Research Article   Open Access

Revolutionizing Tomorrow: Cutting-Edge 3D Printing Materials and Methods for Transformative Real-World Solutions

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ABSTRACT

This study offers an in-depth exploration of the latest advances in 3D printing materials and fabrication technologies that are driving a transformation across multiple industrial sectors. Beginning with a review of emerging high-performance polymers, advanced metal alloys, and innovative composite materials, the discussion highlights enhancements in mechanical strength, flexibility, and functional adaptability which are setting new standards for additive manufacturing capabilities. Particular emphasis is placed on sustainable and eco-friendly materials, such as recyclable plastics and biodegradable polymers, reflecting the growing industry commitment to environmentally responsible production.

The overview continues by examining cutting-edge manufacturing methodologies, including multi-material printing and artificial intelligence-assisted design optimization. These advancements enable faster, more precise, and resource-efficient production workflows that reduce waste and costs while expanding the complexity of printable parts. A broad range of sector-specific applications is presented, showcasing the impact of these technologies in aerospace, automotive, healthcare, and personalized medicine, including breakthroughs in bioprinting for customized implants and tissues.

Through illustrative examples and real-world case studies, the presentation emphasizes the shift toward decentralized, on-demand manufacturing models facilitated by these technological innovations. It underscores how 3D printing is evolving from a prototyping tool to an essential production technology, aligned with Industry 4.0 principles. This evolution supports greater flexibility, customization, and sustainability in manufacturing ecosystems, addressing contemporary economic and environmental challenges.

Readers will gain a comprehensive understanding of how these materials and methods converge to revolutionize product design and fabrication, offering new avenues for innovation and competitive advantage. The paper aims to inspire further exploration and adoption of additive manufacturing technologies, accelerating their integration into mainstream industrial practices worldwide.

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Introduction

Additive manufacturing (AM), popularly known as 3D printing, has catalyzed a paradigm shift in modern manufacturing by enabling the fabrication of complex geometries, tailored properties, and customized products that challenge the capabilities of conventional methods. This technology, first primarily used for rapid prototyping, has evolved into a comprehensive manufacturing approach applicable across sectors such as aerospace, automotive, healthcare, and consumer goods [1]. The rapid advancement in 3D printing materials, featuring high-performance polymers, advanced metals, and innovative composites, has been a significant driver of this transformation. These materials provide enhanced mechanical strength, flexibility, and functionality, thereby broadening the range of applications where additive manufacturing can serve as a viable production method [2-4].

Sustainability considerations have become central to material development within the field. Emerging recyclable plastics, biodegradable polymers, and bio-sourced composites are reducing the environmental footprint of additive manufacturing processes. For instance, biodegradable polyesters like polylactic acid (PLA) and polycaprolactone (PCL) have gained attraction due to their renewability and reduced waste impact, although challenges remain regarding their mechanical properties and thermal stability [5-7]. Efforts to enhance these materials' performance through fiber reinforcements and hybrid composites represent critical research directions, helping to meet demanding industrial standards without compromising sustainability goals.
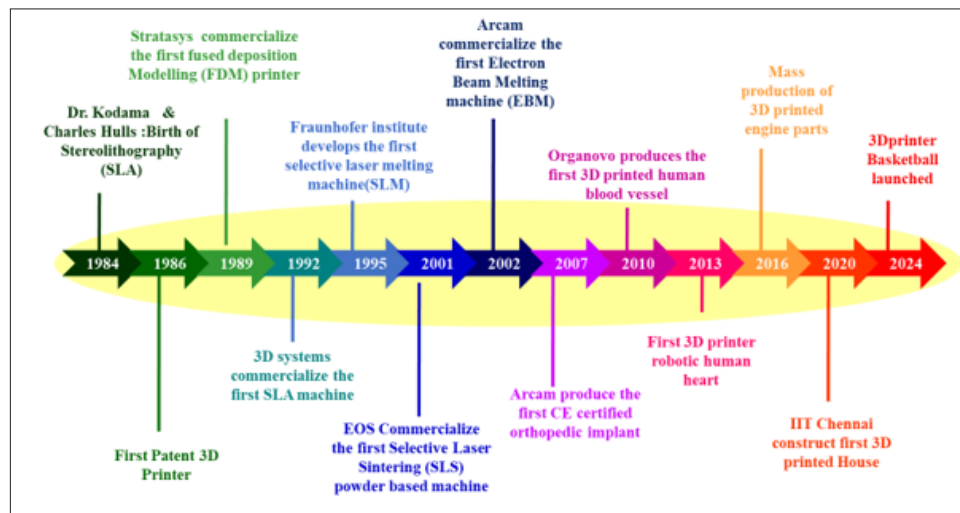
Beyond materials, significant progress in 3D printing methods is revolutionizing production workflows. Multi-material printing allows the simultaneous deposition of diverse materials, enabling the creation of multifunctional parts tailored to specific application requirements [8,9]. Concurrently, artificial intelligence (AI) and machine learning are increasingly integrated into design optimization and process control, leading to accelerated development cycles, improved precision, and minimized waste. AI-driven topology optimization and process parameter tuning are enabling dynamic adjustments during manufacturing, enhancing part quality and reproducibility [10-13].

