DOI: 10.7860/JCDR/2026/84875.22980

Review Article

Dentistry Section

Recent Advances in Dental Bone Grafts: A Narrative Review

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ABSTRACT

Regenerative therapy is considered an essential treatment option in dentistry and maxillofacial surgery for the management of defects caused by degenerative diseases, trauma, congenital abnormalities, and inflammatory conditions. Restoration of hard-tissue architecture requires predictable grafting techniques, as loss of alveolar bone compromises structural integrity and function. Bone graft materials exhibit varying degrees of osteogenic, osteoinductive, and osteoconductive potential and are categorised as autografts, allografts, xenografts, alloplasts, and emerging phytogenic substitutes. Due to their inherent cellular vitality, autografts continue to be regarded as the gold standard, despite limitations related to availability and donor-site morbidity. However, synthetic alternatives such as Hydroxyapatite (HA), β-Tricalcium Phosphate (β-TCP), calcium phosphate cements, and bioactive glasses offer advantages including biocompatibility, structural stability, and a reduced risk of disease transmission. Advances in material science have enhanced regenerative outcomes through the development of growth factor-enriched scaffolds, composite grafts, and nanostructured ceramics. Emerging technologies-including Three-Dimensional (3D)-printed customised scaffolds, controlled-release systems, and stem cell integration-enable precise defect reconstruction with improved biological performance. The present review aimed to analyse the characteristics, clinical applications, and potential future directions of bone grafting materials in dental and craniofacial regeneration.

Keywords: Biomaterials, Bone regeneration, Xenografts, 3D printed Scaffolds

INTRODUCTION

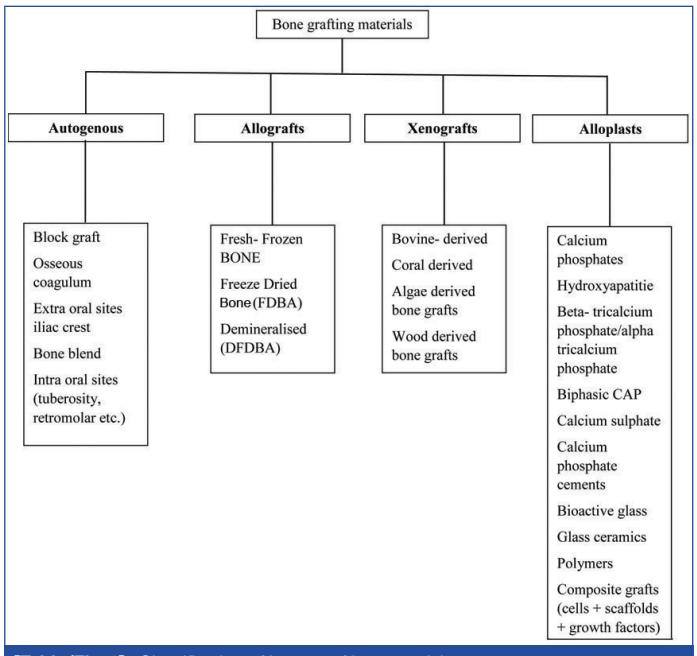
In orthopaedic and maxillofacial surgery, bone defects and fractures resulting from trauma, degenerative diseases, congenital abnormalities, or tumour resections present significant clinical challenges. Although natural bone has a remarkable capacity to heal minor defects, large or critical-sized defects frequently require bone grafts or implants to restore structural integrity and function [1]. Among the conditions leading to substantial maxillofacial bone defects, periodontitis represents a common example in which chronic inflammation results in progressive alveolar bone loss, underscoring the need for advanced regenerative strategies within orthopaedic and maxillofacial disciplines.

Periodontitis is a chronic, multifactorial inflammatory disease affecting the supporting structures of the teeth and is characterised by progressive attachment loss and alveolar bone destruction, ultimately leading to periodontal pocket formation or gingival recession [2]. Initially, inflammation begins in the gingival tissues and subsequently spreads to deeper structures, including the alveolar bone, resulting in the loss of connective tissue and supporting bone around affected teeth [3]. The primary goal of periodontal therapy is the restoration of the lost periodontium, which comprises the periodontal ligament, cementum, and alveolar bone. One of the most effective approaches to achieve such regeneration is the use of bone graft materials, including autografts, allografts, xenografts, and alloplastic materials [Table/Fig-1] [4,5].

