Journal of Chemical Health Risks
www.jchr.org
JCHR (2025) 15(5), 2677-2683 | ISSN:2251-6727

Development of PMMA Monolith Impregnation with Hydroxyapatite Nanoparticles for Bone Regeneration

Mehtab Singh Sidhu[1], Dhanraj Ganapathy[2*], Chitra S [3]

[1] Post Graduate ,Department of Prosthodontics ,Saveetha Dental College and Hospitals, Saveetha Institute of Medical and Technical Science, Saveetha University ,Chennai 77,Tamil Nadu, India

[2] Professor, Department of Prosthodontics ,Saveetha dental college and hospital, Saveetha Institute of Medical and Technical Science, Saveetha University.

Chennai 77,Tamil Nadu, India, [3] Assistant Professor ,Department of Biomaterials, Saveetha dental college and hospital

Saveetha Institute of Medical and Technical Science, Saveetha University., Chennai 77,Tamil Nadu,India

*Corresponding Author- Dhanraj Ganapathy

(Received: 25 August 2025 Revised: 27 September 2025 Accepted: 14 October 2025)

KEYWORDS

PMMA (polymethylmethacrylate), Hard tissue regeneration, Hydroxyapatite (Hap), Phase separation

ABSTRACT:
Introduction: Bone regeneration in maxillofacial and orthopedic applications often requires biomaterials that mimic the structural and functional properties of natural bone. Polymethyl methacrylate (PMMA) is widely used in dentistry and orthopedics due to its biocompatibility and mechanical stability, while hydroxyapatite (HAp) offers excellent osteoconductive properties. However, HAp alone is brittle, limiting its use as a scaffold material. Incorporating HAp nanoparticles into a PMMA monolith may overcome these limitations and provide an effective scaffold for hard tissue regeneration.

Objectives: The study aimed to develop and characterize hydroxyapatite-infused PMMA monoliths and evaluate their morphology, elemental composition, and mechanical properties to determine their potential for bone regeneration applications..

Methods: PMMA (Mw 15,000) was dissolved in an ethanol–water mixture and combined with hydroxyapatite solution prepared via precipitation. The mixture was subjected to phase separation and freeze-drying to form monoliths. Morphological features were analyzed using field emission scanning electron microscopy (FE-SEM), elemental composition was confirmed by energy dispersive spectroscopy (EDS) and elemental mapping, and compressive strength was measured using a universal testing machine following ASTM standards.

Results: FE-SEM analysis revealed highly porous structures with visible impregnation of hydroxyapatite particles within the PMMA matrix. EDS confirmed the presence of calcium and phosphorus, validating the successful infusion of HAp. Elemental mapping further demonstrated the distribution of these bioactive elements. Mechanical testing showed that the PMMA–HAp monoliths exhibited compressive strength up to 3 kN, indicating adequate stability for biomedical applications.

Conclusion: Hydroxyapatite-infused PMMA monoliths demonstrated favorable porosity, bioactive elemental composition, and sufficient compressive strength. These findings suggest that the fabricated composite scaffolds overcome the brittleness of HAp while retaining osteoconductive potential, making them a promising candidate for hard tissue regeneration in dental and orthopedic applications..