These technological advances align closely with Industry 4.0 principles—where cyber-physical systems, IoT connectivity, and digital automation converge to create smart, flexible, and responsive manufacturing environments. Decentralized, on-demand production models enabled by 3D printing facilitate localized manufacturing, reduce supply chain dependencies, and shorten lead times. Such frameworks reflect evolving economic and environmental imperatives, emphasizing resource efficiency, customization, and rapid responsiveness to market needs [14-16].

The biomedical sector has particularly benefited from these developments, with bioprinting emerging as a transformative application of 3D printing technologies. Customized medical implants, tissue scaffolds, and drug delivery devices are being produced with precision tailored to patient-specific anatomies, advancing personalized medicine significantly. Biocompatible and biodegradable inks incorporate living cells and bioactive molecules to support tissue regeneration, demonstrating a promising intersection of material science, biology, and engineering [17-19].

Additionally, aerospace and automotive industries leverage fiber-reinforced composites fabricated via 3D printing to achieve lightweight, high-strength components capable of enduring harsh operating environments. Manufacturers also utilize topology optimization and multi-material printing to design parts that optimize performance while minimizing material usage and weight, contributing to improved fuel efficiency and reduced emissions [20-22]. In parallel, healthcare increasingly adopts additive manufacturing for surgical models, prosthetics, and orthotics, driven by the demand for personalized and adaptive solutions as shown in Figure 1 [23-25].

Figure 1: Evolution of 3D Printing: Key Milestones

Despite these advances, challenges remain in scaling 3D printing for mass production, particularly regarding production speed, quality control, regulatory compliance, and long-term material performance. Research continues to focus on improving the mechanical reliability of printed parts, developing novel materials that balance sustainability with performance, and integrating AI tools for autonomous, real-time process adaptation. Collectively, these trends reflect a maturing industry transitioning from prototyping toward widespread implementation of additive manufacturing as a core, competitive production technology.

This paper provides a comprehensive review of cutting-edge materials and fabrication methods in 3D printing, exploring their real-world applications and roles in advancing sustainable, flexible, and efficient manufacturing ecosystems aligned with Industry 4.0.

Materials and Methods

This section presents an in-depth review of the latest materials and fabrication techniques driving advancements in 3D printing technology. The focus lies on high-performance polymers, metal alloys, composite materials, and sustainable alternatives that form the foundation for innovative additive manufacturing applications. Alongside material descriptions, the methods utilized for fabrication—including multi-material printing and artificial intelligence (AI)-enhanced optimization—are discussed. Evaluation criteria used to assess these materials and methods for real-world relevance and performance are also outlined.

