

Review article

Recent advances in 3D printing technologies for medical applications

Muhammad Akram^{a,*} , Nosheen Aslam^b , Ho Soon Min^c , Naveed Munir^d ,
Mariam Ahsan^e , Abubakar Babangida Usman^f 

^aDepartment Of Eastern Medicine, Government College University Faisalabad-Pakistan

^bDepartment Of Biochemistry, Government College University Faisalabad-Pakistan

^cINTI International University, Putra nilai, Negeri Sembilan, Malaysia

^dDepartment of Biomedical Lab Sciences, School of Health Sciences, University of Management and Technology, Lahore-Pakistan

^eDepartment Of Eastern Medicine, Superior University Lahore-Pakistan

^fDepartment of Immunology, School of Medical Laboratory Sciences, Usmanu Danfodiyo University Sokoto, Nigeria

Abstract

Three-dimensional (3D) printing technology, which can create patient-specific anatomical models, implants, prostheses, surgical guides, medication delivery systems, and tissue-engineered constructs, has become an emerging tool in contemporary healthcare. With the potential to enhance surgical planning, procedural accuracy, functional outcomes, and patient-specific rehabilitation, 3D printing enables greater anatomical precision and customized therapeutic strategies by combining advanced imaging, computer-aided design, biomaterials science, and additive manufacturing. This review summarizes the basic principles of 3D printing technology and its wide range of medical applications. The article analyzes various printing methods, including PolyJet, inkjet binder jetting, electron beam melting, extrusion-based printing, and stereolithography, by examining their operating principles, material use, and relevance to medical applications. Furthermore, this review investigates bone tissue engineering through 3D printing, producing bioceramics, biodegradable polymers, and metal-based implants that maintain strength and biocompatibility during manufacturing. The pharmaceutical field has advanced with the advent of 3D-printable tablets, thereby enabling customized dosages and precise drug-release control. The Food and Drug Administration approval of levetiracetam Spritam® has become a landmark achievement in pharmaceutical production. Scientists and researchers developed a drug-delivery system that integrates with tissue-engineered scaffolds to create innovative regenerative medicine therapies for joint and cartilage regeneration research. Although 3D printing is an emerging technology that helps healthcare professionals deliver improved patient care, organizations still need to create material standards, conduct safety assessments, and obtain regulatory approvals, which may cause technical delays.

Keywords: 3D printing, biocompatibility, bioprinting, medical devices, medicine, printable tablets, safety regulations, tissue engineering.

Additive manufacturing uses three-dimensional (3D) printing technology, a core element in modern medical device development. Three-dimensional printing creates objects by adding material according to a digital design, while traditional manufacturing processes produce final products through material-removal methods. Designers can create desired forms because the method provides them with complete

artistic control to invent complex shapes that were previously impossible to create using traditional manufacturing techniques.⁽¹⁾ This new technology enables manufacturers to create their own custom implants, surgical models, and drug-delivery systems, which have become crucial medical devices that are required for producing personalized medical equipment.

Three-dimensional printing technology began with the development of stereolithography (SLA), which was first introduced in the 1980s. The system used ultraviolet (UV) lasers to convert liquid photosensitive resins into solid materials through a printing process. Technology began as an industrial prototyping tool,

***Correspondence to: Muhammad Akram**, Department of Eastern Medicine, Government College University Faisalabad-Pakistan.
E-mail: muhammadakram@gcuf.edu.pk

Received: March 28, 2026

Revised: August 31, 2026

Accepted: September 18, 2026

which developers later transformed into medical technology through further advancements.⁽²⁾ Surgical planning systems developed surgical medical applications, which created anatomical models to support maxillofacial and orthopedic procedures. The surgical teams developed accurate operation plans using patient-specific anatomical models, which helped them achieve better surgical outcomes and reduce errors.

Researchers have developed new materials, printing technologies, and software, thereby increasing the use of additive manufacturing in medical fields. Medical personnel use biocompatible materials, which combine polymers with ceramics and metals to create secure implants for surgical procedures. In addition, researchers have developed live-cell scaffolds using bioprinting technology for tissue engineering and regenerative medicine research. The digital reconstruction of patient anatomical structures, which supports personalized treatment planning, results from merging computed tomography (CT) and magnetic resonance imaging (MRI) systems with computer-aided design (CAD) systems.

In medical facilities, 3D printing is gaining popularity because it enables personalized treatments that previous methods could not provide. Physicians and surgeons employ additive manufacturing to produce unique implants that surgical teams need because standard prosthetics and implants often require surgical modifications during operations. Users can create their own implants through a digital model creation process that uses CT and MRI scans to develop designs that match various physical conditions. These personalized procedures have increased surgical accuracy, resulting in shorter operating times and improved post-surgical outcomes.⁽³⁾ The process of reconstructing cranial and facial structures requires specific patient implants that match their treatment needs to achieve successful outcomes after their traumatic injuries and tumor excision procedures. Standardized implants are already used to treat patients with bone defects that create aesthetic issues and medical treatment difficulties. Furthermore, 3D printing technology enables surgeons to produce customized titanium and polymer implants that precisely match the patient's body shape, thereby improving weight distribution and mechanical strength.⁽⁴⁾ The use of customized implants that match a patient's natural bone structure results in improved outcomes for orthopedic total knee and hip replacement operations. This narrative review explores the basic principles of 3D printing technology and its

medical applications. The article analyzes various printing methods, including PolyJet, inkjet binder jetting, electron beam melting, extrusion-based printing, and SLA, by examining their operating principles, material use, and relevance to medical applications.

Methods

This narrative review examined 3D printing in medical applications. We conducted an extensive literature search using publication databases such as Scopus, Google Scholar, PubMed, and Web of Science. The search covered published articles from 2015 to 2025. Relevant keywords included "stereolithography technology," "extrusion-based printing technology," "electron beam melting technology," "inkjet technology," "PolyJet technology," "medical treatment and 3D printing," "bone tissue," "3D printing," "pharmaceutical industry," and "surgical planning." We identified 700 English-language papers, of which 552 met the inclusion criteria. Most investigations originated from China, followed by the USA, India, the United Kingdom, and Australia. Of these, 320 assessed 3D printing, 163 assessed surgery, and 68 focused on biomaterial applications. By document type, there were 427 articles, 265 reviews, 47 book chapters, and 33 conference papers. Exclusion criteria included printing technology cost and printing equipment manufacturer.