The present narrative review highlights recent advances in dental bone graft materials, outlining their properties, clinical applications, and emerging innovations to support evidence-based decision-making and improved regenerative outcomes.

Historical Evolution of Bone Grafting Materials

Over the past six decades, bone graft materials have evolved substantially, progressing from simple autologous bone shavings to advanced bioengineered and 3D-printed constructs. Each successive generation of graft materials has contributed to enhanced bone healing, improved predictability, and greater clinical reliability [6-14]. Continuous advancements in biomaterials have culminated in the development of Nanocrystalline HA (nHAp)-Polycaprolactone (PCL) 3D-printed implants, which demonstrate strong potential as safe and effective alternatives to traditional bone grafts [Table/Fig-2] [6-14].



[Table/Fig-1]: Classification of bone grafting materials.

Autografts

Autogenous bone grafting involves the transplantation of bone harvested from the same individual, most commonly from the mandibular symphysis or ramus. The technique used for bone harvesting significantly influences cell viability and graft integration. Autografts containing viable osteoprogenitor cells and osteocytes

S. No.	Author	Year of development	Type of bone graft developed	Contribution	Reference
1.	Nabers CL and O'Leary TJ	1965	Autograft (cortical bone shavings)	Reestablished autogenous grafting in combination with bone shavings from osteoplasty/ostectomy sites.	[6]
2.	Meffert RM et al.,	1985	Hydroxyapatite (HA) alloplast	Demonstrated HA improves probing depth and attachment levels.	[7]
3.	Yukna RA	1994	Coralline calcium carbonate xenograft	Confirmed coral-derived graft as an osteoconductive material for periodontal defects.	[8]
4.	Spector M	1994	Anorganic bovine bone (early forms)	Demonstrated predictable osseous regeneration with processed bovine mineral.	[9]
5.	Richardson CR et al.,	1999	Bio-Oss (bovine xenograft)	Introduced extremely purified anorganic bovine bone widely established in regenerative therapy.	[10]
6.	Pietrzak WS and Ronk R	2000	Calcium sulfate	Established calcium sulfate as an effective bone replacement material.	[11]
7.	Inchingolo F et al.,	2021-2023	Composite grafts (growth-factor enriched)	Demonstrated that combination of integrating osteogenic cells+synthetic scaffolds benefits.	[12]
8.	Ma YF and Yan XZ,	2023	Limitations of GTR membranes and need for advanced graft-membrane systems	Introduced concepts for upcoming generation biomaterial integration.	[13]
9.	Başöz D et al.,	2024-2025	3D printed nHAp PCL implants	In rabbits with large femoral segmental defects, 3D-printed nHAp-PCL implants showed bone healing, callus formation, and biomechanical strength comparable to autografts within 6 weeks. These findings suggest that such implants may serve as a viable alternative to autografts for long-bone defect repair.	[14]

[Table/Fig-2]: Historical timeline of bone grafts [6-14].

are considered ideal; however, mechanical harvesting methods and delays between harvesting and implantation may adversely affect outcomes. These grafts release key growth factors, including Bone Morphogenetic Proteins (BMPs), Platelet-Derived Growth Factor (PDGF), Transforming Growth Factor-β (TGF-β), and Vascular Endothelial Growth Factor (VEGF), and play a role in regulating bone remodelling via the RANKL/OPG pathway. As the gold standard in bone regeneration, autografts are known to enhance healing and stability, particularly in advanced clinical cases.

Autogenous bone grafts may be obtained in block or particulate forms. Particulate grafts are more commonly used due to their reduced donor-site morbidity, ease of handling, and more predictable clinical outcomes. They are often combined with Deproteinised Bovine Bone Mineral (DBBM; Bio-Oss®, Geistlich) to improve regenerative capacity and provide additional structural support [1,5]. Several types of autografts are utilised in bone regeneration therapy, each possessing distinct biological and clinical characteristics [Table/Fig-3] [15-18].