1. Introduction

Clinical dentistry frequently uses a variety of polymers for a broad range of purposes [1]. PMMA, an odourless acrylic acid polymer, was one such polymer that Redtenbacher initially reported in 1843 [2]. However, over several decades, PMMA was developed gradually for use in biomedicine. The paragraph that follows provides a brief synopsis of PMMA's history as a material. Harder PMMA was first made commercially available as sheets in 1931 [3]. Otto Rohm, who claimed credit for their early 20th-century research, produced industrial PMMA in 1936 [4]. PMMA was first made available as a powder in 1937 for use in the creation of denture bases [5]. Neurosurgeons began using PMMA extensively around 1945 for cranioplasties [6]. Cold-cured PMMA, which cures at room temperature, was made commercially available that same year [7]. PMMA took over as the most used material for denture manufacture in 1946 [5]. PMMA was first used by orthopaedic surgeons in the year 1950s to cement prosthetic femurs [6]. Dental experts greatly boosted their usage of PMMA for removable dentures, provisional crowns, and maxillofacial prosthesis between the years 1950s and the 1960s [8]. PMMA materials are now being improved in terms of their mechanical and physical qualities through constant research and advancements [9]. PMMA comes in a powder-liquid combination that is commonly available. The powder is composed of transparent PMMA polymer, with the addition of pigments and acrylic or nylon synthetic fibers to modify its physical characteristics and replicate oral tissues (such as gums and mucosa). Methyl methacrylate, a monomer, some inhibitors, and cross-linking agents make up the liquid component [10]. Polymeric acrylic materials find extensive utilization across various industries such as engineering, healthcare, and dentistry. Within the realm of oral healthcare, PMMA plays a crucial role beyond just denture bases. It is employed in the production of prosthetic teeth, impression trays, provisional crowns, obturators (used in cleft palate patients), occlusal splints, as well as printed or milled casts. Furthermore, PMMA is utilized for denture relining and repair purposes. Various forms of PMMA are available like heat cure PMMA, microwave cured PMMA, cold cure PMMA and light cured PMMA [11,12].

The innate capacity of bone to repair itself occurs during the healing process following injury, during skeletal system development, and remodelling during adulthood [13]. Osteo-induction and osteo-conduction are two well-coordinated biological processes that contribute to the regeneration of hard tissue, particularly bone. Numerous cell types and chemical signalling pathways both inside and outside of the cells are necessary for this complex process. With the goal of maximizing skeletal repair and restoring skeletal function, it adheres to a predetermined chronological sequence [14]. Under some circumstances, a significant amount of bone regeneration is needed during oral and maxillofacial and orthopaedic procedures, surpassing the body's natural healing capabilities. These conditions include the repair of major bone defects caused by infection, trauma, tumor removal, and skeletal deformities. Additionally, conditions where the process of regeneration is impaired, such as avascular necrosis and osteoporosis, also require bone regeneration [15]. In order to speed up the healing process, bone grafting can be done. It is a surgical operation that involves implanting new bone in the spaces left by broken or deformed bones as well as in bone deformities. Depending on their origin, bone grafts can be classified as autografts, allografts, or xenografts [16]. Several biomaterials made of both organic and inorganic content have been created as substitutes for autogenous bone transplants to replace natural bone. Biomaterials, like glasses, polymers and ceramics, have demonstrated efficacy in the regeneration of maxillofacial bones in clinical settings [17]. Distraction osteogenesis is a surgical technique used to extend congenitally defective jaws in the maxillofacial region or to restore the vertical dimension of atrophic jaws [18]. When teeth are missing and the alveolar ridge needs to expand vertically with bone before dental implants are placed, this two-stage surgical approach might be used. It can also be applied when traditional orthognathic surgery is impractical and there is an open bite with good occlusion in the molar region [19]. In the maxillofacial region, guided bone regeneration (GBR) has been used for minor augmentation surgeries as well as before dental implant insertion [20,21,22].

Biomaterials can successfully replace the function of natural bone tissue when it comes to the regeneration of bones in the maxillofacial area. This can be accomplished by making sure that the biomaterial's mechanical characteristics closely resemble those of natural bone. The biomaterial should also be able to convey mechanical signals, since these signals are essential for controlling matrix and cell biology as well as for promoting remodelling and regeneration. Because of their inherent osteo-conductivity, these biomaterials should also be porous, permeable, and diffusible. Moreover, they need to facilitate the fusion of bioactive materials and cells [23]. Many techniques have been created in the creation of biomaterials to successfully accomplish maxillofacial bone repair, reconstruction, and regeneration. These approaches concentrate on the biomaterials' chemical makeup (bioinorganics) as well as their structural architecture. Through the consideration of these characteristics, scientists hope to address problems related to the development of bone both in vitro (lab) and in vivo (live creature) settings [24][25]. Due to its exceptional biocompatibility qualities, nano hydroxyapatite (nHA) is a material for multiple biomedical industries, including bone regeneration and dentistry applications [26]. A novel method in engineering biomaterial structures involves the creation of nanoscale characteristics within a design that specifically caters to macroscopic defects. Nanomaterials and nanocomposites hold great potential as platforms to mimic the structure of the natural extracellular matrix. This is particularly valuable in the creation of functional bone tissues, as the nanostructure closely resembles the architecture found in native bone. Nanostructured scaffolds play a crucial role by providing structural support to cells. Consequently, these scaffolds facilitate the development of functional tissues. One of the key advantages of nanomaterials are their unique properties, such as enhanced wettability and greater surface area.[23] Additionally, computer-assisted design and manufacturing techniques can be employed to produce custom-made scaffolds that match the anatomical requirements [27]. Since hydroxyapatite is porous and PMMA monolith promotes bone regeneration, infusion of hydroxyapatite with PMMA monolith renders it a special material for hard tissue regeneration. This also allows the bone cells to attach themselves to the scaffold's walls.

