Sustainable Materials and Manufacturing 01 (2026) 1–33

Sustainable Materials And Manufacturing

journal homepage: https://sshapi.hapiacademia.com/SMM

Type of the Paper: Review

3D Printing in Artificial Organs and Medical Implants: Technologies, Applications, and Future Perspectives

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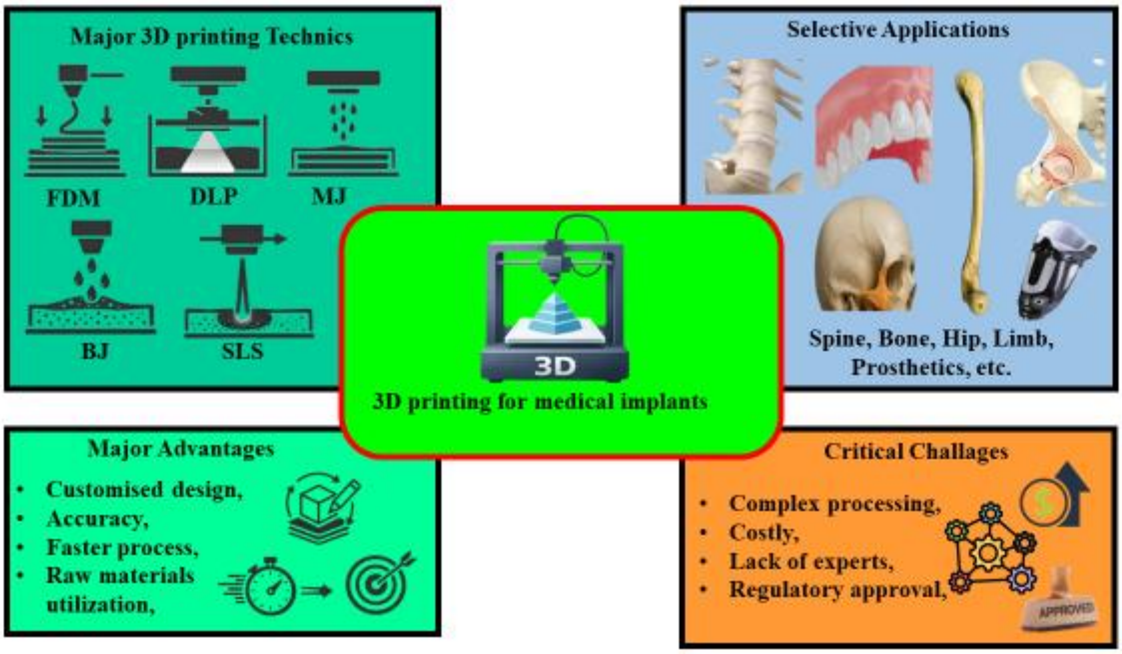
Sustainable Materials and Manufacturing ***2026****, (01), 1-33. https://doi.org/10.67339/qr9dk046* *https://sshapi.hapiacademia.com/SMM*

Abstract

Growing demand for organ transplants alongside the crisis of suitable donors has propelled advances and in regenerative medicine and biomedical engineering. Three-Dimensional (3D) organ printing is a modern technology that meets the criteria for building functional biological structures while maintaining requirements of biomaterial science and additive manufacturing. 3D-printed medical implants are highly customised and functionally appropriate, reducing immune rejection rates and dependence on organ donors. Currently, there are several techniques of 3D printing, like FDM, DLP, SLS, etc. Each of them has its advantages and disadvantages from the point of material selection, physical and chemical conditions of printing ink, process requirements, and final products. Recent decades' major advancements in 3D printing technology, tissue engineering, and printing materials have enhanced the resolution, viability, and functionality of printed tissues. This technology has now shifted towards more complex structures like kidneys, hearts, and livers. This review provides a comprehensive overview of the most popular 3D printing technology used for 3D organ printing, progress, materials, and emerging applications. It also focused on the multidisciplinary nature and potential of 3D printing and discussed existing challenges and future perspectives to better utilize 3D printing to increase surgical efficiency and patient satisfaction.

Keywords: 3D printing, Artificial Organ, Medical implant, Additive manufacturing, 3D printing Applications.

Graphical Abstract



1. Introduction

Three-dimensional (3D) printing is a modern additive manufacturing technology that builds final materials according to Computer-Aided Design (CAD) models, enabling the construction of complex structures. Unlike subtractive manufacturing methods, here materials are added only where they are required, minimizing waste (Kumar *et al.*, 2025). There are different 3D printing methods, distinguished by their processing methods, uses of raw materials, and final product properties. The most popular 3D printing methods include FDM, SLA, DLP, SLS, MJ, and BJ (Hüner *et al.*, 2022). Different 3D printing processes are used to create scaffolds, implants, and tissue models that support healing and regeneration. Stereolithography (SLA) and Digital Light Processing (DLP) are used to generate high-resolution scaffolds by light-curing photosensitive resins (Jeong *et al.*, 2024). Fused Deposition Modeling (FDM) uses thermoplastic polymers to create cost-effective, biocompatible structures, but with lower resolution (Mishra *et al*., 2023). Selective Laser Sintering (SLS) produces porous, durable scaffolds by melting polymer or ceramic powders (Song *et al.*, 2024). Extrusion-based bioprinting is more appropriate in tissue engineering, where bio-inks are deposited and filled with living cells and hydrogels to build tissue-engineered constructs (Chen *et al.*, 2023).

Although 3D printing is used in different areas, in the field of regenerative medicine, it is considered a groundbreaking technological advancement for developing complex geometrical structures. Its main application in the biomedical field is the creation of functional organ models, such as liver, kidney, and heart tissue, used in disease modeling, drug discovery, and personalized therapy. One of the most significant benefits includes high individualization to accommodate patient-specific anatomy, better cell viability due to precise positioning, and the ability to create complex vascular networks. Traditional organ transplantation has several major challenges, including donor scarcity and host response. In this case, the adoption of 3D printing offers a sustainable potential alternative by maintaining patient-specific implants, as prepared based on CAD models. Patient MRI or CT scan data ensures the accuracy of printed enable the integration of living cells, growth factors, and bioactive molecules in printing, enabling the proper mimicry of the natural structure properly, thereby improving the host response. The integration of advanced materials and stem cell biology in bio-printing techniques has improved both the structural and functional properties of printed implants. The adoption of advanced materials as a print raw material further enhances mechanical properties, cell proliferation, and host body responses (Gao *et al.*, 2025). Alongside integration of vascularization and multi-material printing, it has enhanced the viability and durability of long-term applications (Zheng *et al.*, 2024).

The application of 3D-printed organs has extended to encompass disease modeling, surgical planning, and pharmaceutical testing, in addition to transplant implementations. However, existing challenges, such as scalability, vascularization, and functional durability, limit its mass adoption. This review work emphasizes a comprehensive analysis of different 3D printing techniques, materials, progress, applications, challenges, and future innovations. By summarizing the latest research, this review focuses on highlighting the transformative potential of 3D organ printing in regenerative medicine.

2. 3D printing

In the 3D printing manufacturing technique, the object is gradually developed in X, Y, and Z directions according to the predetermined digital model. The traditional manufacturing process typically involves cutting, molding, and other methods, where products are built layer by layer during the printing process (Narongdej *et al.*, 2024). This offers precise control over design and customizable manufacturing with minimal waste. The application of 3D printing techniques has diversified into multiple sectors, such as healthcare, aerospace, fashion, and so on. In healthcare, it is used for prosthetic implants and regenerative medicines (Kanumilli *et al.*, 2024). A wide range of raw materials can be used in 3D printing, including commonly used polymers, metals, and ceramics. Also, there are a few major challenges, such as long print times, specific material limitations, post-processing, and technical difficulties. However, continuous advancements in technology and greater innovations in faster prototyping and designing have made this technology more widespread (Ngo *et al.*, 2018; Said *et al.*, 2025). 3D printing stages vary according to different printing processes, but overall, they follow a general workflow as shown in Fig. 1.