Type of autografts	Clinical significance	Advantages/disadvantages/ indications
Osseous Coagulum [15]	Robinson introduced the technique in 1969. Mixture of bone dust and blood. Produced by collecting intraoral bone with round burs and mixing with blood	Advantages: Small particle size increases surface area and enhances osteogenesis. Disadvantages: Limited quantity availability; technique-sensitive. Indications: Used for various periodontal osseous defects
Bone Blend [16]	Bone is procured from the donor site, ground using a sterilised pestle and capsule into a pliable consistency, and packed into the defect.	Advantages: Good adaptability to defect morphology; autogenous with high biologic potential. Disadvantages: Requires donor site bone harvesting. Indications: Useful for various periodontal regenerative procedures.
Bone Swaging [17]	Movement of neighbouring edentulous bone to a deficient area without cutting its base.	Advantages: Preserves bone vitality due to intact vascularity; avoids separate graft harvesting. Disadvantages: Technique-sensitive; Indications: Ridge augmentation
Autogenous Bone Grafts sources [18]	Intraoral sources: maxillary tuberosity, edentulous ridges, healing bone wounds, extraction sockets, mental and retromolar regions. Extraoral sources: iliac cancellous bone and marrow	Advantages: Gold standard, highest osteogenic, osteoinductive, and osteoconductive potential; predictable regeneration. Disadvantages: Donor site morbidity; limited intraoral quantity. Indications: Sinus lift, ridge augmentation, furcation defects, Periodontal regeneration

[Table/Fig-3]: Classification and clinical applications of autogenous bone graft techniques [15-18].

Allografts

Allografts are human-derived bone graft materials commonly used in reconstructive and periodontal procedures. They are available in fresh, frozen, Freeze-Dried Bone Allograft (FDBA), and Decalcified Freeze-Dried Bone Allograft (DFDBA) forms [19]. FDBA reduces donor-site morbidity and offers several advantages over autografts. In addition, it provides an abundant supply of graft material with a long shelf life when stored under optimal conditions. Allografts also help to prevent complications frequently associated with autografts, such as graft resorption and defect recurrence [20].

Experimental and histological analyses indicate that DFDBA exhibits higher osteogenic potential than autogenous bone, osseous coagulum, or FDBA. Consequently, both FDBA and DFDBA remain effective and safe graft materials for clinical bone regeneration [21]. DFDBA has been widely used over the years, and key findings from earlier and recent literature are summarised in [Table/Fig-4] [22-24].

Author and year	Aim of the study	Key findings on DFDBA	Clinical outcome
Jaiswal Y et al., 2017 [22]	To assess the effectiveness of DFDBA in regenerating bone in small osseous defects during minor oral surgery.	DFDBA showed strong osteoinductive potential due to exposure of BMPs and growth factors after demineralisation.	Significantly higher bone density was observed in defects treated with DFDBA.
Gothi R et al., 2015 [23]	To compare Freeze-Dried Bone Allograft (FDBA) and DFDBA in treating intrabony defects.	DFDBA provided both an osteoconductive scaffold and osteoinductive factors.	Both groups showed significant improvement in probing depth, Relative Attachment Level (RAL), and radiographic defect fill at 6 months.
Kumar S et al., 2022 [24]	To clinically and radiographically compare Biphasic Calcium Phosphate (BCP) and DFDBA in periodontal regeneration.	DFDBA demonstrated superior periodontal regeneration compared with BCP.	Both groups showed good healing and no adverse reactions. DFDBA resulted in greater pocket-depth reduction and better radiographic outcomes, including improved defect fill and bone growth.

[Table/Fig-4]: Summary of key clinical studies on DFDBA [22-24].

Xenografts

Xenografts are animal-derived bone replacement materials. Bovine-derived xenografts are widely used in regenerative dental procedures owing to their osteoconductive properties and volumetric stability. However, their long-term biological behaviour and integration remain subjects of ongoing debate. Current evidence suggests that bovine-

derived xenografts, particularly Bio-Oss®, are associated with favourable long-term outcomes in bone regenerative procedures, demonstrating satisfactory graft integration and high implant survival rates [25].

Abushama AA et al., concluded that synthetic allografts such as PerioGlas® and xenografts such as Bio-Oss® offer comparable benefits and are equally reliable and effective as Guided Bone Regeneration (GBR) biomaterials [26]. Lee DW et al., conducted a long-term comparative study in beagle dogs to evaluate the osteogenic potential of two collagenated xenogenic bone grafts, OCS-B Collagen® and Bio-Oss® Collagen. Their findings demonstrated similar osseointegration and osteogenic potential for both materials, indicating comparable clinical outcomes in terms of implant stability and bone regeneration [27]. Collectively, these studies suggest that autologous, synthetic, and xenogenic bone graft materials exhibit similar potential for promoting bone regeneration and dental implant success.