3D Printing Materials Reviewed

Recent years have witnessed significant innovation in 3D printing materials aimed at overcoming limitations related to strength, flexibility, durability, and environmental impact. High-performance polymers such as polyetheretherketone (PEEK) and polyphenylene sulfide (PPS) offer exceptional thermal stability and mechanical robustness, making them suitable for aerospace and automotive components requiring demanding operating conditions. Advanced metal alloys, including titanium and aluminum derivatives, provide excellent strength-to-weight ratios essential for lightweight structural parts. Composite materials, combining polymers with carbon fibers or ceramic particles, deliver a balance of enhanced stiffness, toughness, and functional versatility. Moreover, sustainable materials like polylactic acid (PLA), biodegradable polyesters, and recycled thermoplastics are gaining prominence, responding to the industry's growing emphasis on eco-friendly manufacturing without sacrificing printability or performance.

Advanced Fabrication Methods

Multi-material 3D printing has emerged as a transformative method that enables the simultaneous deposition of multiple materials within a single build process. This capability facilitates the production of components with graded properties, multi-functionality, or integrated electronics, expanding application possibilities beyond what single-material printing allows. Techniques such as fused filament fabrication (FFF) and inkjet-based material jetting have been adapted to handle different material types during one continuous operation.

Artificial intelligence (AI) and machine learning tools are increasingly integrated into additive manufacturing workflows to optimize design and production parameters. AI-enabled topology optimization allows for the generation of geometrically efficient structures tailored to specific load and performance criteria, minimizing material use while maximizing strength. Machine learning algorithms analyze the effects of various printing parameters on part quality, enabling the real-time adjustment of temperature, layer thickness, and extrusion speed to improve accuracy and reduce defects. These methods contribute to improved repeatability, reduced waste, and accelerated product development cycles.

Evaluation Criteria and Metrics

To systematically assess the suitability of materials and methods for industrial application, several evaluation metrics are applied. Mechanical properties such as tensile strength, modulus of elasticity, impact resistance, and fatigue life are primary indicators of material performance. Thermal stability and chemical resistance are essential for parts exposed to harsh environments. Printability metrics include layer adhesion quality, resolution, surface finish, and dimensional accuracy. From a process perspective, build speed, material consumption efficiency, and energy usage are key factors influencing economic and environmental viability. Furthermore, sustainability criteria encompass recyclability, biodegradability, and life cycle impact, reflecting the growing imperative for green manufacturing practices in additive manufacturing.

Together, these materials and methods form a comprehensive landscape for advancing 3D printing technology toward versatile, reliable, and sustainable real-world manufacturing solutions. This review synthesizes current knowledge, emphasizing innovations that accelerate adoption across diverse sectors.

Advances in 3D Printing Materials
High-Performance Polymers

In recent years, significant advancements have been made in high-performance polymers tailored for additive manufacturing. Materials such as polyetheretherketone (PEEK) and polyphenylene sulfide (PPS) exhibit excellent thermal resistance, mechanical strength, and chemical stability, making them ideal for demanding industrial applications, including aerospace and automotive sectors. These polymers enable the production of lightweight, durable parts that can withstand harsh environments while maintaining dimensional stability. Reinforced polymer composites that incorporate carbon fibers or ceramic particles further improve stiffness and toughness, broadening their applicability in structural components where strength-to-weight ratio is critical. However, challenges like high processing temperatures and cost remain areas of ongoing research to expand broader adoption.

Metal Alloys and Composites

Additive manufacturing involving metal alloys has seen rapid development with processes such as selective laser melting (SLM), direct metal laser sintering (DMLS), and electron beam melting (EBM). Commonly used alloys include titanium, aluminum, stainless steel, and nickel-based superalloys, prized for their superior mechanical properties and corrosion resistance. These methods allow the fabrication of intricate geometries, lightweight structures, and functional parts that would be costly or impossible with traditional manufacturing. Composite materials combining metals with reinforcing particles or fibers are also being explored to enhance performance further. Post-processing techniques like hot isostatic pressing and thermal annealing are frequently employed to improve density, reduce porosity, and strengthen mechanical cohesion. Despite progress, issues such as residual stresses and anisotropy in mechanical properties require meticulous process optimization.