2. Objectives

The primary objective of this study was to develop a composite scaffold material by incorporating hydroxyapatite (HAp) nanoparticles into a polymethyl methacrylate (PMMA) monolith using a phase separation technique. This approach was undertaken with the intention of combining the favorable characteristics of both materials—namely, the excellent biocompatibility, processability, and mechanical stability of PMMA with the osteoconductive and bioactive properties of hydroxyapatite.

3. Methods

preparation of monoliths

PMMA with a molecular weight of 15,000 was procured from HiMedia, India. It was used without any additional purification. Ethanol(E) and distilled water(W) were used as solvents. Initially, 10% weight PMMA was dissolved in 70 mL of ethanol and 30 mL of water E-W mixture. E-W mixture was taken in the ratio of 70:30 and heated for 3 hours upto 50°C to dissolve the PMMA in these mixtures. Simultaneously, aqueous Hap solution was prepared by precipitation method by mixing equal volumes (25 mL) of 0.1 Mol Calcium and 0.6 Mol Phosphorus. The pH of the solution was maintained at 10 with addition of Ammonia (NH_4OH). Then 30 mL of Hap solution was added to the PMMA solution kept at 50°C for 24 hours at continuous stirring. 50 mL of this solution was then poured in a beaker and kept at -80°C for 24 hours to form as monoliths.[28]

Material Characterization

Morphology and elemental composition of the obtained scaffolds were investigated using field emission scanning electron microscopy (FE-SEM JEOL JSM IT 800), and energy dispersive spectroscopy (EDS) analyzer (Oxford Instrumentations) respectively. Further, the compression strength was performed as per the ASTM standard D695-91 using Universal compression testing machine(Instron ElectroPuls E3000).

4. Results

FIELD EMISSION SCANNING ELECTRON MICROSCOPY

The high resolution, field emission, scanning electron microscopes (FE-SEM) can produce accurate images of the surfaces of biological specimens and materials which can help to analyse the morphological properties of the material.

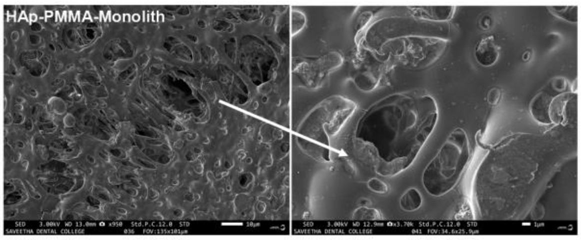

Figure 1 - Morphological analysis of the monolith by FESEM

Porous structures were observed through FE-SEM analysis that indicates the basic morphology of PMMA. Inside the polymeric base hydroxyapatite particulates are impregnation was visible through micro-graphic images. Similar observations were seen in a study by Mahammod et al [29] where the ultrafine grains of hydroxyapatite (HAp) improved the overall mechanical strength by increasing compaction and mainly enhancing the bioactivity. Similar morphology improves the materials ability to bind to the bone, and thus is preferable for dental and medical applications [30].

ENERGY DISPERSIVE SPECTROSCOPY AND MAPPING

Energy dispersive spectroscopy is a tool of analysis used for characterizing samples chemical constituents.

