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3D PRINTED BIOMATERIALS IN DENTAL AND MAXILLOFACIAL SURGERY: A COMPREHENSIVE REVIEW

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ABSTRACT

This review provides a comprehensive and methodologically structured analysis of advancements in additive manufacturing (AM) and bioprinting for dental and maxillofacial reconstruction between 2017 and 2025. AM has become an essential component of personalised medicine, enabling the fabrication of patient-specific implants, functional scaffolds, and biologically active constructs that enhance surgical precision and regenerative outcomes. The rapid development of titanium lattice frameworks, bioactive ceramics, biodegradable polymers, and hybrid multimaterial systems has significantly improved the biomechanical and biological performance of craniofacial reconstructions. Concurrently, innovations in bioprinting—including next-generation bioinks, cell-laden hydrogels, microvascularisation strategies, and tissue-specific regeneration—have expanded the potential for restoring dental pulp, periodontal ligament, alveolar bone, and soft tissues using biologically integrated constructs. This review synthesises data from 164 peer-reviewed publications, outlining key technological progress, material innovations, in vitro and in vivo biological responses, translational findings, and clinical outcomes. Despite substantial progress, challenges persist, including vascularisation of large constructs, long-term immunomodulatory behaviour, standardisation of evaluation protocols, and regulatory integration into clinical practice. Future directions highlight the growing impact of AI-assisted design, automated point-of-care manufacturing, and 4D dynamic biomaterials capable of functional adaptation. Overall, AM and bioprinting are positioned to become central technologies shaping the next generation of personalised maxillofacial reconstruction.

KEYWORDS

Additive Manufacturing, 3D Printing, Bioprinting, Maxillofacial Reconstruction, Titanium Implants, Tissue Engineering, Dental Regeneration, Scaffolds, Personalised Medicine

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1. Introduction

Additive manufacturing (AM), encompassing 3D printing and bioprinting, has revolutionised surgical planning and reconstruction across the dental and maxillofacial disciplines. Traditional approaches to bone and soft-tissue repair rely heavily on free flaps, autogenous grafts, and preformed implants, all of which carry limitations regarding intraoperative adaptability, donor-site morbidity, imperfect anatomical conformity, and prolonged operative times. AM technologies address these limitations by providing clinicians with the ability to fabricate anatomically precise, patient-specific constructs that correspond directly to digital imaging data. The integration of cone-beam computed tomography (CBCT), micro-computed tomography (micro-CT), magnetic resonance imaging (MRI), intraoral scanning, and sophisticated segmentation software has dramatically improved preoperative planning and enabled precise translation from virtual simulation to physical constructs.

From 2017 to 2025, research has expanded the capabilities of AM through improved materials, enhanced mechanical and biological performance, and increasingly refined printing modalities. The introduction of high-resolution photopolymerisation, powder-bed fusion of titanium alloys, thermoplastic extrusion with gradient control, and cell-laden hydrogel bioprinting has positioned AM as a core technology in precision medicine. This review provides a rigorous academic analysis of AM developments relevant to maxillofacial surgery, focusing on the technologies, materials, biological considerations, and clinical applications that define current practice and future potential.

2. Methods

This review followed the PRISMA-ScR (Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews) guidelines for data collection, screening, and synthesis. Literature published between January 2017 and January 2025 was identified using PubMed, Scopus, Web of Science, SpringerLink, IEEE Xplore, and Google Scholar. Search terms included: "3D printing", "bioprinting", "additive manufacturing", "maxillofacial reconstruction", "tissue engineering", "dental implants", "bone scaffolds", "titanium lattice", "bioactive ceramic", "periodontal regeneration", and "pulp bioprinting".

Inclusion criteria comprised original experimental studies, clinical trials, scoping reviews, systematic reviews, meta-analyses, and translational reports related to dental and maxillofacial applications of AM. Exclusion criteria included non-peer-reviewed articles, conference abstracts without full papers, and studies unrelated to craniofacial or dental reconstruction. After assessment and reduction of duplicates, 164 studies were included, with 52 selected for detailed synthesis based on methodological quality and relevance.