Sustainable and Biodegradable Materials

Sustainability has become a critical focus in the development of 3D printing materials. Biodegradable polymers like polylactic acid (PLA), polycaprolactone (PCL), and poly (lactic-co-glycolic acid) (PLGA) have gained popularity due to their renewability and reduced environmental impact. Their applications span biomedical implants, tissue scaffolds, and eco-friendly consumer products. However, limitations such as lower mechanical strength, sensitivity to moisture, and thermal instability pose challenges for broader industrial use. Advances in composite biodegradable materials, incorporating bioactive ceramics like hydroxyapatite or tricalcium phosphate, enhance mechanical and biological performance for medical applications. Additionally, recycled thermoplastics are being integrated into additive manufacturing to promote circular economy principles, reducing waste and energy consumption. Ongoing research aims to optimize these eco-friendly materials' printability and durability to accelerate their adoption.

All these materials are summarized in Table 1.

Table 1: Comparative Overview of Advances in 3D Printing Materials

Material Category	Description	Key Attributes	Typical Applications	Challenges	References
High-Performance Polymers	Polymers such as PEEK, PPS, and reinforced composites with carbon fibers or ceramics	High thermal resistance, mechanical strength, chemical stability	Aerospace, automotive, structural components	High processing temperature, cost, printability	3,4,26
Metal Alloys and Composites	Titanium, aluminum, stainless steel alloys processed via SLM, DMLS, EBM, and composites	Superior strength, corrosion resistance, complex geometry	Aerospace, medical implants, lightweight structures	Residual stress, anisotropy, post-processing needs	26–28
Sustainable & Biodegradable Materials	Biodegradable polymers like PLA, PCL, composites with bioactive ceramics, recycled plastics	Renewability, eco-friendliness, biocompatibility	Biomedical scaffolds, eco-products, circular economy efforts	Lower mechanical strength, moisture sensitivity	2,4,5

Innovations in Fabrication Methods

Recent developments in fabrication methods for 3D printing have significantly expanded the capabilities and application areas of additive manufacturing. One notable advancement is the emergence of multi-material and multi-process printing techniques. These approaches enable the simultaneous use of different materials within a single manufacturing process, allowing the production of components with varied mechanical, thermal, and functional properties tailored to specific needs. Multi-material printing technologies, such as fused filament fabrication with multiple extruders and material jetting, facilitate the integration of rigid, flexible, and conductive materials in one part. This versatility opens new avenues for creating complex devices, including sensors, actuators, and soft robotics, which rely on heterogeneous material distributions.

The integration of artificial intelligence (AI) and machine learning into additive manufacturing workflows represents another transformative innovation. AI algorithms assist in optimizing design parameters, predicting material behavior, and monitoring the printing process to identify and mitigate defects in real time. Machine learning models analyze large datasets of printing conditions and outcomes, enabling adaptive adjustments to process variables such as temperature, print speed, and layer thickness for enhanced quality and consistency. This data-driven approach reduces trial-and-error iterations, accelerates development cycles, and increases overall manufacturing reliability.
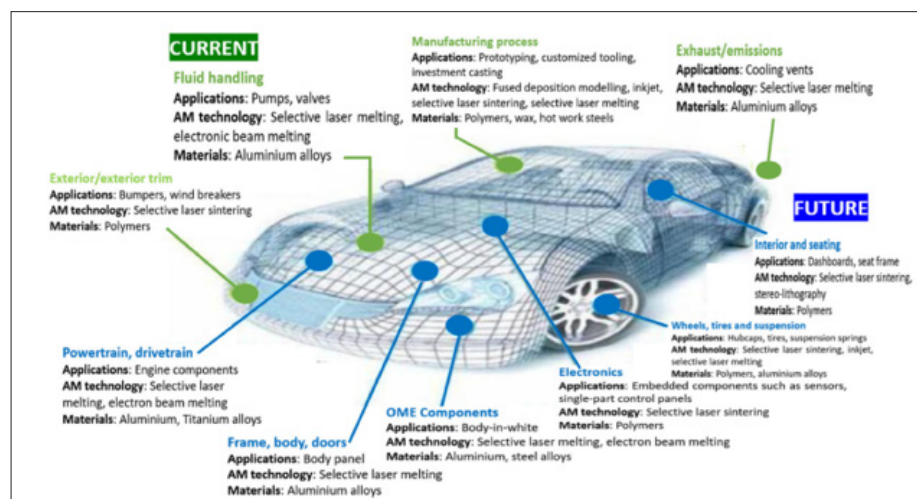
Moreover, these innovations contribute to improved process efficiency, waste reduction, and precision enhancement. Additive manufacturing inherently minimizes material waste compared to subtractive methods, but combining advanced fabrication techniques with AI-driven control systems further optimizes the use of raw materials and energy. Enhanced precision from automated monitoring and feedback loops results in better dimensional accuracy, surface finish, and mechanical performance of printed parts. Collectively, these advancements facilitate sustainable, cost-effective, and high-quality production, reinforcing additive manufacturing's growing role as a practical solution for diverse industrial challenges.