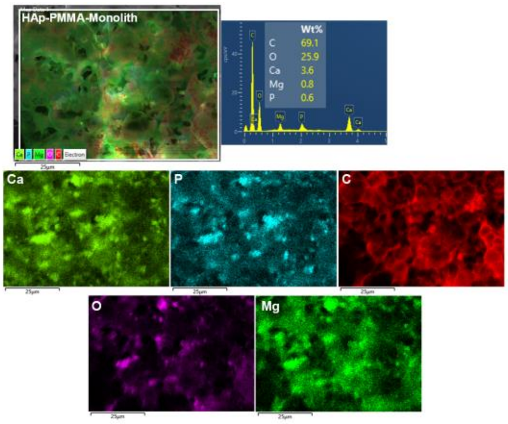

Figure 2 – Elemental analysis of the HAp infused monolith using EDS and mapping

EDS spectra authenticates the elemental composition of prepared materials, in which calcium (Ca) and phosphorus (P) indicates the presents of hydroxyapatite in the polymeric matrix. Similarly, with respect to color relevant elements were observed through the elemental mapping. Similar results were observed in EDS spectra of hydroxyapatite, which revealed the presence of calcium (Ca) and phosphorus (P) along with carbon (C) and oxygen (O) that indicates the HAp in PMMA- monolith [31].

COMPRESSIVE STRENGTH

Compressive strength refers to the ability of a substance or a construction to withstand against forces that tend to decrease its size or break the substance. It is the resistance exhibited by a material against compressive forces or compression, which aim to contract or permanently damage/distort the substance. The universal testing machine (UTM) is one of the commonly used armamentarium for measuring the compressive strength of a material. In the Universal Testing Machine (UTM), the specimen is positioned on a foundation block and gradually lowered by the central grip to exert a load.

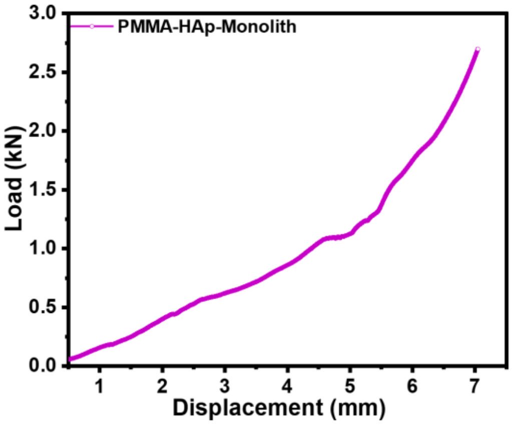

Figure 3 – Compressive strength of the monolith by UTM

Mechanical stability of the materials was analyzed through UTM, here the PMMA-Hap-Monolith explicated the withstanding stability upto 3 kN. The correlation between the compressive strength and the porosity of the scaffold was investigated in a study by Indra et al [32].

Discussion

A vast array of biomaterials, consisting of both organic and inorganic components, has been created with the aim of restoring hard tissue. Biomaterials that have been clinically employed for the purpose of promoting bone regeneration in the craniofacial region include ceramics, glasses, and polymers. Bioceramics like hydroxyapatite (HAp) are frequently utilized as bone graft materials due to their advantageous bioactive characteristics. Since the early 1970s, these bioceramics have been made commercially and have been tested for bone regeneration. They have been effectively used to enlarge the mastoid cavities and the regions of the frontal and ethmoid sinuses [33,34]. Additionally, hydroxyapatite (HAp) has been used to fill in bony defects, preserve the shape of alveolar ridge following tooth extraction, and increase bone volume in conjunction with autogenous bone during treatments like sinus grafting and ridge augmentation [35]. HAp bioceramics' limited solubility and brittleness, however, might prevent them from being used much further in clinical bone regeneration [36]. Tricalcium phosphate (TCP), a biomaterial having plenty of clinical applications, has a different stoichiometric profile but structural similarity to HAp [37]. However the breakdown of tricalcium phosphate does not necessarily lead to the deposition of bone, and its rate of bioresorption is erratic thus limiting its use as a biomaterial for bone regeneration. [38,39]. Bioactive glasses—more precisely, silicophosphate chains—are also used in dentistry as restorative materials, like glass ionomer cement. Over a million patients have had successful use of the original Bioglass 45S5 to treat bone abnormalities [40,41,42]. Due to their favourable physicochemical characteristics and effective use in clinical settings, synthetic biodegradable polymers have drawn particular attention in the vast research on polymeric biomaterials for bone regeneration. Synthetic polyesters that are most frequently utilized in oral and maxillofacial applications include polyglycolic acid (PGA), polylactic acid (PLA) and their combination [43]. Because of its good mechanical qualities and low toxicity, polymethyl methacrylate (PMMA) is being studied to be potentially used as a scaffold material to achieve mechanical stability following implantation over the long term [44]. In order to enhance the mechanical characteristics of bone scaffolds, some research has looked at the creation of PMMA blends for use in biomedical applications [45]. Due to their non-toxicity, affordability, and capacity to enhance cell adhesion and proliferation, polycaprolactone (PCL)/PMMA blends have demonstrated as a promising materials for bone regeneration [46,47].

