

Functionalization Strategies of 3D-Printed Materials for Bone Repair: From Structural Scaffolds to Regenerative Regulation

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Abstract. Bone defects remain a prevalent challenge in oral and maxillofacial surgery, orthopedics, and implantology. Critical-sized defects may not heal spontaneously, while conventional grafts are limited by donor availability, biosafety concerns, and inadequate patient-specific fit. Three-dimensional (3D) printing enables personalized scaffolds with tunable geometry and porosity. This review summarizes functionalized 3D-printed bone repair materials, including material selection, fabrication methods, and core design requirements. It examines strategies that combine osteogenic growth factors, bioactive ions, antimicrobial agents, and immunomodulatory components to promote vascularized osteogenesis, control infection, and regulate the local immune microenvironment. The technology supports structural customization and incorporation of multiple biological functions, extending scaffolds beyond passive defect filling. However, unresolved issues include controlled bioactive release, coordination of mechanical performance with degradation and regeneration, inconsistent evaluation standards, manufacturing reproducibility, and clinical translation. Emerging directions include artificial intelligence-assisted design, multimaterial printing, and microenvironment-responsive scaffolds. This review provides a framework for optimizing functionalized 3D-printed scaffolds and evaluating their translational potential in bone repair.

Keywords: 3D printing, bone regeneration, functionalized scaffolds, vascularized osteogenesis, microenvironment regulation

1. Introduction

Bone defects are common and serious clinical problems in oral and maxillofacial surgery, orthopedics, and implant dentistry. According to statistics, there were 178 million new fracture cases worldwide in 2019. The demand for bone grafts ranks second globally, after the demand for blood, and the total number of bone graft surgeries exceeds 2.2 million per year [1]. The main causes of bone defects are trauma, tumor resection, infectious lesions, progressive alveolar bone resorption and insufficient bone volume at the implant site [2]. When a defect exceeds a critical size, spontaneous bone healing may not occur. Approximately 3%–10% of fractures develop nonunion; craniofacial defects may additionally impair mastication and speech and contribute to facial

deformity and psychological distress. Therefore, the development of new restorative materials with good biocompatibility and effective bone-regenerative capacity is of great interest to clinicians.

Current clinical bone repair strategies include autologous bone, allograft bone and synthetic bone substitutes. Autologous bone has long been considered the "gold standard" because of its combined osteoconductivity [1], osteoinduction and osteogenic properties; however, it has considerable limitations, such as a limited bone supply, secondary surgical injury at the donor site, and a high risk of postoperative complications, which restrict its clinical application. Allografts and xenografts can help to alleviate the shortage of donor materials, but there are also risks of postoperative immune rejection and safety issues related to cross-transmission of pathogens. Traditional synthetic bone substitutes, such as hydroxyapatite and β -tricalcium phosphate, are mainly used to promote bone conduction and fill defects. These materials are inherently brittle and generally lack sufficient endogenous bone-inducing activity; in addition, as they are mostly produced in standardized, mass-produced sizes, they are difficult to adapt to various shapes of individual bone defects, and poor interface fit directly affects the outcome of bone healing. Therefore, although all the existing repair strategies have their own merits, they are unable to meet all the requirements simultaneously, such as material supply, biological function, mechanical conformity and personalization.

The limitations of traditional restorative materials in individualized fit and functional integration have encouraged the development of additive manufacturing approaches for bone defects. Using digital imaging and high-precision fabrication, 3D printing can be employed to manufacture customized scaffolds that match patient-specific defect geometry and have controlled pore structures. These structural features can improve the fit between the scaffold and the defect site and provide a favorable environment for cell migration, nutrient supply, and the development of new tissue by adjusting pore size, porosity and connectivity. Recently, researchers have added nano-functional materials, bioactive factors and controlled release drug delivery systems to the printing ink to enhance the multiple therapeutic functions of scaffolds and support a shift in bone repair materials from passive defect filling toward active regulation of regeneration. This shows that the role of 3D printing is no longer limited to supplying physical support, but is gradually expanding to synergistic regulation of osteogenesis, angiogenesis, infection, and the local microenvironment. This paper will introduce research results on functionalized 3D-printed bone repair materials, explore their applications in promoting angiogenesis and osteogenesis, combating infection, regulating the microenvironment, and analyze key problems such as mechanical compatibility, controlled release of active substances, and clinical translation, thus providing a reference for the optimization and broad application of these materials in the future.