Applications and Case Studies
Aerospace and Automotive Sectors

Additive manufacturing has found extensive application in aerospace and automotive industries by enabling complex designs, weight reduction, and rapid prototyping. Aerospace companies employ 3D printing to fabricate intricate engine components, lightweight structural parts, and tooling aids, reducing production costs and enhancing fuel efficiency. For example, leading aerospace manufacturers have successfully integrated 3D-printed parts such as fuel nozzles, turbine blades, and interior cabin components, achieving significant weight reductions and substantial lead-time savings. Automotive industries use 3D printing for rapid prototyping of engine parts, suspension components, and aerodynamic models, accelerating development cycles and improving design flexibility (Figure 2). Case studies, such as Volkswagen's race car development and aerospace firms producing lightweight aluminum alloys, demonstrate how additive manufacturing accelerates design validation while meeting strict industry standards.

Figure 2: Current Application and Future Aspects of Additive Manufacturing in Automotive Sector [29]
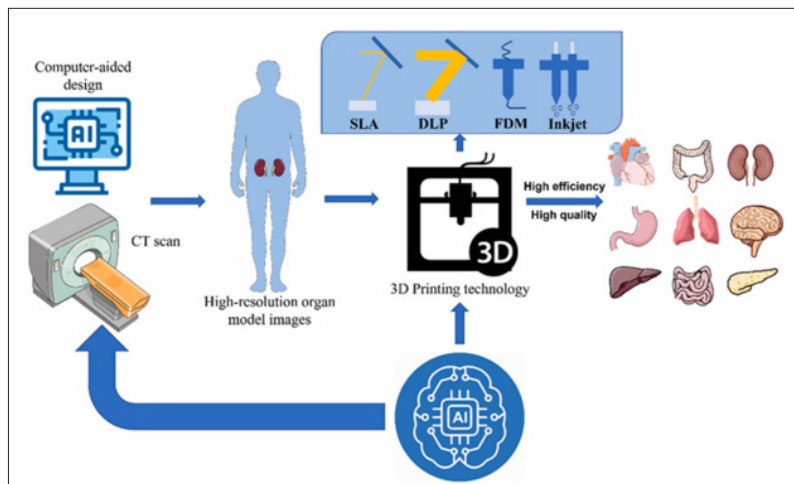
Biomedical and Personalized Medicine

3D printing is transforming healthcare by enabling the production of patient-specific implants, surgical models, and tissue engineering scaffolds. Bioprinting techniques facilitate customized fabrication of scaffolds that mimic native tissue architecture, supporting regenerative medicine advances. Prosthetics and orthotics personalized to individual anatomies improve patient comfort and functionality. The ability to rapidly produce customized medical devices and anatomical models aids surgical planning and reduces operation times. These innovations have been validated in clinical cases, where 3D-printed implants and guides significantly improved treatment outcomes. The integration of biocompatible and biodegradable materials further enhances application potential in personalized medicine.