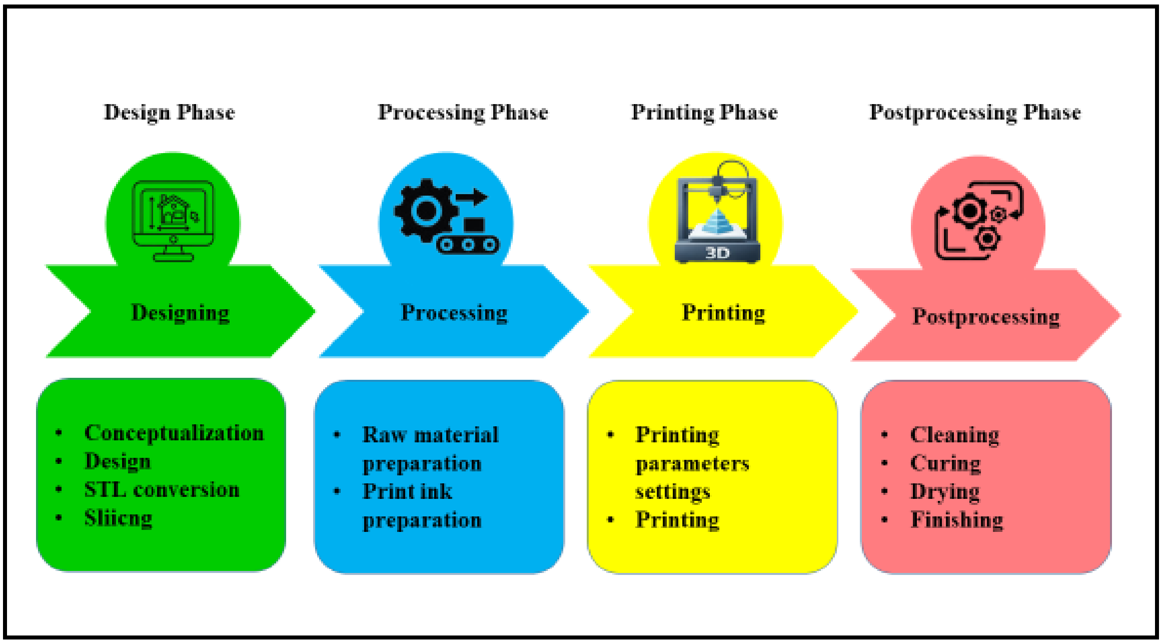


Fig. 1. General workflow of the 3D printing process

3. Major 3D printing techniques for medical implants:

3D printing technology has been considered an effective tool for developing medical implants and artificial organs due to its ability to create personalized structures. Traditional manufacturing methods like machining, casting, and molding are normally subtractive, time-consuming, and inflexible in terms of design (Mobarak *et al.*, 2023). 3D printing technology utilizes virtual models for creating structures. This is significant for biomedical applications, as implants need to be accurately matched to anatomical structure (Kermavnar *et al.*, 2021). For example, 3D-printed implants that are personalized for the specific bone defect in the human body result in better integration and reduce complications during surgery. Moreover, 3D printing technology is particularly advantageous over conventional technology due to its ability to speed up production, reduce material loss, and create prototypes (Safali *et al.*, 2023; Li *et al.*, 2024). There are several techniques of 3D printing, each of which has its advantages and limitations. Based on the material, processing conditions, and final application methods, material development is chosen (Nazir *et al.*, 2023). A few of the most common techniques, Fig.2 includes Fused Deposition Modeling (FDM), Stereolithography (SLA), Selective Laser Sintering (SLS), and Binder Jetting. FDM is commonly used for filament; SLS and DLP are suitable for photopolymer resin that is cured by UV light, and SLS involves laser technology (Bozkurt and Karayel, 2021; Mirshafiei *et al.*, 2024). A detailed discussion will be included in further sections.

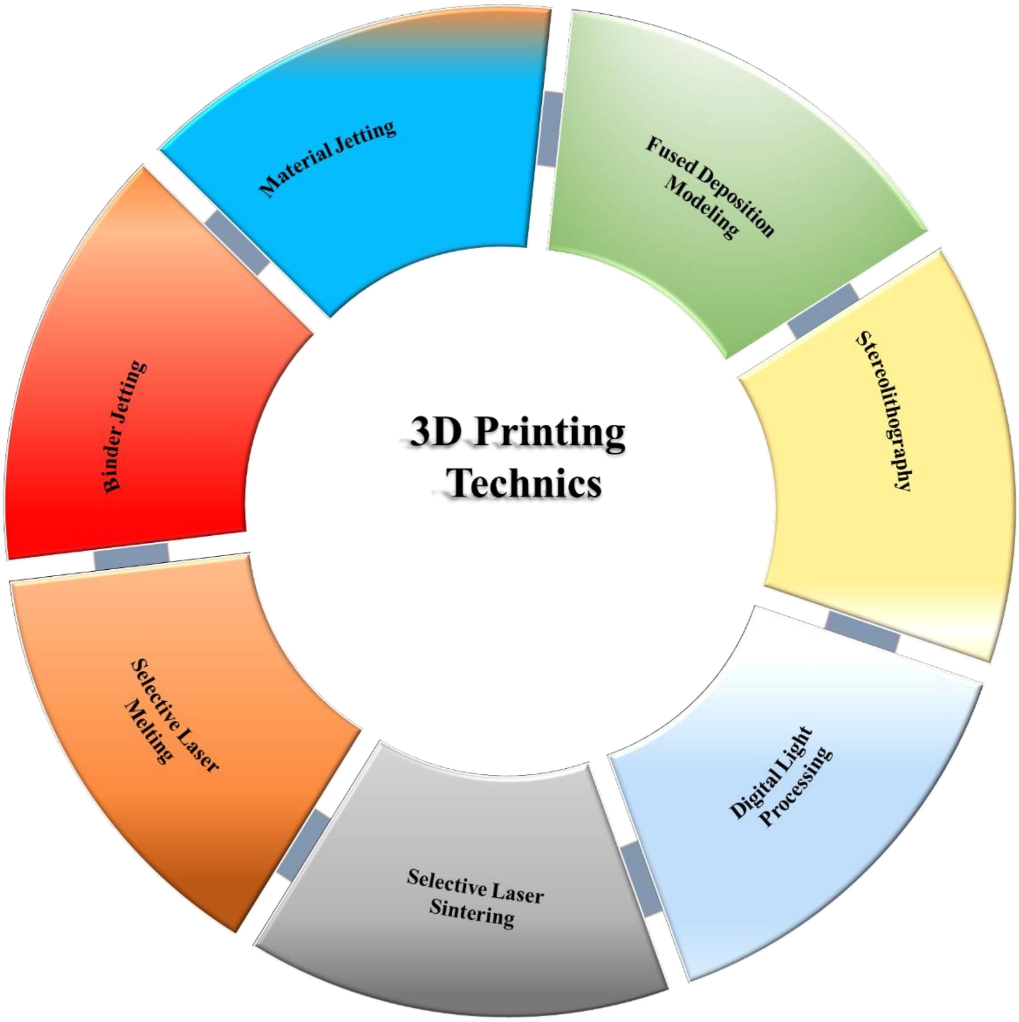


Fig. 2 Major categories of 3D Printing Machines, including Fused Deposition Modeling (FDM), Stereolithography (SLA), Digital Light Processing (DLP), Selective Laser Sintering (SLS), Selective Laser Melting (SLM), Binder Jetting, and Material Jetting.

3.1. Fused Deposition Modeling

Fused Deposition Modeling (FDM) is a popular 3D printing method due to its operational simplicity, affordability, and the versatility of raw materials, making it increasingly popular. FDM printers work by extruding thermoplastic materials through a heated nozzle, where the filament melts in contact with the hot nozzle and deposits it layer by layer onto the build platform. Final products are obtained through cooling by solidification, as shown in Fig. 3a (Mishra *et al.*, 2023).Key segments of FDM printers include the extruder, hot end, control board, and build platform. The entire process is controlled by stepper motors that move the extruder in X, Y, and Z directions, ensuring precise positioning (Doshi *et al.*, 2022). In the past few years, significant improvements have occurred in the advancement of 3D printing, including FDM. Traditional layer-by-layer deposition was fixed in the Z-axis direction only, which is inappropriate for curved surfaces. To optimize layer orientation and surface quality, multi-axis and non-planar printing systems have been developed that include rotational motion (Fig. 3b), which facilitates printing on curved surfaces and reduces the need for support structures (Yao *et al.*, 2024).This has significantly improved surface quality and mechanical performance by optimizing layer orientation. Challenges remain in motion planning, collision avoidance, and the design of advanced slicing algorithms (Afshari *et al.*, 2025). Additional material innovation has also accelerated rapidly; to achieve high performance, the use of composite filaments is increasing. Reinforcement of carbon-fiber, glass-fiber, and nanoparticles into polymers has led to improved properties like strength-to-weight ratios and heat resistance. At the same time, demand for sustainability triggered the development and utilization of bio-based and recycled materials, including natural fibers or industrial by-products, to ensure biodegradability without major losses in printability (Nguyen et al., 2023). FDM machines are being designed for higher speed and mass manufacturing. Motion architectures like Core XY that are optimized, improved hot-end heat management, and cooling techniques now allow much higher speed printing with acceptable dimensional accuracy (Mustaqim *et al.*, 2025). Considering productivity and rapid prototyping, large-format FDM printers are also being utilized for tooling, jigs, and end parts in industry (Klenam et al., 2025).

Updated models also offer dual extrusion for multi-material and multi-color printing. In contrast, visible layer lines and lower resolution are major drawbacks. FDM is popular for rapid prototyping, custom part building, and medical applications. Furthermore, the addition of smart monitoring, automation, real-time extrusion feedback through sensors, and auto-calibration features could significantly improve reliability and reduce print failures.