2. Design principles for 3D-printed functionalized bone repair materials

Scaffolds for bone defect repair need to meet many basic requirements. An ideal bone repair scaffold should have excellent biocompatibility to reduce adverse reactions in the host, an appropriate degradation rate that matches the formation speed of new bone tissue, sufficient mechanical strength to provide structural support during the early stages of healing, and an interconnected three-dimensional porous structure that can promote cell migration, nutrient supply and the removal of metabolic waste [3, 4]. The introduction of additive manufacturing technology offers a way to meet the above demands in a combined manner within a single scaffold; 3D printing can be used to customize the external shape of the scaffold according to the shape of a patient's defect through digital design and, at the same time, create a regular internal pore network to balance the demands for mechanical strength and mass transport [2].

At present, the materials for 3D-printed bone-repair scaffolds mainly fall into the categories of bioceramics, natural and synthetic polymers, and their composites. Hydroxyapatite and β -tricalcium phosphate provide good osteoconductivity and bioactivity, but they are relatively brittle and difficult to process. Polycaprolactone (PCL), polylactic acid (PLA) and polylactic-co-glycolic acid (PLGA) are synthetic polymers that are easy to process and have controllable degradation rates; however, they generally have poor osteogenic ability [3]. Natural polymers such as gelatin, sericin and chitosan are used as cell adhesion substrates to promote the development of cells, but they often lack good mechanical properties. A composite strategy aims to enhance the biological function and processability of ceramic materials by incorporating polymers. Therefore, there is no single "best" or "worst" material; instead, the choice of material should be based on the load-bearing demands of the defect area, the expected service life and any other required biological functions. Extrusion printing technology, which is related to material selection, also has many uses and is relatively low-cost; thus, thermoplastic polymers and their composites are suitable for extrusion printing [5]. Photopolymerization printing technology has higher printing accuracy and is suitable for photoresins and ceramic slurries, while powder bed fusion technology is used for metal and ceramic powders. As shown in Figure 1, the various technologies have different trade-offs in terms of material compatibility, resolution, printing speed and cost, and the selection needs to be based on the particular defect site and repair requirements. Therefore, the material system and the printing process cannot be considered separately; rather, rheological, thermal, or photopolymerization characteristics of the material affect its suitability for processing, and the fabrication process may also modify the structure and biological functions of scaffolds.

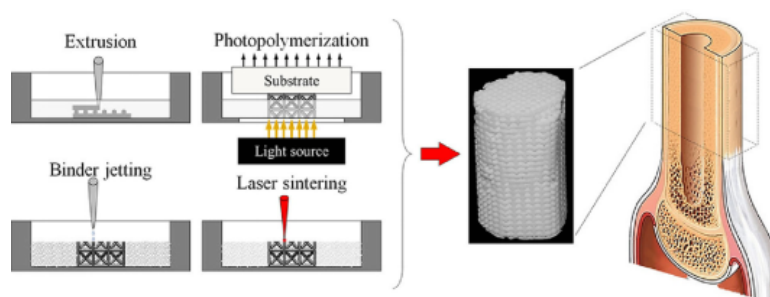


Figure 1. Schematic of four mainstream 3D-printing methods for porous bone repair scaffolds and bone defect reconstruction [4]

Scaffold microstructure also influences bone regeneration. Pore size directly affects cell infiltration and the ingrowth of new bone tissue; if the pores are too small, it may restrict cell penetration and angiogenesis; if they are too large, they can compromise mechanical properties and reduce cell adhesion sites. High porosity and interconnectivity will facilitate the supply of nutrients and the removal of waste products for uniform tissue growth in the scaffold. In addition, the surface features of roughness and microstructure can regulate cell adhesion, spreading and differentiation; thus, a structural gradient design that gradually varies porosity from the outside in is expected to optimize both the cell affinity at the surface and the internal mass transport capability. Porosity, connectivity and mechanical strength are often in opposition to each other; thus, the goal of structural optimization is not to maximize any one of these parameters alone, but to build a combination of parameters that meets the specific requirements of a particular bone defect.