Industry 4.0 Manufacturing Ecosystems and Decentralized Production

Additive manufacturing plays a vital role in the realization of Industry 4.0 by facilitating flexible, interconnected, and data-driven production environments. Smart factories incorporate 3D printing within digital manufacturing ecosystems to enable decentralized, on-demand production close to point-of-use, reducing inventory and supply chain dependencies. The synergy of 3D printing with IoT sensors, AI-driven process controls, and cloud-based data analytics supports adaptive manufacturing that can respond in real-time to

changing requirements (Figure 3). Decentralized production reduces lead times and logistical costs while enhancing customization capabilities. This shift aligns with sustainable manufacturing goals by minimizing waste and energy consumption and supports rapid innovation cycles across industries.
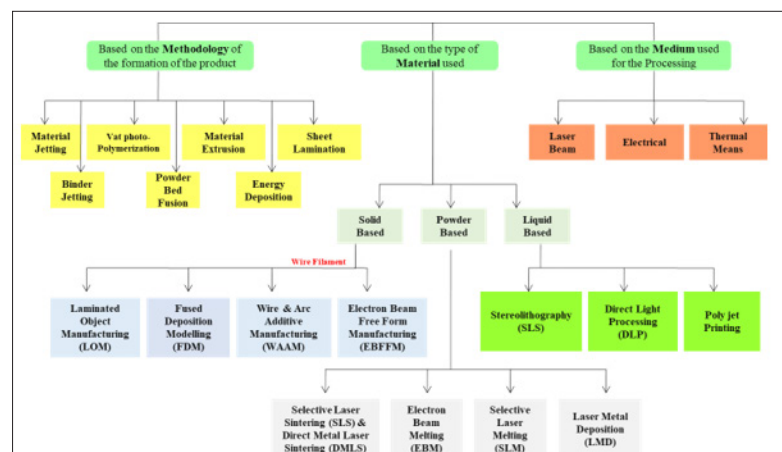

Figure 3: AI-Driven Workflow For 3D Printing

Challenges and Future Prospects
Despite considerable progress, several challenges continue to affect the widespread adoption of 3D printing technologies (Figure 4). One primary concern involves material limitations and mechanical reliability. Although advances have been made in developing durable and high-performance materials, issues such as anisotropy, porosity, and inconsistent mechanical properties persist. Printed parts occasionally show variability in strength and fatigue resistance compared to conventionally manufactured components, complicating their use in safety-critical applications. Further research is needed to enhance material homogeneity, improve bonding between layers, and develop standardized testing protocols that ensure reliable material behavior.

Scalability and quality control present additional hurdles. While 3D printing excels in rapid prototyping and low-volume production, scaling up to mass manufacturing remains a challenge. Factors such as slower build rates, higher per-unit costs, and equipment limitations require optimization to improve throughput. Quality control is complicated by process variability, defects, and the intricacies of monitoring complex geometries in real time. Implementing robust sensor technologies, real-time monitoring, and automated defect detection are key to ensuring consistent product quality as production volumes increase.

Regulatory and sustainability challenges also influence the future trajectory of additive manufacturing. Regulatory frameworks have yet to fully adapt to the unique aspects of 3D-printed products, such as varying material characteristics and decentralized manufacturing models. Certifications, safety standards, and intellectual property protections require revision to accommodate these innovations. Sustainability considerations encompass both material lifecycle impacts and energy consumption, emphasizing the necessity for eco-friendly materials, efficient processes, and circular economy principles to reduce environmental footprints.

Looking ahead, emerging trends and research directions promise to address these challenges and further expand 3D printing's capabilities. Innovations in multifunctional materials, improved process automation, and enhanced AI-driven design and control systems are setting the stage for more reliable, scalable, and sustainable manufacturing solutions. Additionally, hybrid manufacturing, combining additive and subtractive methods, is attracting interest for balancing material efficiency with precision. Efforts to develop open-standard data protocols and collaborative platforms will foster interoperability across machines and industries, accelerating technology adoption. Collectively, these advancements position 3D printing to become a cornerstone of future manufacturing ecosystems.

Figure 4: Multi-Material 3D Printing Technologies

Conclusion

This paper has explored key advancements in 3D printing materials and fabrication methods that are transforming manufacturing industries. High-performance polymers, metal alloys, and sustainable biodegradable materials are expanding the scope of additive manufacturing by delivering improved mechanical properties, environmental benefits, and application versatility. Innovations in multi-material printing and AI-driven process optimization enable complex, precise production workflows that reduce waste and accelerate development. The review highlights diverse applications in aerospace, automotive, and biomedical sectors, alongside the emergence of decentralized, Industry 4.0-enabled manufacturing ecosystems.

