GMR
The Original

MINERAL COMPOSITION AND CRYSTALLINE STRUCTURE OF SYNTHETIC GRAFT SUBSTITUTES VERSUS BONE ALLOGRAFTS: XRD-EDS STUDY

Dr. Neelam Kumar Das[1*], Dr. Ravikiran N.[2], Dr. Vijeta Vyas[3], Dr. Tusharika Sharma[4], Dr. Alquama Rizvi[5], Dr. Ankita Singh[6]

[1*]3rd year Post Graduate student, Department of Periodontology, Darshan Dental College and Hospital, Udaipur, Rajasthan, India. Email: neelamkumardas2@gmail.com ORCID ID: 0009-0008-8143-1174
[2]Professor & Head, Department of Periodontology, Darshan Dental College and Hospital, Udaipur, Rajasthan, India E-mail: ravykiran@gmail.com, ORCID ID: 0000-0003-2238-4167
[3]Reader/Associate Prof, Department of Periodontology, Darshan Dental College and Hospital, Udaipur, Rajasthan, India, Email-id-vijetapanchu@gmail.com, ORCID ID: 0000-0002-9000-945X
[4]Assistant Professor , Department of Periodontology, Darshan Dental College and Hospital, Udaipur, Rajasthan, India. ORCID ID- 0009-0002-9171-6372, Email id: Tusharika4064@gmail.com
[5]3rd year Post Graduate student, Department of Periodontology, Darshan Dental College and Hospital, Udaipur, Rajasthan, India, Email id - rizvialquama96@gmail.com, ORCID ID: 0009-0008-8148-5033
[6]3rd year Post Graduate student, Department of Periodontology, Darshan Dental College and Hospital, Udaipur, Rajasthan, India. Email id: Ankitasingh021@gmail.com, ORCID ID: 0009-0003-8957-6320

ABSTRACT:
Background: Bone graft materials play a critical role in periodontal and implant regenerative therapy, yet the physicochemical differences between synthetic and allogenic grafts remain insufficiently characterized using precise analytical techniques. Hence the aim of our study was to assess and compare the mineral content and crystalline structure of a bioresorbable synthetic graft matrix (BSGM) and DFDBA using XRD and EDS mapping.
Methods & Methodology: With institutitional ethical committee approval & writtten informed consent, we have conducted six powdered samples each of BSGM (PowerBone®) and DFDBA using XRD to determine crystalline pattern, particle size (Debye-Scherrer equation), and crystallinity percentage, followed by EDS mapping on identical samples to assess elemental composition and Ca/P ratio.
Result: BSGM exhibited a sharper diffraction peak (~760 a.u.), higher crystallinity (43.13%), larger particle size (37.6 nm), and a Ca/P ratio of 1.58, indicating a highly crystalline, stoichiometric calcium-phosphate ceramic. DFDBA showed a broader peak (~330 a.u.), lower crystallinity (39.67%), smaller particle size (5.6 nm), and a calcium-deficient Ca/P ratio of 1.31, reflecting a naturally disordered, organically embedded mineral phase. EDS further confirmed DFDBA's organic collagenous nature (high carbon, low Ca/P) versus BSGM's fully inorganic ceramic composition with trace zinc doping.
Conclusion: BSGM demonstrates superior crystallinity and structural stability favoring space maintenance, while DFDBA retains biological reactivity conducive to resorption and osteoinduction, indicating complementary rather than interchangeable clinical roles.

KEYWORDS: Bone Allograft; Synthetic Graft Substitute; X-Ray Diffraction; Crystallinity; Calcium-Phosphate Ratio.

INTRODUCTION

Bone loss resulting from periodontal disease, trauma, or tumor resection remains one of the most significant reconstructive challenges in periodontology and implant dentistry which drives a continuous search for grafting materials those were capable of restoring both structural integrity and biological function (Marian et al., 2024). Bone replacement grafts are broadly classified based on their origin into autografts, allografts, xenografts, and alloplasts (synthetic materials), each differing in their osteogenic, osteoinductive, and osteoconductive potential (Reynolds et al., 2010). While autogenous bone remains the gold standard owing to its unique combination of all three regenerative properties, its clinical use is constrained by donor-site morbidity and limited availability, prompting widespread adoption of allografts and synthetic alternatives as more accessible substitutes (Wang & Yeung, 2017).