Recently, there has been a lot of interest in Nano Zirconia (ZrO_2 nanoparticles) due to its remarkable biocompatibility. Because these nanoparticles can improve the mechanical properties of acrylic resin, they have been categorized as fillers [48, 49]. Numerous advantageous properties, including high toughness, mechanical strength, resistance to abrasion and corrosion, and biocompatibility, are present in ZrO_2. As the material with the highest oxide hardness, nano zirconia is known for its remarkable mechanical qualities that prevent cracks from spreading [50,51]. Another bioactive substance that can be utilized as an additive in polymethyl methacrylate (PMMA) is magnesium oxide (MgO). It has been observed that

osteoblast adhesion to magnesium oxide-containing cement is significantly greater compared to adhesion to PMMA alone, without compromising the material's mechanical strength [52,53].

Nano-hydroxyapatite (nHA), which is mostly used in bone regeneration nowadays, has a number of advantageous mechanical and morphological characteristics. Nano-hydroxyapatite contains special biomaterials and biostructures that enable bone regeneration, which accounts for its numerous medical applications. Furthermore, it has both organic and inorganic elements that make it biologically practical to utilize in bone regeneration. nHA contains a variety of special qualities, including the ability to chemically bind with bone, the inability to cause inflammation or toxicity, and the ability to promote bone growth. The regenerative properties of nHA are sufficient not only for the remineralization of bone, but also for the growth of tissues to maintain their health and improve their resistance to sensitivity as well as any type of stress or strain. Some of the favourable properties of nHA include its non-immunogenic properties, non-inflammatory behaviour, biocompatibility, osteo-inductive capacity, as well as, high osteo-conductivity. The main component of tooth enamel is hydroxyapatite. It plays a crucial role in enamel remineralization by delivering the necessary calcium and phosphate levels. Additionally, nano-hydroxyapatite can be used to fill the small depressions or holes at the surfaces of tooth enamel. In comparison with human bone, nHA has shown superior hard tissue remineralization effects as compared to other calcium phosphate containing compounds in bone.[54]

In this study, hydroxyapatite (as a mineral) has been infused with PMMA monolith. PMMA acts as a mould (base) and supplies calcium and phosphorus, which supports bone regeneration. Hydroxyapatite has been infused with PMMA monolith as the porosity of hydroxyapatite allows the bone cells to adhere to the walls of the scaffold. Another advantage of infusing hydroxyapatite with PMMA is that it overcomes the brittle nature of hydroxyapatite. The brittle nature of hydroxyapatite restricts its application as a sole material for scaffold development [55]. To address this issue, this study developed porous scaffolds by incorporating hydroxyapatite into PMMA matrix.