The implications for manufacturing are profound: 3D printing provides new design freedoms, customization capabilities, and leaner supply chains that support rapid innovation and sustainability goals. However, challenges remain in material reliability, process scalability, regulatory adaptation, and environmental impacts that require coordinated research and development efforts.

Looking forward, the future of 3D printing is promising, driven by advances in intelligent automation, multifunctional materials, hybrid manufacturing techniques, and collaborative digital platforms. These developments will further integrate additive manufacturing into mainstream industrial production, enabling flexible, on-demand, and eco-friendly manufacturing solutions tailored to evolving market and societal needs. Through continued technological refinement and strategic adoption, 3D printing is poised to be a cornerstone of next-generation manufacturing that enhances productivity, sustainability, and competitiveness across sectors.

Acknowledgments

References

1. Gahletia S, Garg RK (2025) Dismantling barriers in integrating patient-centred care with additive manufacturing to assess the fit of orthodontic retainers for futuristic preventative healthcare. Prog Addit Manuf 10: 1063-1084.
2. Ma T, Zhang Y, Ruan K, Guo H, He Mukun, et al. (20024) Advances in 3D printing for polymer composites: A review. InfoMat 6: e12568.
3. Tahir M, Vicini S, Sionkowska A (2023) Electrospun Materials Based on Polymer and Biopolymer Blends—A Review. Polymers 15: 1654.
4. Alarifi IM (2024) Revolutionising fabrication advances and applications of 3D printing with composite materials: a review. Virtual Phys Prototyp 19: e2390504.
5. Malefors C, Strid I, Eriksson M (2022) Food waste changes in the Swedish public catering sector in relation to global reduction targets. Resour Conserv Recycl 185: 106463.
6. Dhingra AK, Chhabra D, Gahletia S, Dhingra S (2024) Driving Design and Performance of Dental Restorations through Next-Generation Additive Manufacturing Resins. In: 2024 3rd International Conference on Computational Modelling, Simulation and Optimization (ICCMSO) IEEE: Phuket, Thailand 344-349.
7. Kumar P, Kaushik A, Gahletia S, Kumar GR, Shivam R, et al. (2023) Investigations of Digital Model Using Extraoral Scanner, Resin Printing and Fused Deposition Modelling to Fabricate a Dental Arch Model. In: 2023 2nd International Conference on Computational Modelling, Simulation and Optimization (ICCMSO) IEEE: Bali, Indonesia 24-252.
8. Peng G, Chang B, Wang G, Gao Y, Hou R, et al. (2021) Vision sensing and feedback control of weld penetration in helium arc welding process. J Manuf Process 72: 168-178.
9. Wang Z, Wang L, Tang F, Chen J (2024) Multi-material additive manufacturing via fused deposition modeling 3D printing: A systematic review on the material feeding mechanism. Proc Inst Mech Eng Part E J Process Mech Eng 09544089231223316.
10. Kumar AS, Agarwal A, Jansari VG, Desai KA, Chattopadhyay C, et al. (2025) Realizing on-machine tool wear monitoring through integration of vision-based system with CNC milling machine. J Manuf Syst 78: 283-293.
11. Elnadi M, Abdallah YO (2024) Industry 4.0: critical investigations and synthesis of key findings. Manag Rev Q 74: 711-744.
12. (2025) Anonymous. AI and 3D Printing – How Innovation Is Reshaping Manufacturing. Neural Concept https://www.neuralconcept.com/post/how-ai-is-transforming-additive-manufacturing.
13. Chhabra D, Punia U, Gahletia S, Kumar GR, Sehrawat R, et al. (2022) 3D Printable NiTi Alloys for Biomedical Applications: A State of Art. In: 2022 International Conference on Computational Modelling, Simulation and Optimization (ICCMSO) IEEE: Pathum Thani, Thailand 301-306.
14. Sharma A, Bharti PS (2025) Optimization of Resin Printing Parameters for Improved Surface Roughness Using Metaheuristic Algorithms: A Multifaceted Approach. J Mater Eng Perform 34: 8525-8539.
15. Singh S, Attri RK, Trivedi S (2025) Optimization of FDM 3D Printing Process Parameters for Improving Wear Characteristics of PLA-nGr Composite using Taguchi DOE. J Mater Eng Perform 34: 15179-15187.
16. Gaikwad MU, Krishnamoorthy A, Jatti VS (2020) Estimation of Surface Integrity Parameters in Electrical Discharge Machining (EDM) Process-A Review. In: Techno-Societal 2018. Springer International Publishing: Cham 601–614.
17. Firlej M, Zaborowicz K, Zaborowicz M, Firlej E, Domagała I, et al. (2022) Mechanical Properties of 3D Printed Orthodontic Retainers. Int J Environ Res Public Health 19: 5775.
18. Legaz J, Sailer I, Mojon P, Lee H, Karasan D (2023) Mechanical Properties of Additively Manufactured and Milled Interim 3-Unit Fixed Dental Prostheses. J Prosthodont 32: 234-243.
19. Gaikwad MU, Gaikwad PU, Ambhore N, Sharma A, Bhosale SS (2025) Powder Bed Additive Manufacturing Using Machine Learning Algorithms for Multidisciplinary Applications: A Review and Outlook. Recent Pat Mech Eng 18: 12-25.
20. Atta I, Bourauel C, Alkabani Y, Mohamed N, Kimbe H, et al. (2024) Physiochemical and mechanical characterisation of orthodontic 3D printed aligner material made of shape memory polymers (4D aligner material). J Mech Behav Biomed Mater 150: 106337.
21. Chhabra D, Kumar Dhingra A, Kaushik A, Dhingra S, Kumar RS, et al. (2024) Transforming Dentistry Using Artificial Intelligence Based Innovations for Advanced Diagnostics and Sustainable Healthcare. In: 2024 3rd International Conference on Computational Modelling, Simulation and Optimization (ICCMSO) IEEE: Phuket, Thailand 176-181.
22. Gaikwad MU, Gaikwad P, Krishnamoorthy A, Jatti VK, Ambhore N, et al. (2023) Fatigue analysis of electro discharge machined Nitinol 60. Innov Emerg Technol 10: 2340009.
23. Jindal P, Juneja M, Siena FL, Bajaj D, Breedon P (2019)