Phytogenic Materials

Phytogenic materials are plant-based bone substitutes used in bone regeneration and dental applications. Gusuibu is a plant-derived dried rhizome obtained from *Drynaria fortunei*, a traditional Chinese medicinal plant used for the treatment of bone fractures and osteoarthritis. It exhibits osteoinductive properties, enhances alkaline phosphatase activity, and promotes bone calcification and remodelling. When combined with a collagen carrier, Gusuibu significantly increases new bone formation compared with Gusuibu alone or absorbable collagen sponge. It is also known to accelerate bone remodelling following orthodontic tooth movement by regulating osteoblast and osteoclast activity [28].

A rabbit calvarial defect model was used to compare the bone-forming potential of Gusuibu extract combined with collagen against autogenous bone grafts, collagen alone, and empty controls. After 14 days, histological evaluation of 150 serial sections revealed that Gusuibu-collagen grafts produced significantly greater new bone formation-24% more than autogenous bone and 90% more than collagen alone-whereas empty defects showed no bone formation. These findings suggest that Gusuibu combined with collagen significantly enhances early bone regeneration and may serve as an effective bone graft material [29].

Coral-based bone substitutes are composed primarily of calcium carbonate derived from natural coral sources. Their biocompatibility, osteoconductivity, and porous architecture make them attractive materials for bone regeneration. However, conventional coral grafts exhibit mismatched degradation rates relative to host bone and lack intrinsic osteoinductivity. To address these limitations, recent studies have introduced strontium and magnesium-doped Coral HA (CHA) variants. These modified materials demonstrated markedly improved biological performance, with enhanced surface area, pore volume, and nanorod morphology supporting increased human Bone Marrow-Derived Mesenchymal Stem Cell (hBMSC) proliferation and osteogenic differentiation. In particular, strontium-doped CHA exhibited optimal ion release, slower degradation, and superior in vivo bone regeneration compared with unmodified coral and Bio-Oss®. These advancements overcome the brittleness and resorption limitations of earlier coral-based materials, making them promising candidates for alveolar reconstruction, sinus augmentation, and periodontal defect repair [30].

AlgiPore™ is a marine algae-derived HA that has been used clinically since 1988. It demonstrates good resorbability, a large protein adhesion surface area, and low immunogenicity, and it serves as an effective carrier for mesenchymal stem cells and growth factors. AlgiPore™ exhibits excellent biocompatibility, biodegradability, and bone-bonding capacity and is often combined with β-TCP to reduce resorption time while maintaining graft volume during healing. A longitudinal study reported a 95% implant survival rate in sinus grafts using AlgiPore™ [31].

Algipore®, a HA derived from seaweed, is a highly biocompatible and osteoconductive bone substitute with predictable and gradual resorption. Long-term clinical data confirm high implant survival rates and stable bone outcomes. Evidence from 43 studies published between 1988 and 2024 demonstrates its reliable performance in periodontal regeneration, sinus floor elevation, and ridge preservation procedures, supporting its role as a promising alternative or adjunct to traditional autografts in bone regeneration therapies [32].

Silk, derived from the silkworm *Bombyx mori*, is primarily composed of fibroin and sericin. Silk Fibroin (SF) is a highly biocompatible and biodegradable biomaterial that can be fabricated into a variety of scaffold forms-including sponges, fibres, films, and hydrogels-once sericin is removed through the degumming process. Clinical studies have demonstrated that, six months following mandibular third molar extraction, silk membranes can support substantial new bone formation of approximately 4 mm. Owing to their high tensile strength and in vivo osteogenic potential, SF membranes have been successfully used after tooth extractions, cyst or tumour enucleation, and in cases of insufficient alveolar bone for implant placement [33].

Wood can be converted into biocompatible scaffolds that closely resemble the trabecular architecture of cancellous bone through processes such as delignification and biomorphic mineral transformation [34]. These grafts demonstrate favourable cell adhesion, tunable porosity, and promising osteoconductive properties, making them potential candidates for bone regeneration. However, limitations related to mechanical strength, standardisation, and the lack of long-term clinical evidence remain significant challenges, restricting their application primarily to preclinical and experimental settings [35].

Alloplasts

Alloplasts are synthetic, inorganic, and biocompatible bone substitutes designed to promote bone healing. Most synthetic grafts function primarily as biological fillers, providing limited true bone regeneration and minimal connective tissue formation. Alloplasts are classified based on their bioabsorbability.