Recent scaffold design has increasingly emphasized active biological regulation in addition to structural substitution. Functionalization strategies are being employed to incorporate nano-functional materials, bioactive factors, antimicrobial agents, and live cells into the printing system

to transform scaffolds into active platforms with biological guidance [6, 7]. Therefore, the design of scaffolds should focus on structural and morphological compatibility in addition to function; that is, how to maintain the bioactivity of active components during the printing process, how to realize controlled release of these components *in vivo*, and how to coordinate the synergy and constraints of multiple functions. In short, the foundation of the design for 3D-printed bone repair materials consists of four interconnected parts: material selection, fabrication process, structural optimization and functional modification. Synergistic optimization of the above factors is required to build high-performance scaffolds [2], but at present, it is still a significant problem to meet all the demands of mechanical properties, degradation behavior and biological activity simultaneously in a single scaffold [4].

3. Functional design of 3D-printed scaffolds to promote vascularization and osteogenesis

Angiogenesis and osteogenesis are closely linked in space and time, and together they make up the necessary biological features of bone healing. Normal bone tissue is rich in a blood supply; thus, oxygen and nutrients can be delivered to osteoblasts, metabolic waste removed, circulating mesenchymal stem cells recruited, and osteogenesis-related signaling molecules transported. In large-volume bone defects, a lack of vascularization in the scaffold is often one of the reasons for poor tissue survival and reduced sustained osteogenesis; early ischemia and limited nutrient diffusion can severely inhibit the formation of new bone tissue [6]. Therefore, the design goal for rapid and sufficient vascularization in 3D-printed scaffolds is to improve the repair effect of large-volume bone defects.

A representative strategy for adding osteogenic activity is to incorporate osteogenic functional components into the scaffold. Currently, the most widely studied group of osteogenesis-related growth factors is the bone morphogenetic protein (BMP) family, and among them, BMP-2 and BMP-7 have been shown to effectively induce the osteogenic differentiation of mesenchymal stem cells. Growth factors have a short *in vivo* half-life and are easily degraded; thus, direct injection cannot maintain an effective concentration over a long period. Therefore, 3D-printed scaffolds can be used as carriers for growth factors, and by altering the material structure, both the release rate and duration of these factors at the defect site can be regulated. In addition to protein factors, inorganic ions such as strontium (Sr^{2+}), magnesium (Mg^{2+}) and copper (Cu^{2+}) have also been found to promote osteogenesis [8]. These ions can be added to the ceramic material by doping or attached to the scaffold through surface modification, and they are released continuously during degradation to provide relatively prolonged osteogenic stimulation.

Development of angiogenic functional components aims to induce the formation of a new vascular network in the scaffold. Vascular endothelial growth factor (VEGF) is a key regulator of new blood vessel formation; it can promote the proliferation, migration and lumen formation of endothelial cells. Loading VEGF onto 3D-printed scaffolds is expected to enhance the retention of VEGF at the defect site and regulate its release, thus promoting vascularization of the scaffold. Copper ions are another class of bioactive ions that can promote angiogenesis [8]. Recently, researchers have also attempted to directly add endothelial cells or endothelial progenitor cells to the printed scaffold to promote scaffold vascularization via the paracrine effect and angiogenesis of these cells [6]. As shown in Figure 2, the existing strategies for scaffold pre-vascularization mainly promote the formation of intrascaffold vascular networks by structural optimization, delivery of bioactive factors, and introduction of angiogenesis-inducing cells. These three approaches to regulating angiogenesis at the level of growth factors, active ions and cells face several problems, including component instability, insufficient release dose, and poor survival of implanted cells.