Mechanical and geometric properties of thermoformed and 3D printed clear dental aligners. Am J Orthod Dentofacial Orthop 156: 694-701.

24. Naeem OA, Bencharit S, Yang I-H, Stilianoudakis SC, Carrico C, et al. (2022) Comparison of 3-dimensional printing technologies on the precision, trueness, and accuracy of printed retainers. Am J Orthod Dentofacial Orthop 161: 582-591.

25. Williams A, Bencharit S, Yang I-H, Stilianoudakis SC, Carrico C, et al. (2022) Effect of print angulation on the accuracy and precision of 3D-printed orthodontic retainers. Am J Orthod Dentofacial Orthop 161: 133-139.

26. Khedkar NK, Sonawane C, Chandras A, Kulkarni A, Sawant R (2022) Experimental and numerical investigation of Cross-Flow nebulizer for developing optimized suction pressure. Mater Today Proc 59: 617-622.

27. Shan W, He X, Liu H, Heidari AA, Wang M, et al. (2023) Cauchy mutation boosted Harris hawk algorithm: optimal performance design and engineering applications. J Comput Des Eng 10: 503-526.

28. Modi KV, Patel UN, Patel SJ, Patel JN, Patel SR (2022) Efficacy of partially and fully submerged circular cross-section metal hollow-fins and black cotton cloth wick-segments on a single-basin dual-slope solar still. J Clean Prod 344: 131059.

29. Yang J, Li B, Liu J, Tu Z, Wu X (2024) Application of Additive Manufacturing in the Automobile Industry: A Mini Review. Processes 12: 1101.