3. Results and Discussion

3.1 Additive Manufacturing Technologies

AM technologies utilised in oral and maxillofacial surgery can be divided into four principal categories: photopolymerisation, powder-bed fusion, extrusion-based printing, and bioprinting.

Photopolymerisation methods—including stereolithography (SLA) and digital light processing (DLP)—allow fabrication of highly detailed surgical guides, occlusal splints, and anatomical models. These systems use photosensitive resins to achieve excellent surface resolution, making them particularly useful for preoperative planning and guided implant placement.

Powder-bed fusion technologies such as selective laser melting (SLM) and electron beam melting (EBM) enable production of dense or porous titanium implants with controlled lattice geometries. These implants demonstrate superior mechanical strength, corrosion resistance, and capacity for osseointegration when compared with machined titanium.

Extrusion-based technologies, including fused deposition modelling (FDM) and direct ink writing (DIW), facilitate the fabrication of polymeric scaffolds and multi-material constructs with tunable porosity, pore orientation, and degradation rates. Their ability to generate gradient architectures is particularly advantageous for mimicking natural bone heterogeneity.

Bioprinting technologies—microextrusion, inkjet bioprinting, and laser-assisted bioprinting—extend AM capabilities into regenerative medicine by enabling precise spatial deposition of viable cells, bioactive molecules, and extracellular matrix analogues. Bioprinting supports fabrication of soft, vascularised, and functionalised tissues in ways not achievable using conventional manufacturing.

Additive Manufacturing Technologies

Additive manufacturing in dental and maxillofacial surgery can be broadly categorised into photopolymerisation-based, powder-bed fusion, extrusion-based, and bioprinting technologies. Photopolymerisation techniques such as stereolithography (SLA) and digital light processing (DLP) are widely used for generating high-resolution surgical guides, dental models, and prototype scaffolds, offering excellent accuracy and surface finish [4,18]. Powder-bed fusion techniques, including selective laser melting (SLM) and electron beam melting (EBM), are used to produce titanium implants and mechanical load-bearing components due to their superior mechanical strength and capability to generate controlled porous structures that enhance osteointegration [3,8,19]. Extrusion-based technologies such as fused deposition modelling (FDM) and direct ink writing (DIW) enable the fabrication of polymeric and composite scaffolds with controlled porosity, gradient structures, and personalised architectures [2,6,20]. Bioprinting techniques—including microextrusion, inkjet, and laser-assisted printing—allow the deposition of cell-laden bioinks for soft tissue and periodontal regeneration [11,21,22]. These approaches differ in printing resolution, material compatibility, biological safety, and mechanical performance. Their selection depends on the clinical indication, required material properties, and biological functionality

.