Figure 2. Schematic overview of 3D-printed bone scaffold systems and diverse prevascularization strategies for bone regeneration [6]

At present, the combined regulation of vascularization and osteogenesis is required for the design of functional scaffolds. Bone regeneration is a multi-stage process that occurs in space and time; first, sufficient blood vessel growth is needed to provide nutrients and recruit cells for other stages, such as the differentiation of osteoblasts around blood vessels and the subsequent deposition of bone matrix. Therefore, an ideal scaffold design should be able to promote the combined release of pro-angiogenic and pro-osteogenic factors; for example, by spatially distributing VEGF at the edge of the scaffold and BMP in its core, or by using a sequential-release strategy to ensure that angiogenesis occurs before osteogenesis [6]. The problem of achieving spatiotemporal coordination is that it is necessary to match the release kinetics of various factors precisely with the natural regenerative process *in vivo*, but the optimal release timing remains uncertain. In short, 3D-printed scaffolds that introduce both osteogenic and angiogenic promoting factors have shown good results in modulating the coupling of angiogenesis and osteogenesis; however, the problem of how to achieve precise spatiotemporal delivery of bioactive factors in line with the natural process of *in vivo* bone regeneration remains unresolved and requires urgent attention.

4. Infection prevention and regulation of the bone repair microenvironment in 3D-printed scaffolds

Infections at the site of bone defects present significant problems in the treatment of bone disorders. The main reasons for the persistence of infection are that bacteria adhere to the surface of an implant and form a biofilm; this biofilm can protect the bacteria from the host immune system and antibiotics, and simultaneously inhibit the function of osteoblasts and osseointegration of the implant through prolonged inflammation. *Staphylococcus aureus* is a common cause of bone infection, and it can invade, proliferate, and persist within bone tissue [9]. If not managed properly, bone infections can directly destroy new bone formation in the alveolar ridge, and prolonged inflammation may also cause peri-implant bone loss and implant loosening. Therefore, incorporating antibacterial properties into the design of bone-repairing scaffolds can help address the problem of infection during tissue engineering at the site of bone defects.

At present, the antimicrobial strategies for 3D-printed scaffolds generally fall into three categories: release of antimicrobial drugs, non-pharmaceutical physical antimicrobial methods, and surface-coated antimicrobial approaches. Antimicrobial drug-release strategies involve loading antibiotics, such as vancomycin and gentamicin, onto a scaffold for localized sustained release via material degradation or diffusion. Therefore, it can increase the concentration of the drug at the site of infection and reduce systemic exposure; however, the actual effect is related to the loading amount, release characteristics and infection model. Drug burst release, a short release duration, and antibiotic resistance are also problems with the current technology [9]. Metal or inorganic nanomaterials, such as silver, copper, and zinc oxide nanoparticles, are antibacterial due to the release of metal ions that damage bacterial cell membranes or the generation of reactive oxygen species. They have a wide range of antimicrobial activities and are unlikely to develop resistance easily; however, care must still be taken to avoid dose-dependent cytotoxicity and the risk of prolonged accumulation. Antimicrobial peptides are another type of antibacterial agent that has gained attention; they kill bacteria by damaging the cell membrane of bacteria directly and are generally less likely to induce resistance. Photothermal therapy is a type of light-responsive material that generates localized high temperatures upon exposure to near-infrared light to kill bacteria on demand. Each strategy has its own strengths and weaknesses: drug-release strategies are reliable in terms of antimicrobial effect but are limited by drug resistance and release kinetics; metal nanomaterials have a broad-spectrum antimicrobial activity but need to address cytotoxicity; and antimicrobial peptides have good biocompatibility but require enhancement of *in vivo* stability.