3D printing technology

Three-dimensional printing technology is transforming medicine by producing custom medical solutions that meet each patient's specific needs through 3D medical designs.⁽⁵⁾ Designers who work with additive manufacturing can create 3D products by transforming digital designs into physical objects, which they build through layer-by-layer construction that produces complete exterior shapes, internal details, and material porosity. Designers use sequential layer-building methods to create complex products that current fabrication methods cannot produce because those methods lack basic design capabilities. The medical field employs 3D printing technology to create customized medical solutions through rapid prototype development, thereby enabling the use of customizable materials for regenerative medicine applications. In addition, clinicians use digital imaging technologies, including CT, MRI, and ultrasound, to generate precise anatomical information. The system takes input data to produce CAD models, which serve as the foundation for additive manufacturing. Specialized

software first divides the CAD model into thin cross-sectional layers, which then controls the printing process.

Medical systems that use 3D printing technology base their printing methods on fundamental elements that enable five printing techniques, including material jetting and binder jetting, powder bed fusion, extrusion-based printing, and vat photopolymerization. Each technology offers unique benefits that depend on the medical setting, materials used and required level of printing accuracy. Material jetting, such as PolyJet technology, allows users to print 3D objects using photopolymer and other liquid materials, which are released in tiny drops onto building surfaces while UV light instantly solidifies the material. This method produces high-resolution results because it uses 16-micron layer thicknesses, thereby creating detailed anatomical models and advanced medical devices. Moreover, artists benefit from material jetting technology because it enables them to create multi-material objects within a single printing process.⁽⁶⁾ The medical field depends on three main functions of material jetting: it supports surgical simulation, anatomical education, and preoperative planning. Surgical simulation creates patient-specific models that duplicate human tissue structure and density to help surgeons practice their surgical techniques. Dental professionals employ PolyJet technology to manufacture various dental products, including crowns and bridges, aligners, and surgical guides.

The binder jetting process requires precise binder distribution across the entire metal, ceramic, and polymer powder bed. The binder connects powder particles through a binding method that follows the CAD model. The object requires post-processing because its mechanical properties and service life depend on sintering and infiltration. The medical field uses binder jetting to create bone tissue engineering scaffolds with porous structures and to develop drug delivery systems.⁽⁷⁾ The binder-jet printing process produces structures that retain their original porosity and permit cell entry and blood vessel development. In addition, essential nutrients for tissue healing can pass through the structure. This system enables users to construct composite scaffolds incorporating various powdered materials, allowing developers to meet mechanical specifications and chemical composition requirements. The manufacturing process is valuable because binder jetting enables manufacturers to create tailored implants and drug-delivery systems.

Several authors have identified powder bed fusion (PBF) as a method that encompasses three primary techniques⁽⁸⁾: selective laser melting, selective laser sintering, and electron beam melting (EBM). This technology uses high-energy laser or electron-beam sources to fuse powder particles by building the material in successive layers. EBM systems require specific environments to protect against oxidation and contamination because they operate under vacuum conditions. This technology enables orthopedic and maxillofacial surgical procedures to create metal implants that can bear weight and exhibit superior mechanical properties.⁽⁹⁾ Medical applications utilize titanium and titanium alloys whose materials provide strength, corrosion resistance, and biocompatibility. EBM-printed implants with porous structures enable bone integration while reducing stress shielding, leading to better results in hip replacements, spinal fusion cages, and cranial reconstructions. Moreover, PBF enables the production of complete solid metal implants, complex lightweight lattice structures, and custom medical devices built from patient imaging data. The industry faces three primary obstacles: expensive equipment, challenging post-processing tasks, and limited ability to combine different materials.

The most common 3D printing method enables low-cost printing because it requires only basic equipment and offers various printing functions that different users can access to meet their requirements.⁽¹⁰⁾ The process needs thermal energy to melt the thermoplastic materials, which contain polylactic acid (PLA), polycaprolactone (PCL), and other biocompatible polymers, because the material needs to flow through a nozzle to create the final object through layer-by-layer material application. Extrusion-based printing is the primary technique used to produce prosthetic devices, anatomical models, and drug-loaded tablets.⁽¹¹⁾ Tissue engineering scaffold technology shows effective results because it uses biodegradable polymers, which naturally decompose during new tissue development. Scientists are now able to create tissue-like structures through bioprinting using cell-laden hydrogels as bioinks.⁽¹²⁾ The bioinks enable researchers to create a biologically accurate environment, which includes stem cells, growth factors, and extracellular matrix elements to support cell growth and differentiation. The extrusion-based printing system allows designers to create prototypes quickly by making multiple design changes. However, the method exhibits lower accuracy than SLA and

PolyJet techniques, which require additional work to achieve better surface quality. Medical additive manufacturing relies on this technology because it provides affordable solutions that support various material applications.

SLA and vat photopolymerization use UV lasers and digital light projectors to build solid objects from liquid photopolymer resins through a sequential process. SLA is applied to produce dental models, surgical guides, and preoperative anatomical replicas because it delivers high-resolution results with smooth surface finishes and accurate size measurements. Using biocompatible resins, SLA now produces sterilizable surgical guides and temporary implants. SLA printing systems now use digital light processing (DLP) technology, thus enabling printers to cure entire layers simultaneously while maintaining quality standards. The combination of SLA and DLP has enabled the development of tissue engineering scaffolds containing bioresorbable materials and cell-laden resins that support cell growth and differentiation. Current additive manufacturing capabilities enable builders to create products that use multiple materials through simultaneous deposition, combining rigid polymers with hydrogels and bioactive components. These hybrid systems create complex designs that replicate natural tissue structure by combining physical strength with biological systems. Hybrid printing technology enables the creation of scaffolds with different mechanical properties and porosity levels, as well as drug-delivery systems used primarily in regenerative medicine. The scaffold uses a rigid polymer structure for support, while the hydrogel core contains stem cells and growth factors that facilitate tissue regeneration.

The primary advantages of 3D printing technology are its ability to create personalized medical implants, prosthetic solutions, and surgical tools that improve patient treatment outcomes. Designers use the system to develop complex architectural designs that combine internal lattice structures with materials with specific density patterns. The design process uses rapid prototyping to create multiple design iterations, thereby helping doctors practice surgical procedures. This technology enables facilities to manage multiple materials, including metals, polymers, ceramics, hydrogels, and bioactive substances. The system uses imaging technology to create accurate anatomical models that show detailed human body structures. Medical 3D printing technology provides multiple advantages to the field. However, it continues to encounter various challenges, including regulatory

requirements because there are no established rules for testing medical devices; material constraints, which impact product durability and human safety; financial barriers, which emerge from PolyJet systems that need special tools and expert knowledge; and the need to create uniform workflows, which require precise image analysis, model development, and post-processing work for consistent results.