Materials for Additive Manufacturing

The selection of biomaterials for additive manufacturing substantially influences mechanical stability, degradation behaviour, cellular interactions, and clinical applicability. Biomaterials used in 3D printing for dental and maxillofacial surgery include metals, ceramics, biodegradable polymers, composites, and hydrogels. Each category presents specific advantages and limitations that determine their suitability for particular applications. Metallic biomaterials, particularly titanium and its alloys such as Ti–6Al–4V, remain the gold standard for patient-specific implants (PSIs) due to their exceptional mechanical strength, biocompatibility, corrosion resistance, and established clinical track record in implantology and reconstructive surgery [3,19,23]. Additive manufacturing using SLM or EBM enables the fabrication of highly porous titanium structures that mimic trabecular bone, facilitating mechanical interlocking and enhancing osteointegration. Pore sizes of 300–800 μm have been shown to support osteoblast adhesion, vascular infiltration, and bone ingrowth [5,8]. Titanium implants produced through AM also allow the creation of complex geometries such as lattice zones, integrated fixation points, and gradient porosity that cannot be achieved with subtractive manufacturing. However, metallic implants remain essentially bioinert, prompting research into surface modification techniques, such as plasma spraying, anodisation, or coating with hydroxyapatite, bioactive glass, or calcium phosphates, to enhance biological integration [17,24]. Ceramic biomaterials, including hydroxyapatite (HA), tricalcium phosphate (TCP), biphasic calcium phosphate (BCP), and bioactive glasses, represent another key class of materials used in 3D-printed scaffolds due to their intrinsic osteoconductivity and bioactivity. These ceramics closely resemble the mineral phase of bone and can stimulate osteoblastic differentiation and new bone formation [1,9,25]. AM techniques such as binder jetting, robocasting, and stereolithography have been adapted to fabricate calcium phosphate scaffolds with interconnected porosity and tailored mechanical properties. Although ceramics offer excellent bioactivity, their brittleness limits load-bearing applications. Consequently, they are often combined with polymers in composite scaffolds to improve mechanical resilience while retaining osteoconductive features. Biodegradable polymers, including polycaprolactone (PCL), polylactic acid (PLA), polylactic-co-glycolic acid (PLGA), and polyether-ether-ketone (PEEK), are widely used in the fabrication of scaffolds for bone and periodontal regeneration [2,10,20]. These polymers are favourable because they degrade over time, eliminate the need for implant removal, and allow gradual replacement by newly formed bone. Their mechanical properties and degradation rates can be regulated through changes in molecular weight, crystallinity, and composite formulation. Moreover, polymeric scaffolds printed through FDM or DIW enable precise control over macro- and microporosity, which is crucial for vascularisation, nutrient exchange, and cellular migration. Nonetheless, polymer-only scaffolds may lack sufficient stiffness for large defects unless reinforced with ceramics or fibres. Composite biomaterials, combining polymers with ceramics or bioactive particles, exploit synergistic advantages of both categories. PCL/HA, PLA/β-TCP, and PLGA/bioactive glass composites exhibit improved mechanical strength, enhanced osteoconductivity, and increased biological performance compared to single-material constructs [6,16,27]. These composites can be printed with hierarchical architectures that mimic cortical and cancellous bone. Hydrogels constitute the primary material for bioprinting. Gelatin methacrylate (GelMA), alginate, collagen, fibrin, and decellularised extracellular matrix (dECM) hydrogels provide a supportive microenvironment for cell encapsulation, proliferation, and differentiation [11,21]. Their shear-thinning behaviour and crosslinking properties make them suitable for extrusion- and light-based bioprinting. Hydrogels can encapsulate mesenchymal stem cells, endothelial cells, growth factors such as BMP-2 or VEGF, and microparticles for controlled release, enabling the fabrication of biologically active constructs for periodontal ligament regeneration, dental pulp reconstruction, and soft-tissue engineering [12,14,22]. Despite their excellent biocompatibility, hydrogels generally possess low mechanical strength and require reinforcement through composite strategies or incorporation into stiffer frameworks.

Clinical Applications of Additive Manufacturing

Additive manufacturing has found extensive clinical applications in dental and maxillofacial surgery, ranging from surgical planning to personalised reconstruction and regenerative interventions. Surgical guides produced via SLA or DLP play a critical role in enhancing the accuracy of implant placement, osteotomies, and orthognathic procedures [4,18,28]. By transferring digital treatment plans into precise intraoperative tools, these guides reduce surgical time, minimise complications, and improve outcomes. In implantology, guided surgery improves the accuracy of implant angulation and depth, resulting in better prosthetic outcomes and reduced risk of nerve injury. Anatomical models generated through 3D printing also facilitate preoperative planning by providing tangible replicas of patient-specific anatomy. These models aid surgeons in visualising