Regulation of the immune microenvironment has been one of the leading research directions for bone repair in recent years. Macrophage polarization and other immune responses regulate the healing process of bone injuries by controlling inflammation and tissue regeneration; specifically, after injury, macrophages switch from an M1 (pro-inflammatory) state to an M2 (pro-repair) state and thus influence osteogenesis and angiogenesis [5]. Dysregulated macrophage responses frequently result in fibrous encapsulation or nonunion. 3D-printed scaffolds can modulate this phenomenon by adjusting the material composition, surface features and active substances; for example, a slow release of bioactive ions (such as Mg^{2+} and Sr^{2+}) can promote the M2-polarized state of macrophages; at the same time, physical characteristics of the scaffold, such as surface nanostructure, pore size and surface charge, can affect the response of immune cells; and the addition of immunomodulatory molecules can further direct the local immune microenvironment towards an osteogenic-friendly state [8]. Precise regulation of the immune microenvironment is also necessary; full suppression of inflammation may prevent the start of tissue regeneration, and prolonged inflammation can inhibit osteogenesis. Therefore, the purpose of immune regulation is not to suppress inflammation unilaterally, but to enable the transition of the inflammatory response to the tissue repair stage in time.

The combined action of anti-infection, immune regulation and osteogenesis is an important goal in the design of multifunctional scaffolds. The three factors are also intertwined; for example, antimicrobial components may induce an inflammatory response and kill bacteria, but excessive immune suppression can increase the risk of infection [9]. A good scaffold design should be suitable for cells and osteogenic in nature, inhibit infection, regulate inflammation, and achieve a dynamic balance of the above three. Therefore, a scaffold that is merely a passive carrier of drugs is insufficient; it should also be able to release active components in response to the microenvironment through other means. In summary, 3D-printed scaffolds have introduced antibacterial materials and immune-regulating components to enhance infection control and optimize the osteogenic

microenvironment; however, the optimal combination of antibacterial activity, immunomodulation, and osteogenesis promotion for long-term safety has not yet been determined [8].

5. Challenges in drug delivery, performance evaluation, and clinical translation

The loading and controlled release of active ingredients are technical problems that need to be solved before functionalized 3D-printed scaffolds can be applied in clinical practice. The printing process itself is a risk factor for drug and bioactive substance instability; high-temperature printing, the use of organic solvents or UV-curing may cause protein denaturation or drug degradation. This is also the main deficiency of photopolymerization and high-temperature fused-filament printing for incorporating protein-based bioactive factors. Therefore, a suitable printing technology and mild processing conditions should be selected to maintain the function of bioactive substances. Even after successful loading, there are many problems with the release behavior of bioactive substances: sudden release leads to excessively high concentrations early on and low levels later; it is difficult to meet the long-term requirements for bone regeneration in terms of release profile; and independent dose control of multiple bioactive factors is challenging. Researchers have employed various means to achieve more controlled release, such as polymer coating, microsphere encapsulation and multilayer structural design; however, these methods often increase the complexity of scaffold fabrication and make it difficult to maintain batch-to-batch consistency in large-scale production.

At present, it is still difficult to combine the demands of biology and mechanics in scaffold design. To promote cell migration and blood vessel formation, high porosity is required; however, it will reduce the load-bearing capacity of the scaffold. Rapid degradation promotes the gradual replacement of the scaffold with new bone tissue; however, if the strength is lost prematurely, the structure may collapse early in the healing process. The introduction of active components may also affect the material's mechanical behavior—for example, a high proportion of ceramic filler, while enhancing bioactivity, may increase brittleness. An ideal scaffold should provide adequate mechanical support in the early stages after implantation to keep the defect site stable, and as new bone tissue develops and gains mechanical strength, the scaffold should gradually degrade and transfer the load to the new tissue [3]. This dynamic balance of "strength, degradation and regeneration" requires that the degradation rate of the scaffold be temporally aligned with the speed of new bone formation; thus, to achieve this synchronization, accurate prediction is required for both the material's degradation characteristics and the process of *in vivo* osteogenesis.