CONCLUSION

Various materials have been used for hard tissue regeneration. To overcome the shortcomings of current materials, hydroxyapatite infused PMMA monolith was fabricated. The morphological analysis of the hydroxyapatite PMMA monolith showed porous structures . The elemental analysis was authenticated by EDS spectra, and the presence of hydroxyapatite was indicated by Calcium and Phosphorus. With respect to colour, the same elements were observed through the elemental mapping. The compressive strength of the material was analysed through the UTM, it was observed that the PMMA hydroxyapatite monolith had significant compressive strength. It was comprehended that the fabricated hydroxyapatite PMMA monolith overcame the shortcoming of hydroxyapatite being brittle and it could be considered as a potential candidate to replace the existing materials for hard tissue regeneration.

FUNDING

None.

CONFLICT OF INTEREST

Authors have no conflict of interest.

References

1. Rokaya, D.; Srimaneepong, V.; Sapkota, J.; Qin, J.; Siraleartmukul, K.; Siriwongrungson, V. Polymeric materials and films in dentistry: An overview. J. Adv. Res. 2018, 14, 25–34
2. Redtenbacher, J. Ueber die zerlegungsprodukte des glyceryloxydes durch trockene destillation. Justus Liebigs Ann. Chem. 1843, 47, 113–148.
3. Rueggeberg, F.A. From vulcanite to vinyl, a history of resins in restorative dentistry. J. Prosthet. Dent. 2002, 87, 364–379.
4. Neher, H.T. Acrylic resins. Ind. Eng. Chem. 1936, 28, 267–271.
5. Peyton, F.A. History of resins in dentistry. Dent. Clin. North Am. 1975, 19, 211–222.
6. DiMaio, F.R. The science of bone cement: A historical review. Orthopedics 2002, 25, 1399–1407.
7. Kraft, J. Polymethylmethacrylate—A review. J. Foot Surg. 1977, 16, 66–68.
8. Frazer, R.Q.; Byron, R.T.; Osborne, P.B.; West, K.P. PMMA: An essential material in medicine and dentistry. J. Long. Term. Eff. Med. 2005, 15, 629–639.
9. Zidan, S.; Silikas, N.; Alhotan, A.; Haider, J.; Yates, J. Investigating the mechanical properties of ZrO2-impregnated PMMA nanocomposite for denture-based applications. Materials 2019, 12, 1344.
10. Deb, S. Polymers in dentistry. J. Eng. Med. 1998, 212, 453–464.
11. Zafar MS. Prosthodontic applications of polymethyl methacrylate(PMMA): An update. Polymers. 2020 Oct 8;12(10):2299
12. Duraisamy R, Ganapathy DM, kumar Shanmugam R. Nanocomposites Used In Prosthodontics And Implantology-A Review. Int J Dentistry Oral Sci. 2021 Sep 21;8(9):4380-7.