Among allogenic materials, demineralized freeze-dried bone allograft (DFDBA) has been extensively used in periodontal therapy owing to its recognized osteoinductive potential, attributed to the exposure of embedded bone morphogenetic proteins (BMPs 2, 4, and 7) during the demineralization process (Jaiswal et al., 2017). Histologic evidence has demonstrated that DFDBA can promote true periodontal regeneration, including new cementum, organized periodontal ligament, and alveolar bone formation, in a substantial proportion of treated

intrabony defects (Bowers et al., 1989). However, considerable batch-to-batch variability exists in commercial DFDBA preparations, with reported differences in particle size, mineral residue, and osteoinductive capacity depending on donor source and tissue bank processing protocols, raising ongoing questions about the material's compositional consistency and predictability (Ansari et al., 2025; Schwartz et al., 1996).
In parallel, synthetic alloplastic materials, particularly calcium phosphate ceramics such as hydroxyapatite (HA) and β-tricalcium phosphate (β-TCP), have gained popularity because their physicochemical properties can be precisely tuned during manufacture, offering more predictable resorption kinetics, radiopacity, and space-maintaining capacity compared to biologically derived grafts (Mishchenko et al., 2023). These synthetic substitutes function primarily through osteoconduction rather than osteoinduction, acting as a scaffold that supports vascular and cellular ingrowth from adjacent native bone (Rodham et al., 2023). Comparative studies have shown that synthetic HA/β-TCP composites can achieve bone regenerative outcomes comparable to DFDBA and autografts in certain periodontal defect types, though their long-term resorption behavior and mineral composition differ considerably from natural bone, findings largely attributed to differences in crystallinity and stoichiometry between manufactured ceramics and biologically processed tissue (Kumar et al., 2022 ; Wang & Kang, 2025).
Despite the widespread clinical use of both DFDBA and synthetic bone graft substitutes, a clear compositional and structural comparison using precise material characterization techniques remains limited in the periodontal literature. X-ray diffraction (XRD) and Energy Dispersive Spectroscopy (EDS) mapping are well-established analytical methods capable of quantifying crystalline phase, crystallinity percentage, particle size, and elemental composition (including the clinically relevant Ca/P ratio) with high precision, providing objective, reproducible data beyond what clinical or histological assessment alone can offer. Given that graft material selection in periodontal regenerative therapy should ideally be guided by an evidence-based understanding of each material's intrinsic mineral and structural properties rather than clinical tradition alone, there exists a clear need for a direct, standardized physicochemical comparison between a commercially available bioresorbable synthetic graft matrix and bone allograft. This study was therefore undertaken to assess and compare the mineral content and crystalline structure of a bioresorbable synthetic graft matrix and bone allograft using XRD and EDS mapping, with the aim of generating objective compositional data to better inform rational, defect-specific graft selection in periodontal and implant regenerative procedure.

Objective of the Study

1.To study the mineral content and crystalline structure of bioresorbable synthetic graft matrix using X-ray diffraction and EDS mapping.
2.To study the mineral content and crystalline structure of the bone allograft using X-ray diffraction and EDS mapping.
3.To make a comparison between the mineral content and crystalline geometry of bioresorbable synthetic graft matrix with bone allograft using X-ray diffraction and EDS mapping.

METHODOLOGY

Study Design & Participants

Our in-vitro comparative analytical study was conducted in the Department of Periodontology and Implantology at Darshan Dental College & Hospital, with laboratory analysis performed at the XRD laboratory of Jawaharlal Nehru University (JNU), Delhi, and the EDX mapping laboratory at IIT Delhi. As this was a purely material-based in-vitro study, patient selection criteria were not applicable, and no human participants were involved at any stage of the research.

Randomization and Study Groups

The two test materials were allocated into two distinct groups without the need for randomization, since group assignment was determined by the inherent material type rather than participant characteristics. The Bioresorbable synthetic graft matrix (25×25×2 mm), designated as Sample 1, was assigned to Group 1 as shown in figure 1,

FIGURE 1 : POWERBONE® FLEXIBLE GRAFT STRIP

while the Bone allograft (DFDBA, 20×15×5 mm), designated as Sample 2, was assigned to Group 2 as shown in figure 2.