Evaluation of functionalized scaffolds spans material characterization through preclinical testing. At the material level, the scaffold's chemical composition, microstructure, porosity, and mechanical properties require comprehensive characterization [4]. Cell experiments *in vitro* are carried out to evaluate the biocompatibility of scaffolds, cell adhesion and proliferation, as well as the osteogenic induction or antibacterial properties of various functionalization strategies. Antimicrobial tests and biofilm-inhibition experiments are conducted *in vitro* to confirm the antibacterial properties of the scaffold [9]. Animal bone defect models are necessary for *in vivo* performance evaluation; histology, imaging and mechanics tests are used to assess the effect of scaffolds on bone regeneration, degradation in the body and inflammation [3]. However, there are currently no standardized norms in various studies for selecting animal models, defect size, evaluation indicators and observation periods; thus, the results of these studies are not easily comparable. In addition, a single cell indicator or imaging result generally cannot confirm that a functionalized scaffold has fully promoted bone regeneration; therefore, multi-dimensional evidence is needed to assess the structure of the tissue, the extent of vascularization, material degradation, and mechanical performance of the repaired site.

The development of additively manufactured bone repair materials is not a linear process from material preparation to scaffold implantation; instead, it is a closed-loop system that integrates patient data collection, scaffold design and manufacturing, performance evaluation, and feedback-based optimization (Figure 3). Clinical translation presents additional challenges. Before widespread clinical use, functionalized scaffolds require reproducible large-scale manufacturing, validated sterilization and long-term storage, long-term safety and efficacy evidence, and clear regulatory pathways [4]. Products containing bioactive factors or living cells may pose greater complexity in regulatory classification, quality control, and preclinical evaluation than conventional medical devices [10]. Personalized production may also increase design, manufacturing, and quality-control costs, and its cost-effectiveness remains uncertain. Standardized evaluation could facilitate comparisons among materials and designs [8]. Artificial intelligence (AI)-assisted design, multimaterial printing, and microenvironment-responsive scaffolds may improve personalization and functional integration [11], but their clinical value requires reproducible and clinically meaningful evidence.

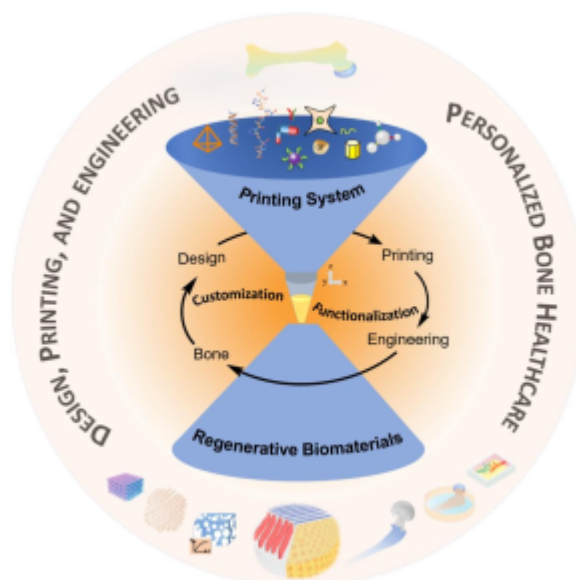


Figure 3. Closed-loop workflow for developing additive manufacturing-based biomaterials toward personalized bone healthcare [2]

6. Conclusion

Repair of severe bone defects requires both accurate structural reconstruction and regulation of scaffold biological function. Traditional bone repair materials have limitations in source availability, safety, and anatomical adaptation and therefore may not meet these requirements simultaneously. Digital customization allows 3D printing to improve conformity to defect geometry, while controlled pore architecture can support cell migration, vascular ingrowth, and mass transport. Functionalization can further add biological activity: growth factors and bioactive ions may promote osteogenic differentiation and angiogenesis, antimicrobial components may support infection control, and immunomodulatory molecules may influence the local regenerative environment. Scaffolds are therefore developing from passive structural supports toward platforms with active biological functions. Nevertheless, promising preclinical results do not by themselves establish

clinical benefit; materials, processes, structures, and functions require integrated optimization and rigorous translational validation.