Bioabsorbable synthetic materials include ceramics, β-TCP, HA, calcium sulfate, calcium carbonate, demineralised dentin matrix, bioactive glasses, porous titanium granules, and composite grafts [7].

A recent systematic review and network meta-analysis of 74 randomised controlled trials evaluated the effectiveness of alloplastic materials, used alone or in combination with biologics, for the treatment of periodontal intrabony defects. The analysis revealed that defect depth and wall morphology influenced outcomes at six months but had minimal impact at 12 months. Biphasic Calcium Phosphate (BCP), nanohydroxyapatite (nHA), and bioglass demonstrated the greatest improvements in clinical attachment level gain, probing depth reduction, and radiographic bone fill. Notably, the combination of nHA and Platelet-Rich Fibrin (PRF) outperformed open flap debridement alone [36].

3D Printing Technology and Nanomaterials

As the global population continues to age, chronic degenerative bone diseases such as osteoporosis and osteoarthritis are becoming increasingly prevalent, thereby raising the incidence of bone defects. Limitations associated with graft material availability and incomplete regeneration restrict the effectiveness of conventional treatment approaches, highlighting the need for more advanced therapeutic strategies.

Bone Tissue Engineering (BTE) has emerged as a promising solution, enabling the development of bioactive, porous scaffolds

that enhance angiogenesis, cell adhesion, proliferation, and overall tissue regeneration while providing adequate mechanical support. Due to its precision in controlling complex geometries and internal pore architecture, 3D printing has become one of the most widely used techniques for fabricating BTE scaffolds [37].

The 3D printed scaffolds facilitate bone repair through three principal mechanisms:

- Delivery of exogenous stem cells to enhance osteogenesis;
- Incorporation or activation of bioactive signalling molecules that stimulate endogenous cell proliferation and differentiation; and
- Controlled release of therapeutic agents to modulate the local healing environment.

Scaffold design significantly influences biological outcomes, with interconnected porosity, optimal pore size, and adequate mechanical strength being critical determinants of success. Common bone scaffold materials include calcium phosphate-based ceramics, metals, polymers, and composite formulations, each offering distinct advantages for mechanical stability and biological integration [38].

Three-dimensional printing in dentistry has advanced rapidly due to improvements in digital design, biomaterial development, and reduced production costs. This technology now enables the fabrication of precise, patient-specific structures for periodontal regeneration, orthodontics, maxillofacial surgery, and tissue-engineered scaffolds. Although advances in biomaterials and computer-aided design workflows have improved accuracy and biological performance, further clinical trials and optimisation remain necessary [39].

Recent research from the University of Waterloo highlights this progress, demonstrating a 3D-printable biopolymer nanocomposite that mimics natural bone and exhibits high mechanical strength, excellent biocompatibility, and enhanced cell proliferation. This material offers a customisable alternative to metal implants or donor grafts and is currently undergoing further evaluation, with potential implications for future regenerative therapies [40].

CONCLUSION(S)

Advancements in material science-particularly nanotechnology, bioactive ceramics, composite grafts, and growth factor-enriched scaffolds-have significantly improved the predictability and efficacy of regenerative outcomes. Furthermore, the integration of stem cells, controlled-release systems, and 3D printing technologies represents a major step toward personalised and biologically responsive grafting solutions. Despite these substantial advances, no single graft material currently fulfils all ideal biological and mechanical requirements, underscoring the need for continued research focused on improving clinical predictability, mechanical performance, biodegradation profiles, and biocompatibility. A comprehensive understanding of graft material properties and clinical indications enables clinicians to tailor treatment strategies to individual defect characteristics, ultimately leading to more reliable and durable regenerative outcomes.

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PLAGIARISM CHECKING METHODS: [Jain H et al.]
- Plagiarism X-checker: Oct 18, 2025
- Manual Googling: Jan 03, 2026
- iThenticate Software: Jan 06, 2026 (1%)

ETYMOLOGY: Author Origin

EMENDATIONS: 6

AUTHOR DECLARATION:
- Financial or Other Competing Interests: None
- Was informed consent obtained from the subjects involved in the study? NA
- For any images presented appropriate consent has been obtained from the subjects. NA

Date of Submission: **Oct 13, 2025**
Date of Peer Review: **Nov 03, 2025**
Date of Acceptance: **Jan 08, 2026**
Date of Publishing: **Apr 01, 2026**