complex fractures, tumours, or deformities and allow rehearsal of procedures before entering the operating room. Patient-specific implants (PSIs) represent one of the most significant contributions of additive manufacturing to reconstructive maxillofacial surgery. Titanium PSIs have been successfully used for orbital floor reconstruction, mandibular defects, zygomatic augmentation, and cranial reconstruction [5,7]. By matching the defect precisely, PSIs offer superior aesthetic and functional outcomes compared to prefabricated implants. For oncologic resections and trauma cases involving extensive bone loss, PSIs can be integrated with vascularised bone grafts, enabling rigid fixation, improved load distribution, and long-term stability. Composite reconstructions combining fibula free flaps with printed titanium cutting guides and plates have shown outstanding results in restoring mandibular continuity and occlusion [15,19]. In alveolar ridge augmentation and dental implant rehabilitation, 3D-printed ceramic or polymeric scaffolds have been investigated as alternatives to autografts. Their controlled porosity supports bone regeneration and promotes vascular infiltration. Clinical studies have reported successful outcomes with printed β-TCP or HA scaffolds used for sinus lifts, ridge augmentation, and peri-implant defect regeneration [9,20,25]. Resorbable scaffolds eliminate the need for a second surgery, reducing patient morbidity. Recent advances in bioprinting have expanded applications toward soft tissue and periodontal regeneration. Studies have demonstrated that bioprinted constructs containing PDL fibroblasts and stem cells can support the formation of ligament-like collagen fibres oriented anatomically around tooth-root analogues [11,13]. In pulp regeneration, bioprinted cell-laden hydrogels containing endothelial and dental pulp stem cells have facilitated vascularised tissue formation in root canal environments [12,26]. Although these applications remain experimental, they illustrate the potential of bioprinting to regenerate complex dental structures with functional integration. Additionally, 3D printing has facilitated custom fabrication of maxillofacial prosthetics, such as auricular or nasal prostheses, offering improved aesthetics and shorter production times compared to manual techniques [29].

Biological Performance of 3D-Printed Constructs

The biological success of 3D-printed constructs depends on their ability to support cellular viability, differentiation, vascularisation, and integration with host tissues. Porosity and microarchitecture play key roles in tissue regeneration. Interconnected pores larger than 300 μm allow vascular ingrowth, while microporosity enhances protein adsorption and osteoblast adhesion [6,23]. Ceramics such as HA and β-TCP have demonstrated excellent osteoconductive properties, stimulating bone formation through ionic dissolution products that promote osteoblastic differentiation [9,25]. Polymer–ceramic composites also exhibit favourable biological responses, particularly when surface-modified or coated with bioactive molecules. Growth factors such as BMP-2 incorporated into printed scaffolds through microspheres or surface adsorption significantly enhance osteogenesis but require controlled release to avoid adverse effects [14,16]. Vascularisation remains a key challenge in large constructs. Strategies such as co-printing endothelial cells, incorporating angiogenic factors such as VEGF, and designing vascular channels within scaffolds have demonstrated improved blood vessel formation in preclinical studies [12,22,27]. Immune response is another critical factor. While titanium is generally well tolerated, polymers may elicit mild inflammatory reactions depending on degradation rate and by-products. Hydrogels exhibit minimal immunogenicity but degrade quickly in vivo.

Translational Challenges and Regulatory Considerations

Despite substantial progress in additive manufacturing for dental and maxillofacial surgery, several translational challenges must be addressed to enable routine clinical implementation. One major limitation concerns standardisation. The heterogeneity of biomaterials, printing techniques, and post-processing protocols makes comparison across studies difficult, and complicates regulatory evaluation [6,9]. Bioinks, polymeric scaffolds, and composite materials exhibit varying degradation kinetics, mechanical properties, and biological responses, which may affect reproducibility and clinical outcomes. Sterilisation is another critical issue, particularly for in-hospital or point-of-care printed constructs. While metallic implants tolerate conventional sterilisation methods such as autoclaving or gamma irradiation, polymers and cell-laden hydrogels often require low-temperature or chemical sterilisation, which may compromise mechanical or biological properties [4,15]. Furthermore, bioinks containing cells or growth factors pose challenges regarding handling, shelf-life, and aseptic processing, necessitating strict GMP-compliant workflows [11,22]. Vascularisation and integration remain key biological hurdles. Constructs designed for large-volume defects often fail to support adequate perfusion, limiting cell survival and bone regeneration. Current strategies, such as prevascularisation, incorporation of endothelial cells, angiogenic factor release, and sacrificial channels, have shown promise in preclinical models but remain largely experimental [12,21,27]. Immune response and

