valued for its biodegradability and suitability for applications like medical implants and packaging [34]. ABS, a petroleum-based polymer, is favoured for its robustness and thermal stability, making it ideal for functional prototypes and automotive components [35,36]. However, the environmental performance of these materials depends on several factors, including energy-intensive manufacturing processes, material sourcing, and waste management [37].

The life cycle assessment (LCA) of AM polymers provides critical insights into sustainability. For example, PLA has a 25% lower carbon footprint during production compared to ABS, but its mechanical durability and recyclability remain challenges [38]. Conversely, ABS offers greater robustness but demands higher energy inputs and results in greater carbon emissions. Emerging trends in LCA focus on integrating recycled polymers, which can reduce resource depletion and greenhouse gas emissions, and reinforced polymers, such as carbon fibre composites, which enhance material efficiency and performance.

Despite these advancements, the proliferation of diverse polymers poses challenges for collection, separation, and recycling, contributing to global pollution. Materials scientists and engineers must adopt a holistic approach, considering the environmental impact of polymers throughout their lifecycle. Tools such as SolidWorks Sustainability can help assess environmental impacts at the design stage, enabling the optimisation of costs and environmental performance.

Looking ahead, innovations in AM polymers will require a balance between performance, cost, and sustainability [39]. Reinforced composites and bio-based alternatives represent promising solutions, but addressing recycling challenges and energy efficiency will be key to achieving a circular economy in additive manufacturing.

6. Challenges and Future Directions

The field of polymer additive manufacturing (AM) faces several challenges that hinder its widespread adoption. Therefore, expanding production capacity to meet the diverse demands of industries such as the aerospace, healthcare, and automotive industries remains a primary obstacle. Key issues include improving production speed, cost-efficiency, and quality control, especially for large-scale applications. Ensuring material uniformity is also critical, as inconsistencies in layer deposition can lead to defects like anisotropy and voids, limiting AM's reliability in safety-critical applications.

Material selection and optimisation present additional challenges. Customising polymers to meet specific performance requirements, such as strength and thermal resistance, while maintaining sustainability, is complex. The proliferation of diverse polymer materials also complicates recycling processes, making it difficult to implement effective waste management strategies [40].

The future of polymer AM lies in advancing materials, sustainability, and technology to address these challenges [41]. High-performance polymers and smart materials, such as shape-memory and self-healing polymers, will enable innovations in the aerospace, automotive, and medical sectors [42]. Reinforced composites, including graphene-infused and carbon fibre polymers, will enhance strength-to-weight ratios, facilitating broader adoption in energy storage and structural applications [43,44]. Figure 4 illustrates an example of the expanding use of additive manufacturing in the production of hydrogen pressure vessels.

Sustainability will play a pivotal role, with increased use of bio-based and recycled polymers supporting a circular economy. Closed-loop recycling systems and lifecycle assessments will be critical for minimising environmental impact. For example, integrating recycled thermoplastics can reduce resource depletion by up to 30% while maintaining material performance [45].

Technological advancements will further drive the evolution of AM. Multi-material and nano-scale printing will enable the fabrication of complex, multi-functional components for electronics and biomedicine [46]. Innovations like continuous liquid interface production (CLIP) will reduce production times by up to 40%, enabling cost-effective mass production. Embedding electronics into printed polymers will expand applications in IoT and wearable devices. Artificial intelligence and real-time monitoring systems will optimise AM processes, ensuring consistent quality and scalability [47].

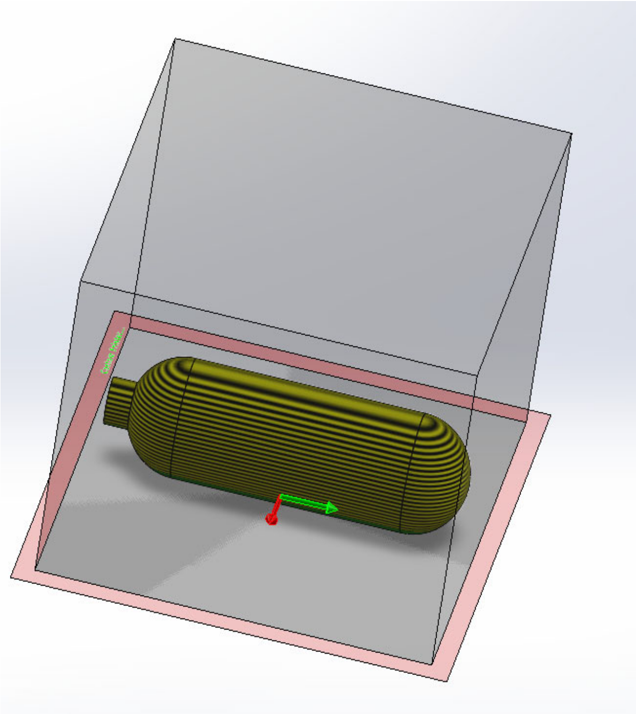

Figure 4. Hydrogen pressure vessel polymer liner model in SolidWorks 3D printing with visible striation lines.

With these advancements, polymer AM is poised to revolutionise manufacturing, offering versatile, eco-friendly, and high-performance solutions across diverse industries. By addressing current challenges and leveraging emerging technologies, the field can achieve its full potential in driving innovation and sustainability.

7. Conclusions

Research in additive manufacturing (AM) with polymers is advancing rapidly, driven by innovations in materials, sustainability, and technology. High-performance polymers such as PEEK are enabling the development of lightweight, durable components for aerospace applications, while shape-memory materials are transforming biomedical devices like self-expanding stents and responsive implants. Reinforced composites and bio-based polymers are fostering sustainable practices, supporting the shift towards a circular economy through recycling and reduced resource consumption.

Technological advancements, including multi-material and nano-scale printing, are broadening the scope of AM applications, enabling the production of complex, multi-functional components. Real-time process monitoring and AI-driven optimisation are enhancing precision, efficiency, and scalability, paving the way for cost-effective mass production. However, to fully realise AM's potential, challenges such as energy consumption, material recyclability, and scalability must be addressed.

By overcoming these barriers, AM with polymers has the potential to revolutionise manufacturing, delivering versatile, eco-friendly, and high-performance solutions across industries. Continued collaboration among researchers, engineers, and policymakers will be critical in driving innovation, ensuring sustainability, and maximising the benefits of polymer AM in the years to come.

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