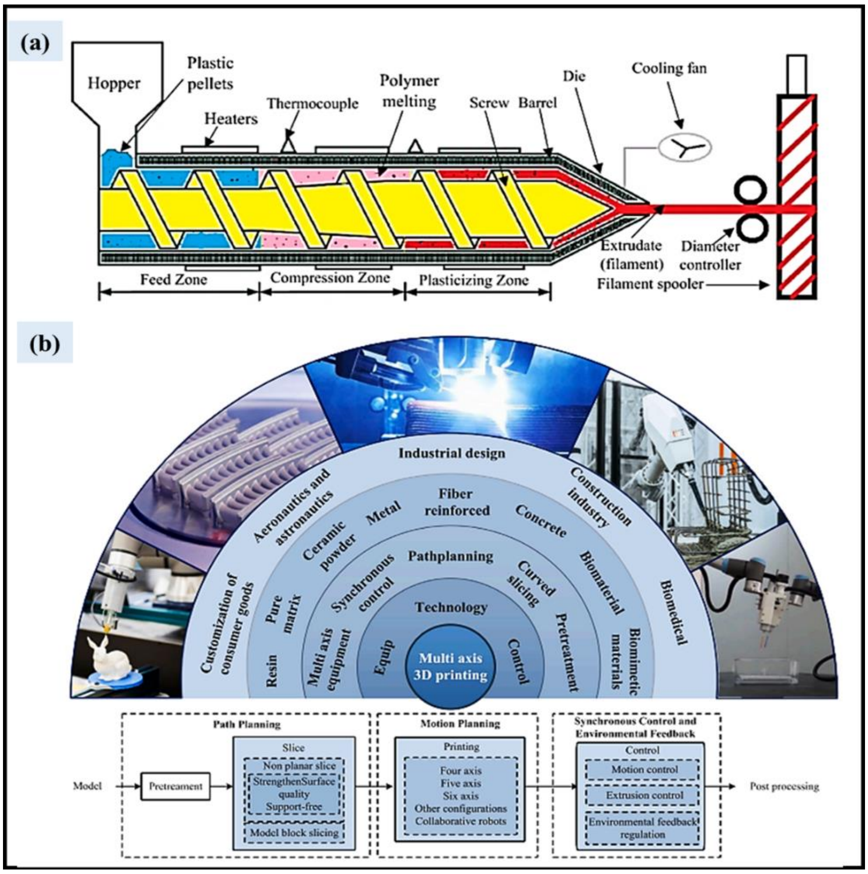


Fig. 3. **(a)** Schematic illustration of the extrusion process (Mishra *et al*., 2023) **(b)** Overview of the multi-axis 3D printing process (Yao *et al*., 2024).

3.2. Stereolithography (SLA)

Stereolithography (SLA) is a pioneer and one of the most precise 3D printing techniques. SLA is popular for its high resolution and smooth surface objects. The object is built through photo-polymerization, in which a digital light projector or laser selectively cures a liquid photopolymer. At the initial stage, the 3D model of the object is sliced into parts, and during printing, the build platform is submerged into a vat filled with photopolymer resin; subsequently, a light source is applied to the selected area. After light exposure, the photopolymer starts solidifying. The build platform travels in the Z direction after the formation of each layer, allowing the next layer to form on top of the previous one (Quan *et al.*, 2020).

In the material & resin domain, use of functional and biocompatible resins is emerging (for medical/dental applications) with improved mechanical properties that reduce post-processing burdens. The development of novel photopolymer resins that reduce post-processing time while improving print quality. Also, there is work on tunable-modulus resin blends achieving PDMS-like elasticity in SLA microfluidic work (Ahmadianyazdi *et al.*, 2023). From a resolution/fidelity/ print-quality perspective, SLA continues to lead in fine features/surface finish, and recent work is further pushing boundaries: improved laser/optics, better control of curing front, and machine-learning-assisted parameter optimization to reduce defects. Another emerging direction is large-format, high-throughput SLA and volumetric approaches, where full 3D volumes are cured rather than layer-by-layer, which is being explored, improving speed and scalability (Chandan *et al.*, 2026).

Alongside process and materials, applications are expanding in medical/dental, microfluidics, functional prototypes, and even end-use parts rather than just aesthetic prototypes to meet the demand for functionality such as durability, heat resistance, biocompatibility, and multi-material resins. To increase sustainability, processes are being optimized for waste minimization, reducing support requirements, and post-processing (Mobarak *et al.*, 2023; Tuli et al., 2024).

SLA offers very accurate surface finishing, making it suitable for critical application fields like dental models, jewelry, and prototypes. Also, photopolymers used in SLA can be further modified to improve flexibility, transparency, and biocompatibility according to product specifications (Jeong *et al.*, 2024). In contrast, curing under UV light and resin recovery are major drawbacks of SLA printing. Also, under prolonged exposure to UV light, the brittleness of the resin increased, which could affect the structure (Miedzińska *et al.*, 2020). Overall, SLA is a widely used 3D printing technique, particularly to build sophisticated objects where high precision is essential.

3.3. Digital Light Processing (DLP)

In the Digital Light Processing (DLP) 3D printing technique, in the presence of UV light, the photopolymer resin starts curing, and the objects are built layer by layer (Deng *et al.*, 2022). Before printing the 3D model of the object, it needs to be designed and sliced into thin layers using specialized software. The printer vat is subsequently filled with liquid photopolymer resin. After the vat is filled, the UV light source is employed on a selective area. The projected light source starts to solidify the resin. The build platform, initially positioned just below the surface of the resin, gradually moves upward in the Z direction as each layer is cured, allowing the next layer to be formed on top of the previous one (Huang *et al.*, 2024).

The adoption of Digital Light Processing (DLP) 3D printers has expanded due to their precision, accuracy, and convenience. Major innovations have happened in photopolymer resin and print materials recently that offer functional properties for the end products, while maintaining printing requirements (Hussain *et al.*, 2025). To improve functional properties like mechanical, thermal, and optical properties, photopolymer resins can be further engineered to be rigid, flexible, transparent, or to improve biocompatibility. Washing and additional UV curing are often required during post-processing to fully cure the printed object and remove any residual uncured resin (Hussain *et al.*, 2024). New commercial resins possess long-term flexibility with low compression set, offering good dimensional stability, high wear, and thermal stability. A part of this, ceramic-based print materials, is developed for DLP-enabled fabrication of high-strength, fully dense end products (Chen *et al.*, 2019). However, DLP 3D printing has relatively high costs for materials and equipment, as well as the need for careful handling of the resin, while using toxic resin (Zhao *et al.*, 2020).

Innovation in high-resolution DLP printers included precision, making them suitable for precision-based applications such as dental work and jewelry-making (Su *et al.*, 2023). Residual resin utilization always remains a major limitation for DLP printing. Considering sustainability, reusable and recyclable DLP resins have been studied by many researchers to reduce environmental impact (Maines *et al.*, 2021). The market forecast shows robust growth in the 3D printing industry with a projected market value of $871 million in 2025, driven by applications in jewelry, dentistry, and other sectors. This reflects the adoption and expansion of DLP technology across various industries (Zoting, 2025). Further advantages include the utilization of machine learning and artificial intelligence (AI) in the DLP to increase process optimization and real-time error detection, which will certainly increase the precision and productivity of printing (Sani *et al.*, 2024).

3.4. Selective Laser Sintering (SLS)

In the Selective Laser Sintering (SLS) technique, a high-powered laser is used to fuse powdered material into a solid structure. At the initial stage, a thin layer of material (powder form) spreads homogeneously across the build platform. Subsequently, a controlled laser selectively sinters the powder particles according to the cross-sectional pattern of the build. Once a layer is finished, the platform lowers incrementally, and subsequently, a fresh layer of powder is again spread over the build platform (Charoo *et al.*, 2020; Song *et al.*, 2024).

Recent advancements in Selective Laser Sintering (SLS) 3D printing in the past 2–3 years have significantly enhanced its speed, precision, and versatility to be increasingly suitable for production scale in industry (Ali *et al.*, 2023). New powder materials have been used to build parts with enhanced mechanical properties and tailored thermal or electrical conductivity. These advancements have extended SLS use in aerospace, automotive, and medicine (Tan *et al.*, 2020). Furthermore, multi-material printing has also opened up the possibility of combining different powders for one print. It also allowed mixing multiple powders for one print job, which ensures the creation of complex parts with different material properties with minimal post-processing (Nazir *et al.*, 2023).

The major advantage of the SLS technique over other techniques is that SLS allows complex geometrical structures, while maintaining lattice structures and internal channels, to be built without a support structure. Here, unsintered powder acts as a natural support during printing. Besides, SLS builds objects that show high strength and durability, suitable for hard tissue and implants with high mechanical strength (Ahmadi *et al.*, 2022). Major drawbacks include costly equipment and proper post-processing to improve surface smoothness by removing residual powder (Korkmaz *et al.*, 2022). Overall, SLS offers unique capabilities for rapid prototyping, more suitable for small-batch production.