13. Bates P, Ramachandran M: Bone injury, healing and grafting. In Basic Orthopaedic Sciences. The Stanmore Guide. Edited by: Ramachandran M. London: Hodder Arnold; 2007:123-134.
14. Einhorn TA: The cell and molecular biology of fracture healing. Clin Orthop Relat Res 1998, 355(Suppl):S7-21
15. Dimitriou R, Jones E, McGonagle D, Giannoudis PV. Bone regeneration: current concepts and future directions. BMC medicine. 2011 Dec;9(1):1-0.
16. Sàndor GKB, Lindholm TC, Clokie CML (2003a) Bone regeneration of the cranio-maxillofacial and dento-alveolar skeletons in the framework of tissue engineering. Topics in tissue engineering
17. Jazayeri HE, Tahriri M, Razavi M, Khoshroo K, Fahimipour F, Dashtimoghadam E, Almeida L, Tayebi L. A current overview of materials and strategies for potential use in maxillofacial tissue regeneration. Materials Science and Engineering: C. 2017 Jan 1;70:913-29.
18. Cheung LK, Chua HDP, Hariri F, et al. (2010) Distraction osteogenesis. In: Andersson L, Kahnberg KE, Pogrel MA (eds) Oral and maxillofacial surgery. Wiley-Blackwell, Hoboken, pp 1027–1059
19. Cano J, Campo J, Moreno LA et al (2006) Osteogenic alveolar distraction: a review of the literature. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 101(1):1
20. Buser D, Brägger U, Lang NP et al (1990) Regeneration and enlargement of jaw bone using guided tissue regeneration. Clin Oral Implant Res 1(1):22–32
21. Simion M, Jovanovic SA, Tinti C et al (2001) Long-term evaluation of osseointegrated implants inserted at the time or after vertical ridge augmentation. Clin Oral Implant Res 12(1):35–45 Singh M, Haverinen HM, Dhagat P et al (2010) Inkjet printing—process and its applications. Adv Mater 22(6):673–685
22. von Arx T, Hardt N, Wallkamm B (1996) The TIME technique: a new method for localized alveolar ridge augmentation prior to placement of dental implants. Int J Oral Maxillofac Implants 11(3):387
23. McMahon RE, Wang L, Skoracki R et al (2013) Development of nanomaterials for bone repair and regeneration. J Biomed Mater Res B Appl Biomater 101(2):387–397
24. Christenson EM, Anseth KS, van den Beucken JJJP et al (2007) Nanobiomaterial applications in orthopedics. J Orthop Res 25(1):11–22
25. James R, Deng M, Laurencin CT et al (2011) Nanocomposites and bone regeneration. Front Mater Sci 5(4):342–357
26. Abere DV, Ojo SA, Oyatogun GM, Paredes-Epinosa MB, Niluxsshun MC, Hakami A. Mechanical and morphological characterization of nano-hydroxyapatite (nHA) for bone regeneration: a mini review. Biomedical Engineering Advances. 2022 Oct 13:100056.
27. Jiang X (2011) On novel options for oromaxillofacial functional restoration. Int J prosthodont 25(2):132–134
28. Radha G, Balakumar S, Venkatesan B, Vellaichamy E. A novel nano-hydroxyapatite—PMMA hybrid scaffolds adopted by conjugated thermal induced phase separation (TIPS) and wet-chemical approach: Analysis of its mechanical and biological properties. Materials Science and Engineering: C. 2017 Jun 1;75:221-8.
29. Mahammod BP, Barua E, Deb P, Deoghare AB, Pandey KM. Investigation of physico-mechanical behavior, permeability and wall shear stress of porous HA/PMMA composite bone scaffold. Arabian Journal for Science and Engineering. 2020 Jul;45:5505-15.
30. Barua E, Deoghare AB, Chatterjee S, Sapkal P. Effect of ZnO reinforcement on the compressive properties, in vitro bioactivity, biodegradability and cytocompatibility of bone scaffold developed from bovine bone-derived HAp and PMMA. Ceramics International. 2019 Nov 1;45(16):20331-45.
31. Tithito T, Suntornsaratoon P, Charoenphandhu N, Thongbunchoo J, Krishnamra N, Tang IM, Pon-On W. Fabrication of biocomposite scaffolds made with modified hydroxyapatite inclusion of chitosan-grafted-poly (methyl methacrylate) for bone tissue engineering. Biomedical Materials. 2019 Feb 26;14(2):025013.
32. Indra A, Hadi F, Mulyadi IH, Affi J. A novel fabrication procedure for producing high strength hydroxyapatite ceramic scaffolds with high porosity. Ceramics International. 2021 Oct 1;47(19):26991-7001.
33. Weissman JL, Snyderman CH, Hirsch BE (1996) Hydroxyapatite cement to repair skull base defects: radiologic appearance. Am J Neuroradiol 17(8):1569–1574
34. Dhanvanth M, Ganapathy D, Jain AR. Alloplastic bone grafts in periodontal surgery. Drug Invent Today. 2018 Dec 1;10(12):2383-9.
35. Sàndor GKB, Lindholm TC, Clokie CML (2003a) Bone regeneration of the cranio-maxillofacial and dento-alveolar skeletons in the framework of tissue engineering. Topics in tissue engineering
36. Fleming JE Jr, Cornell CN, Muschler GF (2000) Bone cells and matrices in orthopedic tissue engineering. Orthop Clin North Am 31(3):357–374
37. Hollinger JO, Schmitz JP, Mizgala JW et al (1989) An evaluation of two configurations of tricalcium phosphate for treating craniotomie
38. Ohgushi H, Okumura M, Tamai S et al (1990) Marrow cell induced osteogenesis in porous hydroxyapatite and

tricalcium phosphate: a comparative histomorphometric study of ectopic bone formation. J Biomed Mater Res 24(12):1563–1570