Medical 3D printing technology requires smart materials that create scaffolds that modify their properties in response to various mechanical and chemical environmental changes.⁽¹³⁾ The medical 3D printing process needs basic technological components, which require artificial intelligence systems to support the design activities for implants and development work for surgical planning software. Scientists will develop organ bioprinting technology that produces vascularized tissues and essential organ structures for transplantation. Point-of-care manufacturing technology enables hospitals and clinics to produce personalized medical devices that their patients require at their treatment locations. Furthermore, drug-loaded scaffolds create a system that enables targeted medicine delivery through tissue engineering. Additive manufacturing is rapidly expanding because it combines engineering, materials science, and clinical medical operations. This technology allows doctors to design custom medical devices, including surgical models, regenerative scaffolds, and specialized pharmaceutical solutions. Technology is essential to enabling precision medicine initiatives to function across various medical domains.

Types of 3D printing technology and their characteristics

- **Polyjet technology**

PolyJet technology creates solid objects by producing photopolymer droplets, which the system converts into solid materials using UV light. The system achieves highly detailed 3D printing because it can print different materials while producing continuous surface patterns. The standard tools used in surgical simulation and anatomical education use PolyJet models. The materials used in this process produce weaker results than thermoplastics and metals. PolyJet printing is a material jetting technology because it uses inkjet printing methods to apply photopolymer liquid to different surface areas. The system uses UV light to cure each droplet immediately, creating solidified layers. The process builds 3D objects layer by layer. The technology enables PolyJet to create accurate anatomical models by maintaining a minimum layer thickness of 16 microns.

The main benefit of PolyJet systems is their ability to print different materials simultaneously.⁽¹⁴⁾ The system uses two types of photopolymers to create a single product, which replicates the mechanical properties found in human biological tissues. The complete body structure displays all soft tissues, including blood vessels, cartilage, and skin, along with three different types of bone structures. The PolyJet system supports surgical teams during preoperative work by creating realistic touch sensations. The medical education program uses PolyJet-printed models to provide precise, patient-specific anatomical models that medical students use to study CT and MRI data. Unlike standard plastic models, these customized prints replicate real medical conditions, including tumors, congenital deformities, and vascular abnormalities. Surgical residents can reduce risk during actual operations by practicing complex procedures in a safe environment before entering the operating room.

Surgeons use CAD software to create 3D vascular models, which they can investigate using PolyJet printing technology. Doctors use printed cranial models in neurosurgery to create precise surgical plans that guide them through tumor removal and reconstructive procedures. Dental professionals can use these technologies to create orthodontic aligners and reconstructive solutions for maxillofacial treatment. The system offers several benefits but also has several limitations. PolyJet printing requires photopolymer materials, which produce prints with weaker mechanical strength and lower durability than thermoplastics and metal-based printing materials. Photopolymers lose their structural integrity when exposed to UV light for extended periods and when subjected to mechanical pressure. Certain photopolymers create sterilization challenges because they become sensitive to the high-temperature conditions required for autoclaving. The project requires one more element that needs evaluation. The high cost of PolyJet systems and their proprietary photopolymer materials creates access barriers for users who need these technologies in resource-limited environments. Medical additive manufacturing achieves its highest level of precision through PolyJet systems, which function as advanced additive manufacturing equipment that supports multiple material combinations.

Researchers investigate biocompatible photopolymers and improved resin formulations to

expand the potential uses of PolyJet technology in creating implantable medical devices. The PolyJet technology is currently being developed to enable future applications, including surgical simulations, prosthetic prototype development, and customized medical device production.

• Inkjet technology

The 3D printing system uses inkjet technology to produce 3D objects by applying a liquid binder to powdered materials. The technology creates scaffold systems with pores that serve as materials for bone tissue engineering and drug-delivery systems.⁽¹⁵⁾ The application of post-processing techniques, which include sintering, leads to stronger mechanical properties in materials. The binder jetting process requires operators to spread a fine powder layer containing ceramic, metal, and polymer materials over the building surface. Digital design information guides the print head to distribute liquid binder onto the powder surface. The binder creates a solid layer by binding the particles together. After workers complete powder distribution for the new layer, the building platform descends. The complete formation of the object marks the end of the process.

The operational benefits of binder jetting technology enable users to produce highly porous materials.⁽¹⁶⁾ Bone tissue engineering materials require specific design parameters, which create porous structures that enable cell movement, blood vessel development, and nutrient transport throughout the tissue. Researchers determine required pore sizes by investigating powder particle sizes and binder-to-powder ratios. Scientists use the binder jetting process to test various materials, including hydroxyapatite and tricalcium phosphate ceramics, to study methods for bone regeneration. The post-processing stage begins after the printed parts complete all necessary processes, including sintering to improve density and strength. Metal printing processes use bronze and other alloy materials for infiltration, which produce stronger printed components. Inkjet-based systems in pharmaceutical manufacturing print active pharmaceutical ingredients (APIs) onto edible substrates. The method enables users to produce their own drug mixtures while providing accurate control over dosage levels. Through inkjet printing, manufacturers can create complex release patterns, which traditional tablet compression techniques do not permit.

Binder-jet printing offers two benefits to businesses: it enables high-speed production, which increases output.⁽¹⁷⁾ The manufacturing process requires dedicated production runs to produce multiple implants and scaffolds because it needs to establish systems with extensive operational capabilities. The printing process uses surrounding powder to support the object, enabling complex overhang structures without extra support materials. Binder jetting technology has operational limits that restrict its possible uses. Printed components have low green strength because they must undergo sintering to achieve full strength. Sintering requires operators to maintain precise control because any size reduction will affect the final dimensions of the objects. Achieving mechanical strength is challenging because it requires complete dissolution of the metal parts. Researchers work on improved binder materials and optimized sintering techniques while testing bioactive molecules during scaffold printing. Clinical research evaluates hybrid binder-jet systems that combine growth factors and antimicrobial agents to improve patient outcomes.

• EBM technology

The EBM process begins by melting metal powder when the EBM activates its electron beam system. The method proves effective for titanium orthopedic implants because it delivers strong mechanical properties and biocompatible performance.⁽¹⁸⁾ The medical staff uses the system to develop customized implants, which they need for their hip and spinal surgical operations. EBM operates as a PBF system and requires high-vacuum conditions to function. The system uses an electron beam to melt metal powder layers according to CAD design specifications. The vacuum environment prevents oxidation, helping maintain material purity and preserve mechanical properties. EBM primarily uses titanium alloys, with Ti-6Al-4V being the most common choice because of its high strength-to-weight ratio and exceptional osseointegration properties. EBM produces bone implants that can withstand high-stress, weight-bearing activities, including hip stems, spinal cages, and knee components. EBM enables the creation of porous lattice structures that replicate trabecular bone. The porous structure enhances stability by enabling bone ingrowth. By adjusting the beam energy, scan speed, and layer thickness, EBM implants can achieve different mechanical properties.