3.5. Selective Laser Melting (SLM)

The Selective Laser Melting (SLM) technique is generally used to create complex, high-precision metal parts. Like powder bed fusion (PBF) technology, high-power lasers are used to melt and fuse metallic powder particles to build objects layer by layer (Papazoglou *et al.*, 2022). In recent years, it has seen significant improvement in machine, materials, and process optimization. Innovation, including multi-laser systems, results in higher productivity and reduces the production cost (Gunasekaran *et al.*, 2021). The slicing software determines the 3D model and slices it into thin cross-sectional layers. A focused laser beam is used to scan over the thin layer of metal powder spread across the build platform, which melts the powder particles and fuses them. After completing each layer, the build platform is lowered (a few microns), and fresh powder is laid down over the previous layer to construct the next layer. This cycle continues until the complete object is built (Alsaddah, 2023).

In powder metallurgy, ultrasonic atomization techniques have been used for the creation of metal powders with high sphericity and low oxygen content, which ensures dense and defect-free end products (Sojoodi et al., 2025). SLM printing lasers use power ranging from 100 W to 1 kW, with common wavelengths of 1070 nm (fiber lasers) or 1064 nm (Nd: YAG lasers), achieving spot sizes between 50–200 μm. Layer thicknesses range change within 20 to 100 μm, according to material and desired resolution (Alsaddah, 2023). Common raw metallic materials include stainless steels (316L, 17-4PH), titanium alloys (Ti-6Al-4V), aluminum alloys (AlSi10Mg), and nickel-based superalloys (Inconel 718, 625) (Alsaddah *et al.*, 2022). SLM achieves very high density (>99.5%) with mechanical properties. An inert atmosphere is essential during printing, which is maintained by Argon or Nitrogen, with oxygen levels maintained below 0.1% to prevent oxidation (Becker & Dimitrov, 2016; Wegewitz et al., 2023).

Besides, process optimization has also been studied by researchers to determine the influence of various parameters on the mechanical behavior of built parts. Studies found that major control parameters, including laser power, scanning speed, and layer thickness, have a significant influence on the microstructure and mechanical performance of the printed components (Chia *et al.*, 2022). In addition, SLM produces near-net shape and requires less post-processing, making the process very attractive. Also, raw materials used for SLM are application-specific (Iftekar *et al.*, 2023). However, major limitations include comparatively slow and costly critical process optimization. Also, high thermal gradients during melting and solidification lead to residual stresses and distortions in the final object (Gao *et al.*, 2023). Despite these drawbacks, SLM is widely used in different fields of modern engineering sectors.

3.6. Binder Jetting (BJ)

In Binder Jetting (BJ) methods, a liquid binding agent selectively binds powder particles to build the object in a layer-by-layer fashion. Initially, powder materials (metal, sand, ceramics, or polymer) are spread evenly across the build platform by a roller or blade (Li *et al.*, 2020). Binder droplets are deposited by the print head across the powder bed, building the objects according to the 3D design. Here, binder droplets bind the powder particles together, forming a solid layer of the object. After completing each layer, the build platform lowers slightly, and a fresh layer of powder is spread over the previous one (Mirzababaei and Pasebani, 2021).

Binder jetting 3D printing has seen technological improvement in recent years. At the material level, enhancing the quality and performance of printed parts using silicon carbide (SiC) powder binder jetting facilitates high-quality formation of green bodies and efficient post-densification processes by optimizing process parameters, paving the way for SiC-based ceramic parts in industrial applications (Liu *et al.*, 2025).

Similarly, advances in metal binder jetting have led to increased part density and mechanical properties, making it an alternative to the traditional method of casting and machining (Li *et al.*, 2020). Fresh advancements have also improved the understanding of densification behavior while sintering, allowing for more control and accuracy of the final properties of the printed parts (Du *et al.*, 2020).

Common acrylic-based photopolymers, elastomers, and composites are cured subsequently via UV light after deposition, whereas multi-material jetting systems, such as PolyJet (Stratasys) and Nano Particle Jetting (XJet), allow simultaneous deposition of different materials or colors together, helping to achieve functional properties and complex geometries (Chmielus *et al.*, 2025).

Binder Jetting enables building of complex structures, while maintaining intricate details, without support structures, as the surrounding powder provides support during the build process. Faster cycle makes BJ suitable for both prototyping and large-scale production. However, Binder Jetting builds objects that often require post-processing, such as curing, sintering, or infiltration, to improve surface finishing (Lores *et al.*, 2022). Overall, Binder Jetting offers cost-effective and colored parts, which are popular in healthcare.

3.7. Material Jetting (MJ)

Material jetting (MJ) has similarities with inkjet printing. In MJ, liquid photopolymer is used on the build platform instead of ink. During printing, a piezoelectric printhead deposits droplets in a controlled manner; subsequently deposited droplets are immediately cured by using UV light (Gülcan *et al.*, 2021).

In recent years, material jetting (MJ) has also witnessed vast improvements that have broadened its applications in a wide range of industries. These include: photopolymers with high resolution that improved the mechanical qualities and elasticity of components obtained by the MJ, well-suited for medical implants (Timofticiuc et al., 2023). Also, developments in biocompatible and biodegradable materials have provided new horizons for MJ in medicine, with the possibility to design and develop patient-specific implants and prosthetics with excellent surface finish (Nizam et al., 2024). Besides, MJ methods allow deposition of multiple materials simultaneously, offering multi-material and multi-color parts for functional applications. It also supports a variety of photopolymers that make it suitable for rapid prototyping. However, MJ builds objects that show a tendency to brittleness and structural damage at prolonged exposure to UV light, which limits its application for certain functional objects (Chokshi *et al.*, 2025).

Implementation of the most recent technologies, like machine learning (ML) and artificial intelligence (AI), into MJ systems has the potential to further advance print quality and precision by providing real-time monitoring and adaptive control (Ma *et al.*, 2023). Overall, MJ is ideal for applications that demand high resolution and multi-material capabilities.

4. Applications

3D printing has garnered significant attention in medical implants Fig. 4, as this cutting-edge technology offers highly customized complex geometries, enabling porous structures that facilitate bone ingrowth in orthopedic implants. In dentistry, 3D-printed implants, crowns, and bridges ensure proper fittings, while in cranial or maxillofacial surgery, implants can be designed to match exact bone defects that increase surgical efficiency.

4.1. Prosthodontics

Recent advancements in prosthodontic applications include the utilization of advanced technology like intraoral scanning and computer-aided design (CAD), increased production efficiency, and accuracy with patient-specific prostheses (Beefathimathul, 2025). Also, groundbreaking work is being conducted on raw materials like resin and polymers to improve their biocompatibility and mechanical properties, which expands their application and product lifetime (Dimitrova *et al.*, 2023). Methacrylate-based photopolymer resins are popular materials used in 3D printed prosthodontics due to their good biocompatibility, acceptable mechanical properties, and ease of processing. They are mostly used for building temporary crowns, bridges, and surgical guides. However, Polyetheretherketone (PEEK) is used for durable and long-term dental implants for its strength and biocompatibility (Haleem & Javaid, 2019).