Translation from laboratory studies to clinical products remains limited by bioactive instability during printing, burst release, insufficient release duration, and uncertainty in dose control. Mechanical design must also reconcile the trade-off between porosity and strength and coordinate scaffold degradation with new bone formation. Substantial heterogeneity in animal models, defect types, outcome measures, and observation periods restricts comparison across studies. Manufacturing consistency, sterilization and storage stability, long-term safety, and regulatory pathways create additional barriers. Standardized, multidimensional evaluation should therefore combine structural, biological, mechanical, and clinically relevant outcomes. Artificial intelligence-assisted design, integrated multimaterial printing, spatiotemporally controlled delivery, and microenvironment-responsive scaffolds may improve personalization and functional integration. Future work should determine whether these advances reproducibly improve meaningful bone repair outcomes while remaining safe, manufacturable, and cost-effective.

References

- [1] Zhang, J., Zhang, W., Yue, W., et al. (2025). Research progress of bone grafting: A comprehensive review. *International Journal of Nanomedicine*, 20, 4729–4757. <https://doi.org/10.2147/IJN.S510524>
- [2] Jia, Z., Xu, X., Zhu, D., et al. (2023). Design, printing, and engineering of regenerative biomaterials for personalized bone healthcare. *Progress in Materials Science*, 134, 101072. <https://doi.org/10.1016/j.pmatsci.2023.101072>
- [3] Ansari, M. A. A., Golebiowska, A. A., Dash, M., et al. (2022). Engineering biomaterials to 3D-print scaffolds for bone regeneration: Practical and theoretical consideration. *Biomaterials Science*, 10(11), 2789–2816. <https://doi.org/10.1039/D2BM00035K>
- [4] Mirkhalaf, M., Men, Y., Wang, R., et al. (2023). Personalized 3D printed bone scaffolds: A review. *Acta Biomaterialia*, 156, 110–124. <https://doi.org/10.1016/j.actbio.2022.04.014>
- [5] Chen, Y., Quan, S., Huang, S., et al. (2024). Applications and progress of 3D printed bioceramic scaffolds in bone tissue repair and immune regulation. *Ceramics International*, 50(23), 48891–48908. <https://doi.org/10.1016/j.ceramint.2024.09.294>
- [6] Duan, Q., Shao, H., Luo, N., et al. (2025). 3D-printed artificial bone scaffolds: The design of materials, the incorporation of bioactive substances, and the integration of vascularized tissue flaps. *Frontiers in Bioengineering and Biotechnology*, 13, 1614727. <https://doi.org/10.3389/fbioe.2025.1614727>
- [7] Zhan, L., Zhou, Y., Liu, R., et al. (2025). Advances in growth factor-containing 3D printed scaffolds in orthopedics. *BioMedical Engineering OnLine*, 24(1), 14. <https://doi.org/10.1186/s12938-025-01346-z>
- [8] Hui, X., Shang, D., Li, S., et al. (2026). Engineering immuno-smart bone scaffolds: Macrophage-centric strategies in 3D-printed tissue regeneration. *Tissue and Cell*, 103, 103705. <https://doi.org/10.1016/j.tice.2026.103705>
- [9] Chen, X., Li, X., Li, Q., et al. (2025). Recent progress of antibacterial strategy for 3D-printed bone repair scaffold. *Surfaces and Interfaces*, 66, 106601. <https://doi.org/10.1016/j.surfin.2025.106601>
- [10] Todd, E. A., Mirsky, N. A., Silva, B. L. G., et al. (2024). Functional scaffolds for bone tissue regeneration: A comprehensive review of materials, methods, and future directions. *Journal of Functional Biomaterials*, 15(10), 280. <https://doi.org/10.3390/jfb15100280>
- [11] Yuan, X., Zhu, W., Yang, Z., et al. (2024). Recent advances in 3D printing of smart scaffolds for bone tissue engineering and regeneration. *Advanced Materials*, 36(34), e2403641. <https://doi.org/10.1002/adma.202403641>