Orthopedic cancer specialists create customized implant solutions for their patients who undergo complete bone tissue destruction using evidence-based medical practices as their primary approach.⁽¹⁹⁾ The researchers use additive manufacturing technology to create accurate 3D models, which display complete anatomical details that remain unchanged after the removal of tumors. The system has three main limitations because it requires expensive machinery and specialized operating environments, and it offers fewer material options than polymer-based printing. The EBM manufacturing process produces durable, biocompatible metal implants that meet current orthopedic surgical standards.

• Extrusion-based printing technology

The Fortus 3D printing method uses extrusion-based fused deposition modeling (FDM) technology to produce 3D objects by applying thermal energy that melts PLA and PCL thermoplastic materials. The method shows wide-ranging uses, including creating prosthetic devices, producing anatomical models, and manufacturing drug-filled tablets.⁽²⁰⁾ Bioprinting adaptations enable the placement of cell-filled hydrogels through their printing process.

FDM is the easiest-to-operate 3D printing technique and requires the least financial backing. A thermoplastic filament becomes semi-liquid when heated, then is pushed through a nozzle onto a build surface.⁽²¹⁾ The material solidifies into layers, which form through the cooling process. FDM serves the medical field as a cost effective way to create prosthetic limbs that can be customized quickly. Prosthetics designed with lightweight materials tailored to patient dimensions provide improved mobility. Hot-melt extrusion helps the pharmaceutical industry create drug-loaded filaments needed for production. The filaments are printed into tablets with specific shapes and infill patterns that enable controlled drug release.

Bioprinting skin is a highly advanced medical technique that uses 3D printing to deposit layers of living human skin cells, collagen, and gel-based substances called bioinks (**Figure 1**). It produces functional, multi-layered skin for burn injuries, drug testing, and skin diseases. Bioprinting adaptations use extrusion systems to deposit hydrogels containing living cells. The constructs function as scaffolds, enabling the creation of cartilage, skin, and vascular tissues.

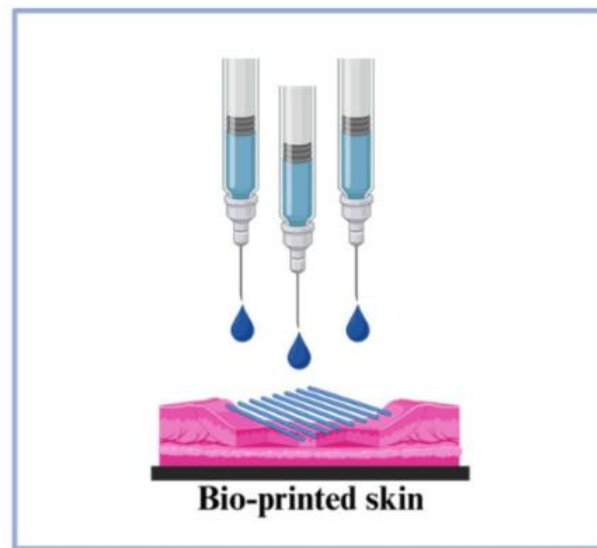


Figure 1. Bio-printed skin.

FDM offers three main benefits: lower cost, broad material compatibility, and ease of operation. The system has three primary disadvantages: it produces less detailed images than SLA and PolyJet systems, it can leave visible layer lines, and it may damage delicate biomolecules via thermal exposure. Research has continued to improve three key areas, namely, nozzle precision, multi-material capability, and bioink compatibility. Advanced regenerative capabilities in extrusion systems come from combining smart polymers with temperature-sensitive hydrogels.

• SLA technology

Additive manufacturing technology began with SLA, which became a standard industrial method as different sectors adopted it. The system creates 3D objects using an UV laser projection system that projects laser beams onto the liquid photopolymer resin filling the vat, according to CAD specifications.⁽²²⁾ The laser generates a two-dimensional object, which starts the photopolymerization process that changes the liquid resin into a solid material. The 3D building process begins when the machine creates new layers by moving the platform and applying resin to finished areas until the 3D model reaches its final shape. The SLA printing system achieves high precision by producing detailed results and exceptional surface finishes. Users can create accurate layer thicknesses ranging from 25 to 100 micrometers, enabling them to build complex microstructures and exact anatomical parts. Dental professionals use SLA technology because it enables the exact production of dental materials needed for dental work, maxillofacial treatments, and surgical guide development. Dental practitioners use SLA technology to manufacture

dental crowns, bridges, aligner molds, surgical drilling guides, and implant positioning templates. The smooth surface finish reduces the need for extensive post-processing, improving operational efficiency in clinical workflows. The process enables fast production of customized orthodontic appliances from intraoral scan results, improving treatment precision and patient satisfaction.

SLA models provide the basic framework that maxillofacial and craniofacial surgical professionals need for preoperative planning and simulation. The surgical team creates complete reconstruction plans using CT-derived anatomical models that show each patient's specific details. The surgical team needs to develop precise osteotomy and implant positioning plans after the surgeon completes tumor removal from the patient. The surgical team needs SLA models to create precise 3D models, allowing them to perform procedures with improved accuracy and faster results. Research shows that biocompatible, sterilizable resins enable SLA technology for medical applications. Medical-grade resins now meet International Organization for Standardization (ISO) biocompatibility requirements, allowing their use in surgical guides used during operations and in temporarily implantable devices. Researchers have developed specific resins that can withstand sterilization procedures that use ethylene oxide gas and low-temperature plasma sterilization. Users of SLA technology gain various benefits, but they must also manage several drawbacks. Photopolymer resins are more brittle than that of thermoplastics used for extrusion-based printing. The materials degrade after extended exposure to UV radiation. Cleaning uncured resin residues requires special attention because

isopropyl alcohol acts as a solvent, while post-curing under UV light is required for the material to reach its best mechanical strength.

Current SLA technology development relies on DLP, which enables systems to build complete layers using projection methods instead of standard laser printing technologies.⁽²³⁾ Scientists have developed micro-SLA systems, which enable the production of microscale scaffolds that function as materials for tissue engineering purposes. Researchers created bioresorbable photopolymers that enable SLA production of scaffolds that break down during regenerative medicine applications. The system offers additional clinical advantages because it can combine bioactive molecules with antimicrobial agents and drug-delivery systems. SLA technology remains the primary method for creating high-precision medical 3D-printed products. This technology remains important in dental practices, surgical procedures, and biomedical device manufacturing because it delivers exceptional resolution and a refined surface, and it offers an increasing selection of materials safe for medical use.

3D printing methods and materials: bone tissue

Bone tissue engineering is needed because it requires developing scaffolds that can replicate actual bone structure. Bone is living tissue that develops into a system that includes cortical and cancellous bone, which have different physical traits. Scientists need efficient methods to reconstruct entire bone structures, including all their internal components. Additive manufacturing has transformed bone tissue engineering by enabling researchers to design scaffolds that meet exact specifications for design elements, internal scaffold structure, material distribution, and assembly procedures.