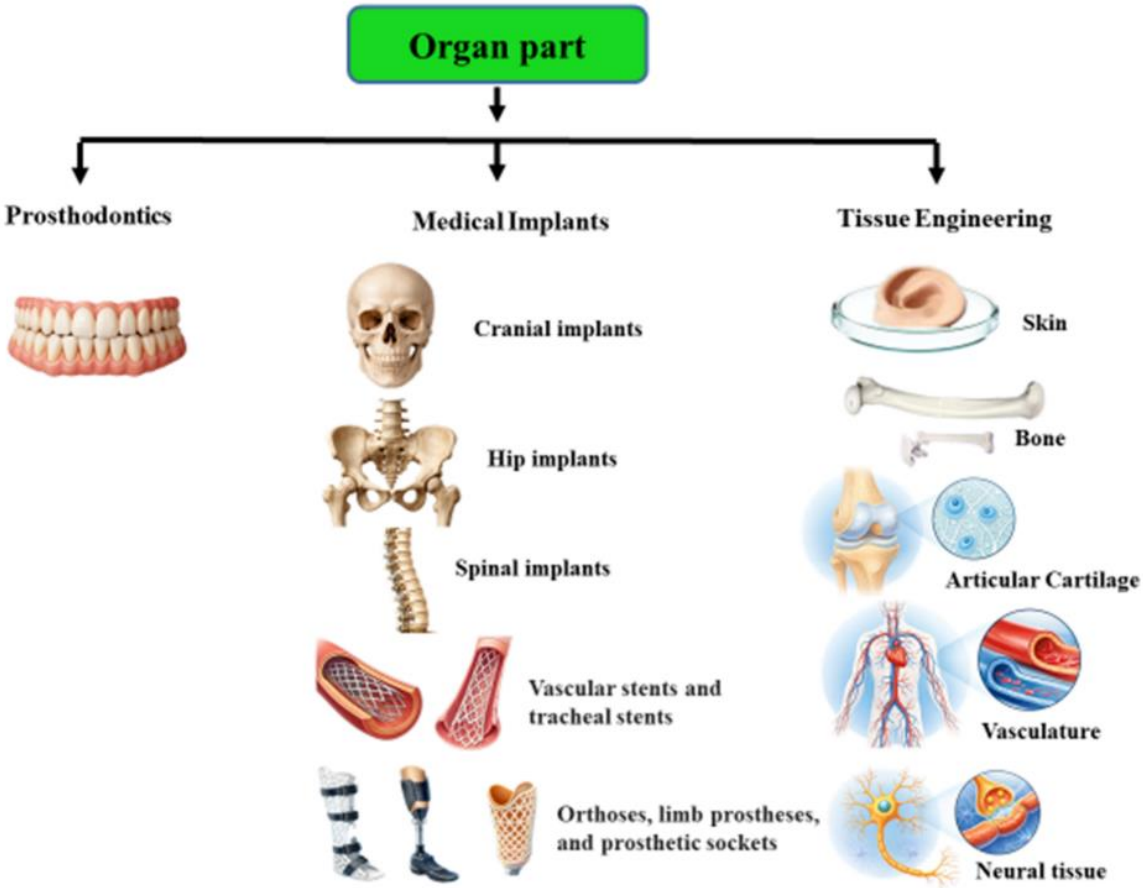


Fig. 4. Applications of 3D Printing and Additive Manufacturing in Organs, such as Prosthetics, Medical Implants (Cranial, Spinal, Hip, Vascular Stents, Tracheal Stents, and Limb Prostheses), and Tissue Engineering (Skin, Bone, Articular Cartilage, and Vasculature).

Besides, advancements in Zirconia, Lithium, and Titanium-based ceramic materials offer excellent mechanical properties ideal for permanent restorations like crowns and bridges that need to handle more load stress (León *et al.*, 2020). Much research works are ongoing on developing composites with the combination of ceramics and polymers to optimize biocompatibility, strength, and aesthetics for the creation of prosthetics with different textures and mimicking natural colors without compromising their functionality. It is possible to incorporate both rigid and flexible materials in a single prosthetic (Tian *et al.*, 2021). Studies are also focusing on developing bioactive materials that help tissue regeneration and better integration with the host body to enhance osseointegration.Very recent AI algorithms and Machine learning are being integrated with CAD software, which optimizes prosthetic designs for the best fit and aesthetic considerations (Chander & Gopi, 2024). Adopting these technologies gives advantages in time efficiency and surgical error minimization compared to the traditional method.

4.2. Medical implants

4.2.1. Cranial implants

3D printed cranial implants are a significant forward step in the regenerative medicine field by offering a customized solution to patients. Advanced imaging techniques like Computed Tomography (CT) or Magnetic Resonance Imaging (MRI) scans are used to develop personalized skulls, especially for trauma, tumors, or congenital defect patients who require skull reconstructions (Kopačin *et al.*, 2024).

The key requirement of printing materials is biocompatibility; additionally, materials with high mechanical strength, low cytotoxicity, and minimal host response are prioritized. Commonly used materials in 3D printing include Titanium, PEEK, or other medical-grade polymers. Titanium offers excellent durability and osseointegration, and PEEK shows very good stiffness to mimic human bone (Ebel *et al.*, 2023; Pietzka *et al.*, 2023).In addition, newer materials for 3D-printed implants (such as PEEK or advanced titanium alloys) bring advantages like radiolucency (in the case of PEEK), lower thermal mismatch with bone, and reduced imaging artefacts. This means post-operative monitoring via imaging can be easier, and the risk of thermal discomfort or "cold/heat headaches" from metal implants is reduced (Dallal *et al.*, 2025).

This high degree of customization improves anatomical fit, which leads to better aesthetic outcomes, less dead space, and typically fewer adjustments during surgery. Furthermore, 3D printed implants allow novel material and structural design opportunities: for example, implants can incorporate porous or lattice internal structures that promote osseointegration (bone ingrowth) and vascularisation, as well as reduce stress shielding by more closely matching the mechanical properties of native bone (Li *et al.*, 2022; Singh *et al.*, 2024). The addition of special features like embedding antimicrobial coating or drug-eluting into implant design has the potential to prevent infections (Liu *et al.*, 2021).

In traditional methods, implants require a long process to manually shape and fit, whereas 3D printed objects are ready to use with little intraoperative modification. It reduces the total surgery duration, risk of bleeding, and infection, which improves patient outcomes, which is critical to meet the demands in urgent and critical cases (Zaszczyńska *et al.*, 2021). Operationally, because the implant is pre-conceptualized and pre-fabricated for the defect, surgical procedures can be streamlined, resulting in fewer intraoperative modifications, fewer trial-and-error adaptations, shorter operating time, and potentially fewer complications (Ebel *et al.*, 2023).

However, regulatory approval, high cost, specialized equipment, operation, and maintenance are major limitations. Dedicated studies are needed to observe the performance and durability of implants over a prolonged period (Jin *et al.*, 2022). More studies are required to optimize each stage, from material printing methods to final implant, and to collaborate with new technologies like Artificial Intelligence and machine learning.

4.2.2. Spinal implants

Spinal implants require complex geometrical design. In cases of spinal deformities or critical degenerative conditions, 3D-printed build objects offer accurate spinal curvature, size, and shape with appropriate fittings (Kia *et al.*, 2022). Commonly, metal, polymer, and ceramic-based materials are used to build the object according to the final application and processing requirements. For metal, commonly, Titanium (Ti) is mostly used, specifically Ti-6Al-4V, which is the most common one, as it offers very good biocompatibility and excellent corrosion resistance, with a high strength-to-weight ratio (Gayathri *et al.*, 2022). Among the polymer materials, PEEK offers high mechanical strength with good biocompatibility. PEEK elastic modulus is closer to that of bone, which reduces stress shielding (Liao *et al.*, 2020). Hydroxyapatite and tricalcium phosphate are the most common ceramic materials with high osteoconductive and osteoinductive properties, which are ideal for complex porous scaffolds (Liu *et al.*, 2024). Studies are ongoing to combine metal-ceramics, polymer-ceramics, and metal-polymer to combine different properties. In spinal fusion applications, 3D printing facilitates creating in-body cages with complex architecture, which enhances load distribution and gives better support to internal organs (Burnard *et al.*, 2019).Patient-specific spine models allow for visualization and rehearsal of critical surgical steps, which improve accuracy and reduce surgical duration (Jia *et al.*, 2023). 3D printing also allows for building intricate, custom-based functional designs like integrated spikes, fins, or screw and porous structures mimicking the trabecular architecture of natural bone (Chen *et al.*, 2020). The porous structure also helps to maintain controlled, localized drug delivery, allowing implants to be loaded with antibiotics that help reduce infection rates. Under excessive load, a solid implant leads to stress shielding. 3D printing offers stiffness variation in built objects, which increases implant stability by efficient load distribution between the implant and surrounding bone (Viet *et al.*, 2025).

Major challenges include cost and scalability for bulk volume. Although there is significant progress shown in materials development, it is challenging to build the final product with the desired materials using existing methods (Wazeer *et al.*, 2022). Alongside, clear and consistent regulatory guidelines for the design, manufacturing, and clinical evaluation of patient-specific 3D-printed implants are still evolving (Beitler *et al.*, 2022). Studies are required to observe patients' recovery and long-term performance to improve the safety and efficacy.

4.2.3. Hip implants

3D printed hip implants allow for patient-specific, complex, customized implants that reduce post-surgery complications. CAD models of a patient’s hip joint are designed according to their CT scan or MRI report (Maestro *et al.*, 2024). As the implants are created according to individual unique anatomy, they ensure better fits that improve durability, alongside reducing the risk of implant loss and dislocation. Besides, the ability to build a porous structure mimicking natural bone improves bone ingrowth and implant stability (Nikam et al., 2025). This porous structure enhances osseointegration, which helps the growth of bone tissue inside implants. Besides, surface modification according to specific requirements improves bone attachment and integration (Hughes *et al.*, 2017). Using advanced materials like polymer, ceramic, and metal alloys as raw materials improves the strength and biocompatibility of implants. These features are essential for unusual anatomy where standard implants are inappropriate (Okolie *et al.*, 2022). In addition, 3D-printed implants allow design freedom and complex internal architectures that enable mass reduction (lighter implants), tailoring of stiffness (to reduce stress-shielding of the bone), and optimization of load transfer (Deshmukh *et al.*, 2024).

3D-printed models allow surgeons to practice and plan the total procedure, which improves surgical accuracy and time, while maintaining minimal material waste (Barakeh *et al.*, 2024). Also, by better matching the implant to the patient and improving initial fixation, there is potential for improved functional outcomes, higher patient satisfaction, and fewer complications (such as implant misalignment or loosening). Implants can be produced in smaller quantities on demand with minimal inventory to make it cost-competitive (Tikhilov *et al.*, 2025). However, challenges related to ethical and legal regulatory approval, higher material costs, and customization need to be overcome. More research is required for the integration of robot-assisted technology and machine learning for further improvement.