39. Buser D, Hoffmann B, Bernard J et al (1998) Evaluation of filling materials in membrane-protected bone defects. A comparative histomorphometric study in the mandible of miniature pigs. Clin Oral Implant Res 9(3):137–150
40. Cao W, Hench LL (1996) Bioactive materials. Ceram Int 22(6):493–507
41. Hench LL (2011) Bioactive materials for gene control. In: Hench LL, Jones JR, FennNew MB (eds) Materials and technologies for healthcare. World Scientific, Singapore, pp 25–48
42. Mitchell JC, Musanje L, Ferracane JL (2011) Biomimetic dentin desensitizer based on nanostructured bioactive glass. Dent Mater 27(4):386–393
43. Sokolsky-Papkov M, Agashi K, Olaye A et al (2007) Polymer carriers for drug delivery in tissue engineering. Adv Drug Deliv Rev 59(4):187–206
44. Downes S, Archer R S, Kayser M V, Patel M P and Braden M 1994 J. Mater. Sci., Mater. Med. 5 85
45. Kim Y H and Lee B T 2011 Sci. Technol. Adv. Mater. 12 035002
46. So-Ra Son, Nguyen-Thuy Ba Linh, Hun-Mo Yang & Byong-Taek Lee (2013) In vitro and in vivo evaluation of electrospun PCL/PMMA fibrous scaffolds for bone regeneration, Science and Technology of Advanced Materials, 14:1, 015009, DOI: 10.1088/1468-6996/14/1/015009
47. Anbu RT, Suresh V, Gounder R, Kannan A. Comparison of the efficacy of three different bone regeneration materials: An animal study. European journal of dentistry. 2019 Feb;13(01):022-8.
48. Poon, W. C. K. (2002). The physics of a model colloid–polymer mixture. Journal of Physics: Condensed Matter, 14(33), R859.
49. Ahangaran, F., Navarchian, A. H., & Picchioni, F. (2019). Material encapsulation in poly (methyl methacrylate) shell: A review. Journal of Applied Polymer Science, 136(41), 48039.
50. Ahmed, M. A., & Ebrahim, M. I. (2014). Effect of zirconium oxide nano-fillers addition on the flexural strength, fracture toughness, and hardness of heat-polymerized acrylic resin. World journal of nano science and engineering, 4, 50–57
51. Gad, M. M., Abualsaud, R., Rahoma, A., Al-Thobity, A. M., Al-Abidi, K. S., & Akhtar, S. (2018). Effect of zirconium oxide nanoparticles addition on the optical and tensile properties of polymethyl methacrylate denture base material. International Journal of Nanomedicine, 13, 283-292
52. Hickey, D. J., Ercan, B., Sun, L., & Webster, T. J. (2015). Adding MgO nanoparticles to hydroxyapatite–PLLA nanocomposites for improved bone tissue engineering applications. Acta Biomaterialia, 14, 175-184
53. Hegazy, E. S. A., Ghaffar, A. M. A., & Ali, H. E. (2020). Characterization and radiation modification of low density polyethylene/polystyrene/maleic anhydride/magnesium hydroxide blend nanocomposite. Materials Chemistry and Physics, 252, 123204.
54. Abere DV, Ojo SA, Oyatogun GM, Paredes-Epinosa MB, Niluxsshun MC, Hakami A. Mechanical and morphological characterization of nano-hydroxyapatite (nHA) for bone regeneration: a mini review. Biomedical Engineering Advances. 2022 Oct 13:100056.
55. Mahammod BP, Barua E, Deb P, Deoghare AB, Pandey KM. Investigation of physico-mechanical behavior, permeability and wall shear stress of porous HA/PMMA composite bone scaffold. Arabian Journal for Science and Engineering. 2020 Jul;45:5505-15.