The 3D printing process enables users to create 3D objects by assembling them through a sequence of steps employing CAD patterns that medical professionals develop from patient diagnostic imaging results. Standard scaffold production methods, which use solvent casting and gas foaming techniques, fail to produce internal structures that maintain identical structural patterns throughout the manufacturing process.

Bone growth and blood vessel formation perform best when researchers measure pore sizes between 100 and 600 micrometers. The material contains an interconnected porosity system that provides two main functions: enabling cells to stay healthy through nutrient intake and waste removal. Designers of additive

manufacturing processes use measurement parameters that depend on the specific body area and defect size to be measured. Designers develop advanced lattice structures through computational design methods, which achieve maximum mechanical strength while sustaining high levels of porosity.⁽²⁴⁾

Researchers build scaffold systems with various porosity levels to model how bone tissue transforms from cortical bone to trabecular bone, improving biomechanical strength.⁽²⁵⁾ The essential role of mechanical strength becomes critical in areas that experience heavy weight loads. Scaffolds act as temporary building elements, providing structural support until their degradation matches new bone formation. Users of additive manufacturing systems can alter mechanical properties by changing materials and adjusting structural density.

Several material types have been reported in bone 3D printing. Bioceramics such as hydroxyapatite and tricalcium phosphate are widely used because their chemical properties match those of natural bone minerals. Hydroxyapatite serves two functions because it enables bone cell attachment and promotes osteoconduction. The rapid breakdown of tricalcium phosphate allows it to function as an effective temporary scaffold, which supports rapid bone healing.⁽²⁶⁾ The production of ceramic scaffolds occurs through binder jetting and extrusion-based printing methods. Sintering during post-processing enhances mechanical strength, although it can decrease porosity if not managed properly.

Extrusion-based printing commonly uses PLA and polycaprolactone. The materials decompose through body processes, eliminating the need for surgical removal. PLA's main characteristic is its high stiffness, whereas PCL provides greater flexibility, which continues until the material begins to break down. Researchers created combined ceramic-particle materials to develop new composites after finding that polymer scaffolds did not provide sufficient osteoconductivity.

The researchers found that composite scaffolds perform best when bioceramics and biodegradable polymers are combined. Combining ceramic elements with bioactive materials improves bioactivity, while polymer materials can be processed based on their physical properties to achieve better performance. The study materials can be printed using extrusion printing and SLA printing methods. Researchers are studying nanocomposite materials containing bioactive glass and graphene to improve mechanical properties and support cell growth.

Titanium implants produced through EBM can support higher loads than most other materials. Doctors can use permanent metallic implants to treat large defects that need lasting support, but biodegradable scaffolds will stop working after their designated time ends. EBM enables the creation of titanium structures with porous elements that support bone integration while preserving structural strength. Medical professionals use these implants to treat bone injuries and support artificial joint procedures.

Osteogenic growth factors, which contain bone morphogenetic proteins (BMPs), primarily enhance regenerative outcomes. Two proteins that enable osteoblast development work with BMP-2 and BMP-7 to accelerate bone development. Printed scaffolds use controlled-release systems that provide continuous biological activity. Embedding growth factors in polymer matrices enables gradual release, reducing the frequency of required treatments. The study must control dosage distribution because improper dosing can cause dangerous effects, including ectopic bone development.

The research shows that stem cell bioprinting technology can successfully restore extensive bone defects. The combination of specific biochemical and mechanical signals instructs mesenchymal stem cells to differentiate into osteoblasts. Scientists use extrusion-based bioprinting technology to create hydrogels containing cellular materials that function as scaffold components.⁽²⁷⁾ Bioinks containing alginate, gelatin methacrylate, and collagen create protective environments, which enable cell development. Hybrid constructs form when printed structural polymers combine with hydrogels that hold living cells, replicating the structure of natural bone tissue.

3D printing in medical applications

Medical professionals can use additive manufacturing technology to create customized cranial and orthopedic implants that deliver effective results in their procedures. These implants provide patient-specific solutions that use CT imaging data to match anatomical structures precisely. Dentists use titanium and polyetheretherketone implants, which they create through additive manufacturing, to repair cranial defects caused by trauma and tumor removal. The implants restore the original skull shape while protecting brain tissue. Moreover, 3D-printed interbody fusion cages function as surgical implants that maintain spinal stability while enabling bone fusion.⁽²⁸⁾ Through porous material structures, bone tissue establishes permanent bonds with materials, which allow its

movement. The development of custom dental implants has brought major advantages to medical practice because they enable dentists to develop complete bone segment replacements for patients needing orthopedic oncology procedures. These implants help patients regain lost limb movement, improving their overall quality of life.

The first major medical application of 3D printing was surgical planning. The anatomical models that surgeons print help them assess their surgical techniques and identify potential surgical issues.⁽²⁹⁾ Cardiovascular surgery experts utilize customized models of intricate congenital heart defects to develop precise representations of their patients' circulatory systems. The system enables doctors to conduct preoperative testing for device placement and catheter navigation, which reduces unexpected events during surgery.

Neurosurgeons use 3D-printed brain and cranial models to locate tumors, plan deep brain stimulation pathways, and evaluate skull injuries. Furthermore, orthopedic surgeons utilize printed models to develop treatment strategies for osteotomy procedures, joint realignment operations, and fracture fixation methods. The models provide visual guidance, enabling surgeons to practice procedures with customized instruments that match the patient's needs, increasing surgical precision and operating speed. Prosthetic device manufacturing is changing as 3D printing technology becomes essential for specialists who need surgical planning tools during development. Producing traditional prosthetics requires workers to complete several manual tasks, increasing manufacturing costs and extending delivery timelines. Additive manufacturing allows manufacturers to create prosthetic limbs that meet requirements for lightweight design, strong materials, and precise replication of body shape.

Designers can create multiple design options through 3D printing, improving user comfort and product performance based on patient feedback.⁽³⁰⁾ In addition, 3D printing technology enables constant size changes and personalized design for prosthetics, which makes them ideal for pediatric patients who need support during their growth process. The production process for customized prosthetic sockets, orthotic braces, and assistive devices delivers efficient results, lowering production costs and shortening waiting periods. Tissue engineering solutions are needed in the medical field, and 3D printing technology can produce them through scientific research. The 3D-printed bone scaffolds use composite materials,

including polymers and ceramics, to construct structures that replicate trabecular bone patterns. The scaffolds provide a structural foundation that supports mechanical loads while enabling cells to establish contact and develop blood vessels. Printed scaffolds improve regenerative function when combined with bioactive molecules, growth factors, and stem cells. Bioprinting technologies enable users to create bones and cartilage as well as basic organ structures. The layer-by-layer deposition creates tissue constructs that maintain natural tissue characteristics, while hydrogels containing chondrocytes enable cartilage regeneration.