4.2.4. Vascular stents and tracheal stents

Vascular stents are mesh-like tube structures used to improve blood flow and fix narrowed arteries. 3D printed vascular and tracheal stents are patient-specific and appropriate for a unique individual's blood vessels, which reduces restenosis, increasing durability (Khan *et al.*, 2024). The primary objectives of tracheostents are to assist and maintain the airway for patients in case of tracheal stenosis (narrowing) and collapse. Compared to traditional stents, the design and dimensional accuracy of tracheal stents can be efficiently maintained by 3D printing (Li *et al.*, 2023).

From a manufacturing point of view, 3D printing reduces waste (as it is additive, not subtractive), allows rapid prototyping, and can lower costs for customized stents. In short, personalized anatomy fit, new materials (biodegradable ones too), and flexible manufacturing are all great advantages (Wazeer *et al.*, 2022). It reduces the risk of tissue irritation and mucus buildup, further improving comfort and durability. Furthermore, 3D-printing provides material and structural freedom, for example, bioresorbable (i.e., degradable) polymers, shape-memory polymers, and complex lattice structures, that reduce long-term complications like in-stent restenosis (re-narrowing) or permanent implant issues (Sousa *et al.*, 2022).

Biocompatibility is the top criterion for material selection for both vascular and tracheal applications (Veerubhotla *et al.*, 2023). Generally, nitinol and silicon-based materials are more suitable for minimizing immune response. Rapid prototyping by the 3D printing technique helps physicians to check and adjust the implants according to patient specifications (Hua *et al.*, 2022).

For tracheal stenting, 3D printing also brings substantial advantages. Custom, patient-specific airway stents (e.g., built from CT scans of the airway) allow a much better anatomical match in complex cases of airway narrowing or malformation, which can reduce stent migration, irritation of mucosa, granulation tissue formation, and other complications associated with generic straight stents (Aravena & Gildea, 2023; Sanchez et al., 2014). Another advantage is the possibility of using materials and designs that better conform to dynamic airway motion and geometry (flexibility, tailored radial force) because the shape and the mechanical behaviour can be engineered (Krumm & Gesthalter, 2025). Moreover, 3D printing allows faster turnaround of custom devices and can enable interventions in patients who previously had a mismatch with available stents (e.g., very distorted or branching airways). Thus: better fit and comfort, fewer complications from mismatch, more options for difficult airways (Annangi *et al.*, 2020).

4.2.5. Orthoses, limb prostheses, and prosthetic sockets

Recent advances in 3D-printed orthoses, limb prostheses, and prosthetic sockets have concentrated on material innovations and technical workflows that together improve fit, comfort, function, and access (Pereira *et al.*, 2024). Orthosis devices are designed to support, align, and correct the deformities of limbs. 3D printing offers a customized and cost-effective solution for limb prostheses and prosthetic sockets that reduce pressure points and improve comfort and wear time compared to traditional fabrication methods (Borthakur, 2025). Challenges regarding conventional orthoses include bulkiness, time-consuming and costly, whereas 3D printed models offer lightweight, tailored to meet individual requirements.

On the materials side, flexible elastomeric filaments with soft interfaces where the limb contacts the socket, and stiffer structural regions elsewhere improve shock absorption and reduce skin irritation while retaining durability. Rigid engineering polymers used in powder-bed and selective laser sintering offer high strength-to-weight ratios and fatigue resistance for load-bearing prosthetic components, letting designers trade material where needed and add internal lattice or graded infill structures that cut weight without sacrificing strength.

This process enhances patient compliance, especially for foot deformation and post-surgical rehabilitation. Special cases, like child prosthetics, frequently need outgrowths; here, 3D printing offers scalable implants efficiently. The digital nature of AM enables the creation of ventilation channels, variable wall thicknesses, embedded alignment guides, and easier incorporation of sensors (Benady et al., 2025; Borthakur et al., 2026). Collectively, these improvements offer affordable and efficient solutions, especially for disabled persons.

4.3. Tissue Engineering

3D printing has become more popular and widely adopted in tissue engineering to build complex, customized scaffold structures accurately to support cell growth and tissue regeneration (Zaszczyńska *et al.*, 2021). Bio-printing has a few significant advantages, where functional tissues like skin and cartilage are formed layer by layer, and bio-ink contains living cells. It also facilitates drug experiments and disease research by printing organs-on-a-chip models, which are used to reconstruct a drug delivery system, surgical planning, and skin grafting (Veerubhotla *et al.*, 2023). However, challenges regarding bio-compatibility, material selection, and durability need to be addressed.

4.3. 1. Skin

3D bio-printed skin tissue offers a transformative advantage in wound dressing, skin transplantation, and reconstructive surgical applications. During the printing process, the printer deposits bio-inks according to a predetermined 3D design based on the MRI and CT scan report (Choi *et al.*, 2023). Bio-inks are composed of living cells, bio-materials, and growth factors. This composition is specially selected to mimic the extracellular matrix of natural skin. Post-printing incubation allows cells to grow and mature to form functional tissue (Javaid & Haleem, 2021). In the last few years, 3D-printed (bioprinted) skin has gained clear materials and technical advantages: novel bioinks — especially GelMA and advanced collagen-based and decellularized-ECM formulations — now mimic native extracellular matrix chemistry and mechanics more closely, improving cell viability, differentiation, and remodeling compared with older single-polymer hydrogels (Zaupa *et al.*, 2023). Multicomponent and tissue-specific bioinks (including recent work using fish-skin–derived GelMA) let researchers tune stiffness, degradation, and bioactivity to match epidermal and dermal layers, so printed constructs support stratification and barrier-function development.

On the technical side, multi-material and sacrificial-ink printing strategies now produce embedded, perfusable microchannels and pre-patterned vascular networks that markedly improve nutrient delivery and graft survival in vitro and in vivo — a major step toward clinically useful, thicker skin constructs. High-resolution approaches enable rapid fabrication of anatomically layered, full-thickness skin with reproducible microarchitecture and faster build times, which benefits scale-up and repeatability for testing or grafting. Finally, integration of sensors and co-printed cell types (keratinocytes, fibroblasts, endothelial cells, and immune cells) improved bioreactor/perfusion protocols, making printed skin more physiologically functional for drug testing, personalized toxicity screening, and reconstructive applications (Manita *et al.*, 2021).

A customized match of patient skin type and specific area of the body for bio-printed skin graft offers an efficient solution to burned and severe skin injuries. Also, implementing bio-printed skin helps in new tissue growth by offering structural support that enhances healing for chronic wounds. This process will help treat diabetic ulcers, trauma, cosmetic, and post-care of cancer surgery (Javaid & Haleem, 2021). Besides, this printed skin helps pharmaceutical research and innovation to monitor efficiency and safety issues that reduce the dependency on large animal models for in vivo tests (Singh *et al.*, 2016).

Maintaining post-printed cell viability is a major challenge. Also, minimal fatigue is required to resist mechanical stress during printing and the maturation stage. Further, for vascular network structure, the ensuing supply of nutrients and oxygen to the cells, especially for thick and complex tissues, is another major difficulty (Javaid and Haleem, 2021). Higher cost, process complexity, and stringent regulatory approval limit its wide adoption (Balavigneswaran *et al.*, 2023). More research is needed for innovation in existing technology, including advanced materials to meet functional demand in the field of regenerative medicine and personalized healthcare.

4.3.2. Bone

3D-printed bone tissue is a significantly useful addition in regenerative medicine to treat bone damage, injuries, and congenital defects. 3D-fabricated structures combine biocompatible materials, cells, and growth factors by replicating natural bone tissues (Shao *et al.*, 2025). Commonly used bio-inks include calcium phosphate-based ceramics (e.g., hydroxyapatite), polymers (e.g., polycaprolactone), or other printable composites according to their strength and biocompatibility. To enhance tissue regeneration, bio-inks are combined with stem cells or osteoblasts and growth factors (Tolmacheva *et al.*, 2024). The use of bioactive molecules such as hydroxyapatite (HA) and bioactive glass within scaffolds printed using 3D printing technology has been an area of interest in recent years. For instance, it was demonstrated in a study that immobilization of HA onto the surface of PEKK implants improved hydrophilicity and promoted better stem cell adhesion and osteogenic differentiation without compromising the compressive strength of the implant (Goreninskii *et al.*, 2025).

In addition to that, incorporating bioactive glass into titanium alloy implants was discovered to enhance bone ingrowth during the early healing process, osseointegration. Moreover, the development of a new surgical tool—a specialized glue gun—has enabled 3D printing of bone grafts directly onto fractures within the operating room (Lee *et al.*, 2025). The tool uses a composite filament made up of polycaprolactone (PCL), HA, and embedded antibiotics, enabling not only patient-specific grafting but also reducing infection and promoting faster bone healing (Wang *et al.*, 2025). Also, the application of low-temperature printing technology has improved scaffold performance through the preservation of intact bioactive materials and overall quality of the printed material. These developments allow for better surgical procedures and better patient outcomes (Sun et al., 2023). The potential to design connected pore architectures results in enhanced cellular nutrition, proliferation, and migration, as well as the formation of new blood vessels, which are essential for effective bone regeneration (Wang *et al.*, 2023).