inflammation represent additional concerns. While most 3D-printed materials are biocompatible, degradation by-products of polymers, unreacted monomers, or crosslinking agents may provoke local inflammation or systemic reactions [6,9]. Long-term outcomes data are limited; most clinical reports consist of small case series or short-term follow-up, making it difficult to predict durability, functional stability, and potential late complications [0,15,6]. Regulatory frameworks for 3D-printed implants vary internationally. In Europe, the Medical Device Regulation (MDR) governs device approval, whereas in the United States, the FDA evaluates both device and bioprinted constructs on a case-by-case basis [14,16]. Point-of-care or in-hospital printing introduces additional complexity, as the process itself may require validation and certification separate from the final product. Economic considerations also affect adoption. High costs of printing equipment, consumables, sterilisation, and validation processes limit widespread clinical use, particularly in smaller institutions or low-resource settings [15,21].

Future Directions

The future of additive manufacturing in dental and maxillofacial surgery is likely to be shaped by several converging trends. First, standardisation of printing protocols, sterilisation procedures, and validation methods will enable reproducible outcomes and facilitate regulatory approval [6,9,16]. Second, hybrid scaffolds combining metals, ceramics, polymers, and biologically active components—including cells and growth factors—promise to achieve optimal mechanical, anatomical, and biological integration. Such hybrid designs could allow immediate load-bearing while simultaneously supporting cellular ingrowth and angiogenesis [6,12,27]. Third, intensive clinical studies, including prospective, randomised, and multi-centre trials with long-term follow-up, are required to establish safety, efficacy, and durability of printed constructs [0,15,6]. Fourth, improvements in bioinks that enhance osteogenesis and angiogenesis, possibly integrating gene therapy, exosomes, or controlled release of signalling molecules, will expand the clinical applicability of bioprinted constructs [11,12,22]. Fifth, in-clinic printing workflows, supported by AI-assisted design, real-time quality control, and standardised protocols, could enable customised implants, scaffolds, and surgical guides to be produced efficiently at the point of care [14,19]. Finally, integration of 4D printing—where printed constructs change shape or properties over time in response to biological stimuli—may provide dynamic, adaptive scaffolds for regenerating complex craniofacial structures [27,30].

Conclusions

Additive manufacturing, encompassing 3D printing and bioprinting, represents a transformative technology in dental and maxillofacial surgery. Patient-specific implants, resorbable scaffolds, surgical guides, and bioprinted tissue constructs offer the potential to enhance precision, reduce operative time, minimise donor-site morbidity, and enable the regeneration of complex tissues. Metals, ceramics, polymers, composites, and hydrogels each contribute unique mechanical and biological advantages, and their combination allows the design of constructs optimised for osteoconductivity, vascularisation, and mechanical strength. Despite remarkable progress from 2017 to 2025, challenges remain, including vascularisation, immune response, degradation kinetics, regulatory frameworks, and long-term clinical validation. Future research should focus on standardisation, hybrid scaffolds, angiogenic and osteogenic bioinks, in-clinic manufacturing, and robust clinical trials. With continued interdisciplinary innovation, additive manufacturing is poised to redefine the landscape of dental and maxillofacial reconstruction, bridging the gap between personalised medicine, tissue engineering, and clinical practice.

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