The 3D printing process enables bone repair through hydroxyapatite and tricalcium phosphate scaffold production, which features controlled porosity and interconnecting pore structures that facilitate bone tissue integration and vascular development. Technologies that let researchers control scaffold microarchitecture and mechanical properties have revolutionized research methods by offering better options than current bone grafting techniques. Furthermore, 3D printing enables personalized medicine by producing medicines tailored to individual patients' specific health needs.⁽³¹⁾ Medical experts encounter challenges when using standard tablet production methods because these methods create fixed dosage levels, which make it difficult to create personalized medication schedules. The 3D-printed tablets produced by additive manufacturing deliver precise medication amounts through built-in release mechanisms and detailed design elements. The method provides effective treatment for pediatric and geriatric patients who need different medication dosages. The Food and Drug Administration (FDA)-approved 3D-printed drug Spritam® (levetiracetam) demonstrated the clinical viability of this method, expanding its potential use in pharmaceutical development. Drug-loaded scaffolds act as treatment systems that deliver medication throughout tissue engineering procedures. Scaffolds that restore joint tissue regeneration capacity allow defect sites to receive anti-inflammatory medication and growth factors, enhancing tissue recovery while minimizing overall adverse effects.

Drug-delivery systems using 3D printing technology create customized systems that deliver drugs through drug-release mechanisms. Excipients can be printed from materials including polyvinyl alcohol, hydroxypropyl methylcellulose, and Eudragit polymers. Researchers developed three drug-release systems, namely, immediate release, sustained release, and multi-drug release, through the combination of tablet geometry changes with infill density modifications. The FDA approval of Spritam® confirmed clinical feasibility. The 3D-printed scaffolds serve as cartilage repair materials used by medical professionals in joint tissue engineering applications. The study materials comprise hydrogels containing alginate and gelatin and biodegradable polymers containing PCL. The scaffolds support chondrocyte growth, enabling them to develop extracellular matrix structures. The drug-loaded scaffolds deliver anti-inflammatory agents and growth factors to treat osteoarthritis through local delivery. Combining drug-delivery systems with tissue engineering techniques marks a major achievement in regenerative medicine.

Advantages, challenges, and limitations of 3D printing in the medicine industry

Medical professionals in the healthcare industry benefit from 3D printing technology because it provides several advantages in their work (**Table 1**). Medical professionals employ customization to develop customized solutions that address individual patient needs.⁽³²⁾ The rapid prototyping method enables medical professionals to create surgical procedures and medical devices at increased speed while reducing production costs and development time. Moreover, the layer-by-layer fabrication enables the production of 3D objects with internal structures that typical manufacturing methods cannot produce. Scientists use bioprinting technology to develop regenerative medicine procedures that combine living cells with bioactive materials. Implementing a digital workflow system provides three primary benefits: reproducibility, traceability, and compatibility with existing diagnostic and imaging systems.

Table 1. A comparison table summarizing the major three-dimensional printing technologies.

Category	Advantages	Disadvantages
PolyJet	High resolution	High costs
Stereolithography	High accuracy	Material brittleness
Electron beam melting	High speed	Rough surface finish
Extrusion-based printing	Minimal waste	Visible layer lines
Binder jetting	Broad material range	Lower mechanical strength

Medical professionals must meet specific technology requirements to access the full benefits of 3D printing in healthcare. The lack of international and national safety standards prevents regulatory agencies from establishing essential operational requirements needed to evaluate the safety and proper functioning of 3D-printed medical devices. Medical device manufacturers need standardized production methods and materials to develop their manufacturing processes. In addition, 3D printing requires new production methods to create implants, prosthetics, and scaffolds by selecting printers, materials, and digital manufacturing techniques. System testing requires comprehensive preclinical and clinical evaluations to verify operational capability throughout the product's functional lifespan. The FDA, along with other regulatory organizations, has published initial additive manufacturing guidelines. However, comprehensive systems are currently being developed to regulate clinical use, post-market evaluation, and long-term product research. Regulatory frameworks create two benefits through their specific requirements: they protect patient safety and enable medical practitioners to gain investor confidence in 3D-printed medical devices.

Printed implants require two tests that verify biocompatibility and long-term performance. The evaluation process for 3D-printed materials must test titanium alloys, bio-crystals, and biocompatible polymers by assessing tissue integration, material degradation patterns, mechanical properties, and the body's immune response.⁽³³⁾ The metal implants that manufacturers create through the EBM process show high strength and effective osseointegration. However, their overall performance requires evaluation because they may face stress shielding, corrosion, and surface-roughness issues. Tissue engineering requires polymeric scaffolds to achieve two opposing goals: natural breakdown causes tissue loss, while prolonged persistence can trigger chronic inflammatory responses. Bioprinting hydrogels for cartilage and soft-tissue applications requires precise control of crosslinking density, porosity, and nutrient diffusion to sustain cell viability over extended periods. Furthermore, 3D-printed implants and scaffolds require scientific validation, including in vitro toxicity testing and extended in vivo studies to evaluate their safety and performance.

The current state of 3D printing technology for medical applications remains restricted because it depends on materials that have not yet been developed.

The development process must achieve mechanical strength, degradation rate, sterilization compatibility, and surface characteristics that meet multiple clinical requirements. Orthopedic implants need metal or dense bioceramic solutions that provide the required tensile and compressive strength. Soft tissue scaffolds require materials that combine flexible and porous hydrogels to support cellular infiltration and extracellular matrix growth. Most photopolymers and hydrogels face sterilization challenges because they cannot withstand standard autoclaving, requiring gamma irradiation or ethylene oxide treatment to sterilize while preserving their physical and biological properties. Researchers face challenges when creating multi-material constructs because soft bioinks and rigid polymers respond differently to environmental conditions and sterilization methods, leading to device performance issues. Testing requires material testing and standardized fabrication and post-processing procedures to address these material challenges.

The healthcare sector requires expensive 3D printing machines, and medical facilities must provide essential 3D printing services. Organizations need significant financial resources to acquire EBM and PolyJet printers because they require basic equipment, specialized materials, and trained, certified professionals. Organizations also need financial resources to train employees in operating systems, quality assurance procedures, and post-processing. Hospitals need basic equipment to access advanced 3D printing technology, which creates barriers to access. Low-cost extrusion-based printers, which, combined with desktop SLA systems, create printing systems that enable small-scale production facilities to produce prosthetics, surgical models, and educational materials. Upcoming printing technology will deliver economical solutions that make 3D printing standard across multiple medical applications.