Despite these advantages, major challenges are related to meeting mechanical strength and establishing vascularization to support blood vessel formation. Besides, higher cost, technical expertise, scalability, and regulatory approvals are limiting its mass adoption (Lan *et al.*, 2022). Ongoing research studies are focusing on overcoming these challenges by developing advanced materials and method optimizations to improve bone repair and regeneration.

4.3.3. Articular cartilage

Articular cartilage represents smooth, white tissue that covers the ends of bones that come together during joint formation. For smooth, pain-free movement, articular cartilage plays a crucial role, while a lack of blood flow restricts its self-repair process (Li *et al.*, 2022). The traditional process for curing cartilage damage, such as microfracture or joint replacement, offers temporary relief in most cases. 3D printed articular cartilage offers durable solutions by building patient-specific complex cartilage to meet the functions of native tissue (Park *et al.*, 2024).

As a raw material, bio-ink is used, which is composed of biocompatible materials and living cells like chondrocytes or stem cells. By fabricating layered, porous scaffolds, we ensure cell proliferation and enhanced integration of surrounding tissue (Liang *et al.*, 2022). Hydrogels, such as gelatin methacryloyl (GelMA), have emerged as a popular class of bioinks for their excellent biocompatibility, tunable mechanical properties, and ready crosslinking ability under UV light. It is also capable of mimicking the natural cartilage structure with high accuracy (Zaupa *et al.*, 2023; Boretti *et al.*, 2025). Advanced innovations, such as direct-volumetric drop-on-demand (DVDOD) printing, allow the deposition of patterned chondrocytes in microdroplets, which lead to functional cartilage tissues with improved structural integrity.Additionally, studies show that the addition of bioactive molecules such as growth factors or platelet-rich plasma into the bioinks has enhanced chondrogenic differentiation and extracellular matrix deposition (Grottkau *et al.*, 2020). However, material selection for bio-ink with adequate mechanical strength without trading off biocompatibility remains a major challenge. Besides, the host tissue response to the implanted body is also a major concern (Shea *et al.*, 2022).

4.3.4. Vasculature

Vasculature represents a sophisticated network structure of blood vessels (arteries, arterioles, capillaries, venules, and veins) that form a closed circulatory system, which functions to circulate blood between the heart and other tissues and organs (Tomasina *et al.*, 2019). 3D printing technology enables the building of this structure while maintaining highly detailed functional vascular networks mimicking the branching patterns of blood vessels with significant precision (Barua *et al.*, 2023).

From the materials perspective, bioink development has played a critical role. Bioinks with living cells, growth factors, and extracellular matrix components permit the growth of complex vascular networks with proper blood flow (Chen *et al.*, 2023). The integration of endothelial cells and smooth muscle cells in bioinks enabled the generation of branching vessels that closely resemble human vasculature (Lei *et al.*, 2019). These printed vasculature structures also help to study diseases like cancer or atherosclerosis in vitro models to increase the efficiency and safety of new drugs (Mir *et al.*, 2023). Besides, in the field of regenerative medicine, 3D printed vascular networks are crucial to implant into 3D printed organs like kidneys or livers to overcome the challenges related to organ donors (Zheng *et al.*, 2024). However, major challenges regarding mechanical strength, biocompatibility, material selection, and integration of printed vasculature with the host body remain (Lei *et al.*, 2019). More research work is required on material and process optimization to improve scalability and overcome existing challenges.

4.3.5. Neural tissue

Neural or nervous tissue is the key tissue type that builds the human nervous system. This tissue is composed of two major cell types: neurons and glial cells, where the function of neurons is transmitting electrical and chemical signals, while glial cells provide the structural support and protection of neurons (Choi *et al.*, 2025).

From the point of material advancement, recent studies have found that Gelatin methacryloyl (GelMA), when combined with polyethylene glycol diacrylate (PEGDA), enables the fabrication of biocompatible, tunable nerve conduits that promote stem cell growth, which helps in injured nerve repair. Also, incorporating nanofiber scaffolds within these hydrogels improves neural connectivity and neurite extension (Hamedi *et al.*, 2023; Maeng *et al.*, 2025).

Most commonly used for neural tissue fabrication by 3D printing techniques, including extrusion-based or laser-assisted bio-printing, allows high-resolution control over cell placement and tissue origination. Also, microfluidic channels in printed implants allow controlled delivery of neurochemicals and optogenetic stimulation that improve neural modeling and modulation (Mirshafiei *et al.*, 2024). However, major challenges that limit its potential include long-term functionality, ensuring vascularization for nutrient supply, and scalability (Gao *et al.*, 2025). Ongoing research on the transformative tool to bridge the gap between engineering and biology, offering hope for innovative treatments. Here, Fig. 5 shows a selective representation of 3D printing in Oral, Bone, and Cartilage Tissue Engineering, and Table 1 shows a selective summary of applications in medical implants.

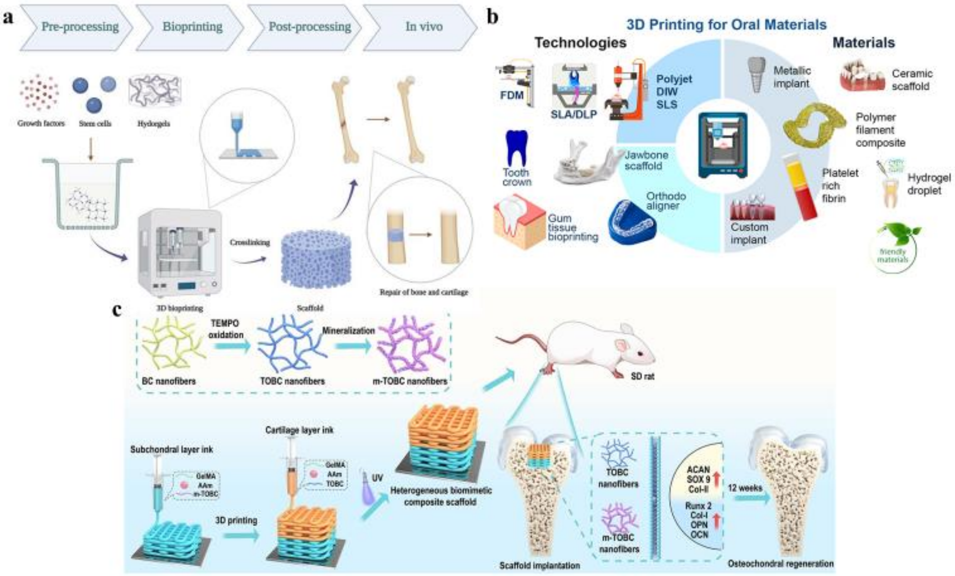


Fig. 5. 3D Bioprinting Strategies for Oral and Osteochondral Tissue Engineering: Materials, Processes, and Regenerative Applications. (a) Schematic of the bioprinting workflow from bioink preparation to in vivo tissue regeneration (Yang et al., 2022). (b) 3D printing technologies and biomaterials are used in dental applications (Hossain et al., 2025). (c) Nanofiber-based bioink fabrication and its application in osteochondral regeneration (Liu et al., 2025).

Table 1. Summary table of the applications

Application Area	Materials	Major Advancements	Key Benefits	References
Prosthodontics	Methacrylate-based photopolymer resin, PEEK, Zirconia, Lithium disilicate, Titanium-based ceramics	New resin and polymer composites; hybrid ceramic– polymer systems; bioactive materials for osseointegration	Improved accuracy, fit, aesthetics, mechanical strength, and biocompatibility	(Zafar, 2020; Dimitrova *et al.*, 2023; Beefathimathul, 2025; Chander & Gopi, 2024)
Cranial Implants	Titanium, PEEK, advanced titanium alloys, medical-grade polymers	Porous/lattice internal structures; antimicrobial coatings;	Enhanced fit, osseointegration, imaging compatibility, reduced surgery time	(Pietzka *et al.*, 2023; Singh *et al.* 2024; Kopačin *et al.*, 2024; Dallal *et al.*, 2025)
Spinal Implants	Titanium (Ti-6Al-4V), PEEK, Hydroxyapatite (HA), Tricalcium Phosphate	Complex geometrical design, porous cages, hybrid composites, and antibiotic-loaded scaffolds	Improved load distribution, osseointegration, drug delivery, and reduced stress shielding	(Beitler *et al.*, 2022; Jia *et al.*, 2023; Viet *et al.*, 2025)
Hip Implants	Titanium alloys, polymers, ceramics, and composites	Porous structures; surface modification; lightweight optimization	Better fit, durability, osseointegration, reduced stress shielding, cost efficiency	(Maestro *et al.*, 2024; Barakeh *et al.*, 2024; Deshmukh, et al., 2024; Tikhilov *et al.*, 2025)
Vascular & Tracheal Stents	Nitinol, Silicone, Biodegradable, and shape-memory polymers	Custom patient-`specific mesh structures; bioresorbable materials; flexible	.`	(Wazeer, *et al.*, 2022; Sousa *et al.*, 2022; Aravena &