The digital workflow management system must adhere to standard operating procedures because the existing imaging system produces inconsistent results among various healthcare facilities through its segmentation process and model training methods. Medical imaging data require complete segmentation of CT, MRI, and ultrasound images because these images generate patient-specific implants, surgical guides, and scaffolds that require identification of anatomical structures. Different segmentation techniques, which combine various imaging methods and CAD software algorithms, can introduce multiple errors that reduce accuracy, performance, and

operational safety for printed devices. Digital workflow standardization develops through printing operations, which must adhere to quality assurance standards that establish operational procedures for clinical workflows. Developers create automated tools and artificial intelligence-assisted segmentation solutions to improve operational efficiency and reduce human error, thereby creating reliable, scalable production processes for customized medical devices.

Surgeons use 3D printing technology to develop surgical training models that realistically simulate human body parts. This method produces three results: reduced operation time, lower health risks, and enhanced surgical accuracy. Clinical results show improvement because doctors can use orthopedic and maxillofacial surgery guides to place implants accurately, helping patients recover more quickly.⁽³⁴⁾ The 3D printing process creates physical models, which help patients understand surgical procedures during their informed consent process.

Regenerative medicine develops tissue-like structures through 3D bioprinting using controlled cell and biomaterial placement combined with growth factor application. Researchers have made substantial advances in developing cartilage, skin, and bone tissue, although they are still researching how to print complete, functional human organs. Bioprinted scaffolds create complex tissue structures with hierarchical pore designs and varying mechanical properties that support cell survival, growth, and differentiation. Three-dimensional bioprinting technology can address complex medical challenges by combining stem cells, growth factors, and signaling molecules to enhance tissue regeneration.

Pharmaceutical research uses 3D printing technology to create custom medical treatments for individual patients. The first FDA-approved 3D-printed drug, levetiracetam Spritam®, established additive manufacturing as an effective way to produce personalized medications that provide precise dosing and controlled drug release. These 3D-printed tablets enable customized treatment solutions for patients who require specialized medication and have difficulty swallowing. Scientists create customized drug-release profiles through tablet design elements, including material selection, shape changes, and internal structure modifications.

The field still faces several challenges because of three key factors: regulatory approval and material standardization, long-term biocompatibility assessment,

and cost limitations. Researchers need to conduct ongoing studies to identify better materials and printing methods and develop standard procedures that produce consistent clinical results. Engineers, materials scientists, clinicians, and regulatory agencies must work together to integrate 3D printing technologies into standard medical procedures. Combining artificial intelligence and machine learning with advanced imaging technologies will enhance 3D printing applications through precise design and manufacturing processes, improving efficiency and production capacity and revolutionizing surgical planning, tissue engineering, drug delivery, and personalized medicine.

Additive manufacturing is still in its early stages, but ongoing technological progress will drive advancements as new medical applications emerge. Medical professionals will use customized implants, prosthetics, and surgical models to improve patient outcomes, make procedures safer, and increase patient satisfaction. Medical professionals will rely on bioprinting and hybrid scaffold technologies because they enable the creation and restoration of human tissues and organs. In addition, 3D printing technology will enable pharmacists to produce personalized medicine solutions and help track patients' absorption rates of different medications. Overall, the combination of 3D printing materials and methods with digital workflows will make additive manufacturing an important way to create precise medical solutions for individual patient needs.

Challenges and future directions

The world has achieved important development milestones, yet it must still address existing challenges. Researchers need to complete their testing because the process requires biocompatibility and degradation testing. Moreover, testing procedures that require regulatory approval must include complete mechanical testing alongside biological testing. System implementation processes also face operational growth challenges because business expansion requires financial resources. The field currently benefits from scientific progress driven by researchers' studies of materials science, automation, and multi-material printing methods. In the future, researchers will study smart scaffolds that use sensor technology to detect biological signals, monitor healing processes, and deliver targeted medical therapies.

Conclusion

By creating patient-specific anatomical models, implants, prostheses, surgical guides, medication delivery systems, and tissue-engineered constructs, medical 3D printing has become a transformative tool in contemporary healthcare. By combining advanced imaging, CAD, biomaterials science, and additive manufacturing, 3D printing enables greater anatomical precision and customized therapeutic strategies that improve surgical planning, procedural accuracy, functional outcomes, and patient-specific rehabilitation. Its growing use also supports the shift from traditional standardized therapies to more individualized, precision-based healthcare. Despite these developments, issues with manufacturing costs, material selection, reproducibility, quality control, biocompatibility, scalability, sterilization, intellectual property concerns, and regulatory harmonization limit the widespread clinical translation of medical 3D printing. Furthermore, establishing the safety, effectiveness, and long-term performance of 3D-printed medical devices requires robust clinical data and standardized production and validation procedures. Therefore, resolving these translational challenges will require ongoing multidisciplinary cooperation between doctors, biomedical engineers, materials scientists, regulatory bodies, and industry stakeholders. Overall, 3D printing's therapeutic potential is expected to expand further through integration with advanced biomaterials, bioprinting, artificial intelligence, computational modeling, and digital health technologies. Taken together, these advancements establish medical 3D printing as a key enabling technology for patient-centered, precise, and increasingly regenerative healthcare.

Author contributions

All authors made substantial contributions to the conception and acquisition of data, participated in drafting or critically revising the article for important intellectual content, and agreed to submit to the current journal.

Acknowledgements

The authors would like to express their gratitude to all participants who were involved in this study.

Conflict of interest statement

All authors have completed and submitted the International Committee of Medical Journal Editors

Uniform Disclosure Form for Potential Conflicts of Interest. All authors declare that they have no conflicts of interest.

Data sharing statement

The present review is based on the references cited. All data generated or analyzed during the present study are included in this published article and the citations herein. Further details, opinions, and interpretation are available from the corresponding author on reasonable request.

AI declaration

Authors clarify that they did not use AI in any part of the manuscript.

ORCID

Muhammad Akram  <https://orcid.org/0000-0002-7457-8572>

Nosheen Aslam  <https://orcid.org/0000-0003-2802-0313>

Ho Soon Min  <https://orcid.org/0000-0002-3697-5091>

Naveed Munir  <https://orcid.org/0000-0003-0380-1332>

Marium Ahsan  <https://orcid.org/0009-0007-8083-4839>

Abubakar Babangida Usman  <https://orcid.org/0000-0002-8219-6785>

References

1. Vaz VM, Kumar L. 3D Printing as a promising tool in personalized medicine. *AAPS Pharm Sci Tech* 2021; 22:49.
2. Leong WY. 3D Printing for Renewable Energy Technologies. *ASM Sci J* 2025;20:1–10.
3. Yao R, Xu G, Mao SS, Yang HY, Sang XT, Sun W, et al. Three-dimensional printing: review of application in medicine and hepatic surgery. *Cancer Biol Med* 2016; 13:443–51.
4. Chen G, Xu Y, Kwok L, Kang L. Pharmaceutical applications of 3D printing. *Addit Manuf* 2020;34: 101209.
5. Trenfield SJ, Madla CM, Basit AW, Gaisford S. Binder Jet Printing in Pharmaceutical Manufacturing. In: Basit AW, Gaisford S, editors. *3D Printing of Pharmaceuticals*. Cham: Springer International Publishing; 2018. p. 41–54.
6. Chokshi S, Gangatirkar R, Kandi A, DeLeonibus M, Kamel M, Chadavada S, et al. Medical 3D printing using material jetting: technology overview, medical applications, and challenges. *Bioengineering (Basel)* 2025;12:249.

7. Gülcan O, Günaydın K, Tamer A. The state of the art of material jetting-a critical review. *Polymers (Basel)* 2021;13:2829.
8. Dev Singh D, Mahender T, Raji Reddy A. Powder bed fusion process: a brief review. *Mater Today Proc* 2021; 46:350–5.
9. Al-Ahmari A, Nasr EA, Moiduddin K, Alkindi M, Kamrani A, editors. Patient specific mandibular implant for maxillofacial surgery using additive manufacturing. *Proceedings of the 2015 International Conference on Industrial Engineering and Operations Management*; 2015 March 3 – 5; Dubai, United Arab Emirates: IEOM; 2015. pp. 1–7.
10. Chia HN, Wu BM. Recent advances in 3D printing of biomaterials. *J Biol Eng* 2015;9:4.
11. Trenfield SJ, Awad A, Goyanes A, Gaisford S, Basit AW. 3D printing pharmaceuticals: drug development to frontline care. *Trends Pharmacol Sci* 2018;39: 440–451.
12. Murphy SV, Atala A. 3D bioprinting of tissues and organs. *Nat Biotechnol* 2014;32:773–85.
13. Ballard DH, Trace AP, Ali S, Hodgdon T, Zygmunt ME, DeBenedictis CM, et al. Clinical applications of 3D printing: primer for radiologists. *Acad Radiol* 2018;25:52–65.
14. Goole J, Amighi K. 3D printing in pharmaceuticals: a new tool for designing customized drug delivery systems. *Int J Pharm* 2016;499:376–94.
15. Kotta S, Nair A, Alsabeelah N. 3D printing technology in drug delivery: recent progress and application. *Curr Pharm Des* 2018;24:5039–48.
16. Daly R, Harrington TS, Martin GD, Hutchings IM. Inkjet printing for pharmaceuticals - a review of research and manufacturing. *Int J Pharm* 2015;494:554–67.
17. Azizi Machekposhti S, Mohaved S, Narayan RJ. Inkjet dispensing technologies: recent advances for novel drug discovery. *Expert Opin Drug Discov* 2019;14: 101–13.
18. Palmquist A, Jolic M, Hryha E, Shah FA. Complex geometry and integrated macro-porosity: Clinical applications of electron beam melting to fabricate bespoke bone-anchored implants. *Acta Biomater* 2023;156:125–45
19. Tamayo JA, Riascos M, Vargas CA, Baena LM. Additive manufacturing of Ti6Al4V alloy via electron beam melting for the development of implants for the biomedical industry. *Heliyon* 2021;7:e06892.
20. Li J, Fischer P. Advances in extrusion-based bioprinting enabled by advanced printhead and nozzle designs. *Mater Today Bio* 2026;37:102941
21. Rony FK, Kimbell G, Serrano TR, Clay D, Ilias S, Azad MA. Extrusion-Based 3D Printing of Pharmaceuticals—Evaluating Polymer (Sodium Alginate, HPC, HPMC)-Based Ink's Suitability by Investigating Rheology. *Micromachines (Basel)* 2025;16:163.
22. Kaza A, Rembalsky J, Roma N, Yellapu V, Delong W, Stawicki S. Medical applications of stereolithography An overview. *Int J Acad Med* 2018;4:252–65.
23. Msallem B, Vavrina JJ, Beyer M, Halbeisen FS, Lauer G, Dragu A, et al. Dimensional Accuracy in 3D Printed Medical Models: A Follow-Up Study on SLA and SLS Technology. *J Clin Med*. 2024;13:5848.
24. Wang Z, Sun Y, Li C. Advances in 3D printing technology for preparing bone tissue engineering scaffolds from biodegradable materials. *Front Bioeng Biotechnol* 2024;12:1483547.
25. Abbas Z, Dapporto M, Tampieri A, Sprio S. Toughening of bioceramic composites for bone regeneration. *J Compos Sci* 2021;5:259.
26. Marin E, Lanzutti A. Biomedical applications of titanium alloys: a comprehensive review. *Mater (Basel)* 2023;17:114.
27. Abdelaziz A, Nageh H, Abdo SM, Abdalla MS, Amer AA, Abdal-Hay A, et al. A review of 3D polymeric scaffolds for bone tissue engineering: principles, fabrication techniques, immunomodulatory roles, and challenges. *Bioengineering (Basel)* 2023;10:204.
28. Dionigi C, Nagy G, Derks J, Ichioka Y, Tomasi C, Larsson L, et al. Titanium micro-particles are commonly found in soft tissues surrounding dental implants. *Commun Med (Lond)* 2025;5:78.
29. Pandey M, Choudhury H, Fern JLC, Kee ATK, Kou J, Jing JIJ, et al. 3D printing for oral drug delivery: a new tool to customize drug delivery. *Drug Deliv Transl Res* 2020;10:986–1001.
30. Savini A, Savini GG, editors. A short history of 3D printing, a technological revolution just started. 2015 ICOHTEC/IEEE International History of High-Technologies and their Socio-Cultural Contexts Conference (HISTELCON); 2015 Aug 18–19; Tel-Aviv, Israel: IEEE; 2015.
31. Prasad LK, Smyth H. 3D printing technologies for drug delivery: a review. *Drug Dev Ind Pharm* 2016;42: 1019–31.
32. Water JJ, Bohr A, Boetker J, Aho J, Sandler N, Nielsen HM, et al. Three-dimensional printing of drug-eluting implants: preparation of an antimicrobial polylactide feedstock material. *J Pharm Sci* 2015;104:1099–107.
33. Vaiani L, Boccaccio A, Uva AE, Palumbo G, Piccininni A, Guglielmi P, et al. Ceramic Materials for Biomedical Applications: An Overview on Properties and Fabrication Processes. *J Funct Biomater* 2023;14:146.
34. Sonowal L, Gautam S, Mambiri LT, Depan D. Advancements of bioceramics in biomedical applications. *Next Materials* 2025;9:101010.