		design; reduced restenosis		Gildea, 2023; Veerubhotla *et al.*, 2023; Khan *et al.*, 2024; Krumm & Gesthalter, 2025)
Orthoses & Limb Prostheses	Elastomeric filaments, engineering polymers (e.g., Nylon, TPU), and composites	Lightweight sockets; variable stiffness and lattice design; embedded sensors	Enhanced comfort, reduced cost, rapid fabrication, scalability	(Pereira *et al.*, 2024; Vennam *et al.*, 2024; Cong & Zhang, 2025; Borthakur, 2025)
Skin Tissue	GelMA, collagen, decellularized ECM, bioinks with living cells	Bioprinting of multi-layered, vascularized skin; integration of sensors and co-printed cells; improved perfusion	Improved graft survival, realistic skin mimicry, and reduced animal testing	(Choi *et al.*, 2023; Shukla *et al.*, 2024; Tanadchangsaeng *et al.*, 2024; Jing *et al.*, 2025)
Bone Tissue	Hydroxyapatite, PCL, bioactive glass, PEKK, composite bioinks	Low-temp printing; antibiotic-loaded scaffolds; bioactive coatings; in-situ grafting with "bone glue gun."	Enhanced bone regeneration, infection resistance, and vascularization	(Goreninskii et al., 2025; Lee et al., 2025; Sun et al., 2023; Tolmacheva et al., 2024; Wang et al., 2025)
Articular Cartilage	GelMA, hydrogels,	Layered porous scaffolds; DVDOD printing; bioactive	Functional cartilage repair, improved ECM	(Liang *et al.*, 2022; Zaupa *et al.*, 2023;

	chondrocyte-laden bioinks	factor incorporation; tissue-specific mechanical tuning	deposition, durable implants	Park *et al.*, 2024; Boretti *et al.*, 2025)
Vasculature	Bioinks with endothelial and smooth muscle cells	Complex vascular network printing; disease modeling; integration with organs-on-chip	Enables organ-level implants, drug testing, and disease modeling	(Tomasina *et al.*, 2019; Barua *et al.*, 2023; Mir *et al.*, 2023)
Neural Tissue	GelMA, PEGDA, nanofiber composites	Tunable hydrogels for nerve conduits; bio-printing with microfluidic channels; optogenetic stimulation	Promotes nerve regeneration, precise cell control, and neural modeling	(Hamedi *et al.*, 2023; Mirshafiei *et al.*, 2024; Choi *et al.*, 2025; Gao *et al.*, 2025; Maeng *et al.*, 2025)

5. Economic, environmental, and societal impacts

Adopting 3D printing for bio-medical applications to create customized prosthetics, dental implants, surgical guides, and orthopedic implants brings significant improvement from an economic point of view, and it has a big environmental and social impact (Sheoran et al., 2020; Sousa et al., 2021). Considering the economic point, 3D printing reduces cost by minimal raw material utilization, wastage minimization, and on-demand production. In traditional methods, more raw materials, wastage minimization, and predicting accurate demand are difficult (Kumar et al., 2025). In the conventional system, manufacturing plans are usually in a separate place; for distribution, it needs a supply chain, and maintaining the supply chain further increases overall cost. Whereas 3D printing allows localized production (in hospitals or clinics) on-site by avoiding a long supply chain and transportation costs (Kantaros *et al.*, 2025).

From an environmental perspective, this technology is very efficient in material utilization and generates minimal wastage during the construction of complex structures. Localizing production reduces transportation, which lowers the carbon footprint by minimizing pressure on fossil fuel consumption (Garg *et al.*, 2023).

In contrast, some of the resin and plastic materials are non-biodegradable and hazardous, requiring careful management to prevent environmental pollution. Alongside high-temperature processes and sophisticated production systems, they are high-energy-intensive. Addressing these challenges, ongoing research works are focusing on making 3D printing more environmentally friendly and sustainable (Haq *et al.*, 2025; Abahussain *et al.*, 2025).

From a social perspective, 3D printing has the potential to revolutionize the healthcare sector. Enabling patient-specific implants, prosthetics, and surgical equipment significantly reduces post-surgical injuries and damages, which improves patient satisfaction (Safali *et al.*, 2023). Besides, 3D printing has increased accessibility, affordability, and market penetration in developing regions that can offer on-site medical devices at low cost (Areyan *et al.*, 2025). Managing organ donors is a very big challenge, where we need to replace damaged natural organs. 3D printed artificial tissues and organs are considered a potential alternative to overcome this organ shortage challenge (Bozkurt & Karayel, 2021; Wang *et al.*, 2024)**.** Also, challenges related to ethical and regulatory issues need to be considered seriously to establish an appropriate safety standard. It also needs to build up a skillful workforce and professionals in these fields (Kantaros *et al.*, 2025). Altogether, this technology offers cost-effective, sustainable, and patient-specific solutions, addressing environmental and social challenges that need to be overcome to utilize the full potential of additive manufacturing.

6. Potential challenges and limitations

3D printing technology has significantly transformed biomedical implant applications by building complex, customized designs with precise accuracy. In contrast to all these advantages, major challenges include appropriate biocompatible materials with biocompatibility and acceptable mechanical properties. Besides, different 3D printing techniques need different physical and chemical properties for raw materials. Meeting the mechanical properties with adequate biocompatibility is very challenging.

In special applications, like small blood vessels, complex organs, or sophisticated tissue structures, durability is a major challenge. In some cases, the implant fabrication processes are quite slow to meet urgent patient treatment needs. Besides, the high cost of initial setup and proper expert personnel also limits its mass adoption. Post-processing treatments like sterilization, UV curing, and surface finishing processes increase both the cost and time. Scalability is also a critical issue; to operate a machine, a minimal amount of raw materials needs to be input, and for very small quantities, the total cost increases significantly. In the case of in vivo applications, host tissue response is also a critical concern. Moreover, regulatory and standardization issues, along with ethical and legal concerns, further complicate the adoption of this technology. Continued research and collaboration across multiple disciplines will guide the future by overcoming current limitations to use the full potential of 3D printing in healthcare.

7. Prospects and conclusion

3D printing has made a few major improvements in regenerative medicine, and ongoing research indicates a promising future by overcoming existing shortcomings. By leveraging 3D printing, it is possible to build complex geometrical structures with higher accuracy, which opens up new possibilities for further innovation.

Bioprinting has huge potential in tissue engineering. Utilizing bio-inks composed of living cells, it shows hope for regenerating damaged tissues and functional organs for transplantation, which will significantly reduce the dependency on organ donors and transplant rejection. 3D printing technology increases the efficiency of the drug delivery system by offering personalized dosages and controlled drug release in the target area. It is crucial for those applications where the simultaneous release of multiple drugs at different rates is needed. It also increases the efficiency of surgical planning and practice by building an anatomical model with high accuracy using patient CT scan or MRI data. It facilitates training tools to rehearse complex processes, which will increase the surgical efficiency of medical professionals. 3D printed custom crowns, bridges, and prosthodontic devices are widely used in dentistry to ensure appropriate implant placement. This technology also helps to reduce dependence on a long supply chain system, which sharply reduces the lead time by offering a localized production system. 3D printing allows clinics and hospitals to produce small-scale implants on-site, which helps with urgent patient treatments. Customized 3D-printed scaffolds provide support for cell growth and tissue regeneration, enhancing stem cell differentiation. Besides, custom-fitted medical devices, including sensors, improve patient monitoring.

Overall, 3D printing technology is a revolutionary tool with huge potential in the biomedical field. While challenges such as vascularization, scalability, and functional integration remain, ongoing advancements suggest that bio printing could play a vital role in overcoming the organ shortage and advancing personalized regenerative medicine. The future of 3D printing in biomedical applications greatly depends on the innovation of advanced materials, multi-material combined printing, process optimization, and advancements in vascularization. Close integration of automation and AI could increase efficiency by optimizing designs and the printing process. Also, the establishment of clear regulatory guidelines is required to ensure safety and efficacy.

Author Contributions:

"Conceptualization, writing—original draft preparation, writing—review and editing, methodology, software, data curation, writing—review and editing, resources, data curation, supervision, project administration- Najmul Hossain;

Validation, visualization, formal analysis, and investigation, writing, review, and editing- Rasheed Ahmad;

All authors have read and agreed to the published version of the manuscript."

Funding Information: "This work received no external funding".

Institutional Review Board Statement: "Not applicable."

Informed Consent Statement: "Not applicable."

Data Availability Statement:

All data used in this review are obtained from previously published studies, which are cited within the article. No new data were generated for this work.

Conflict of Interest

The authors declare that they have no conflict of interest.

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