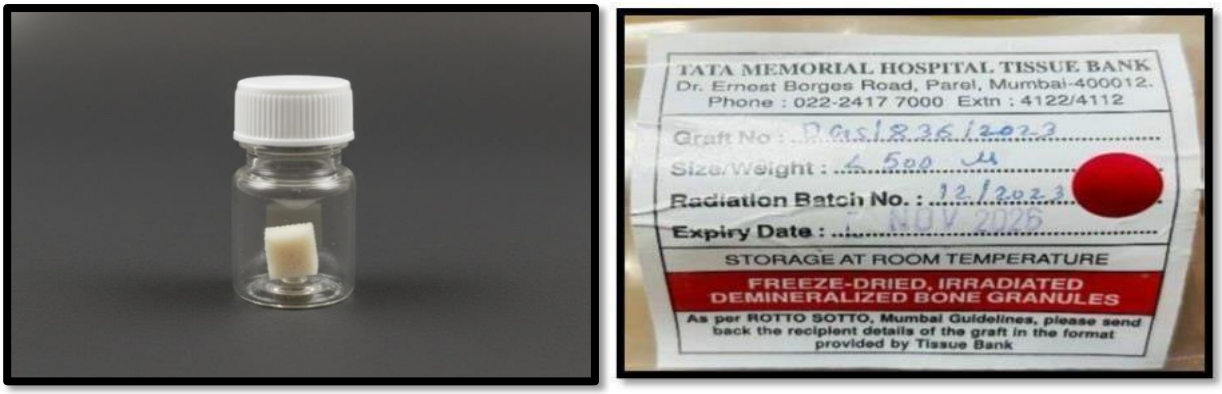


FIGURE 2 : DFDBA

Each group comprised six uniform samples (N = 6 per group), which were prepared by a laboratory technician in accordance with the size specifications and protocols mandated by the XRD laboratory.

Procedure

Both materials were first pulverized into fine powder particles using a dentin grinder and stored in sterile bone graft containers prior to sample division. For XRD analysis, each of the six samples per group was positioned on a zero-background silicon holder, with butter paper used to ensure even distribution of the powdered material across the holder surface. The holder was cleaned with ethanol between successive sample loadings to prevent cross-contamination. Each
sample was then subjected to X-ray diffraction using an X-ray diffractometer as shown in figure 3.

FIGURE 3 : X-RAY DIFFRACTOMETER

and this process was repeated sequentially until all twelve samples (six from each group) had been analyzed. Following XRD analysis, the identical samples underwent EDS mapping to determine their elemental and mineral composition, after which the resulting graphs and numerical readings were compiled and organized into tabular format for comparison.

Outcome Assessment

The primary outcomes assessed were the crystalline structure and mineral composition of both materials, captured through XRD graphs plotting intensity on the Y-axis against diffraction angle (2θ) on the X-axis, along with elemental composition data obtained via EDS mapping. Differences in crystallinity percentage, particle size, and diffraction pattern between the BSGM and DFDBA groups were recorded and tabulated for direct comparison. The elemental makeup of each material, including calcium, phosphorus, and other mineral

constituents, was further evaluated through EDS mapping to characterize compositional differences between the synthetic graft matrix and the bone allograft.

Sample Size Estimation

A sample size of six specimens per group (N = 6 each, total N = 12) was used for this in-vitro comparative analysis, consistent with standard practice for material characterization studies of this nature involving XRD and EDS techniques. The XRD and EDS data points were processed and analyzed using specialized analytical software, such as OriginLab, to generate diffraction graphs and quantify variations in crystallinity percentage, particle size, and mineral composition between the two groups.

Statistical Analysis

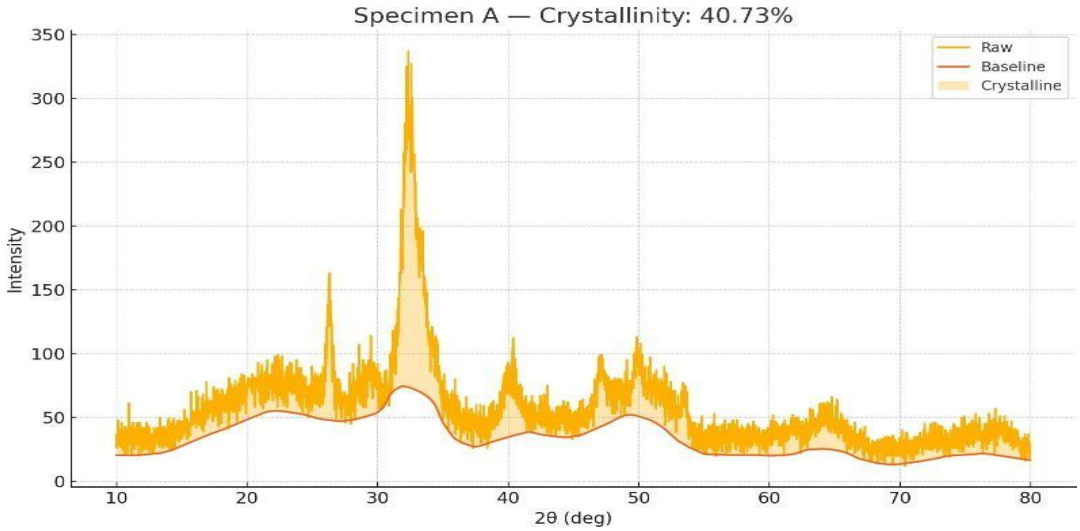
Depending on the distribution of the data, appropriate statistical tests (such as an independent samples t-test or Mann-Whitney U test for non-parametric data) may be applied to compare mean crystallinity and elemental composition values between Group 1 and Group 2, with a p-value of less than 0.05 considered statistically significant.

RESULT

1.XRD Analysis

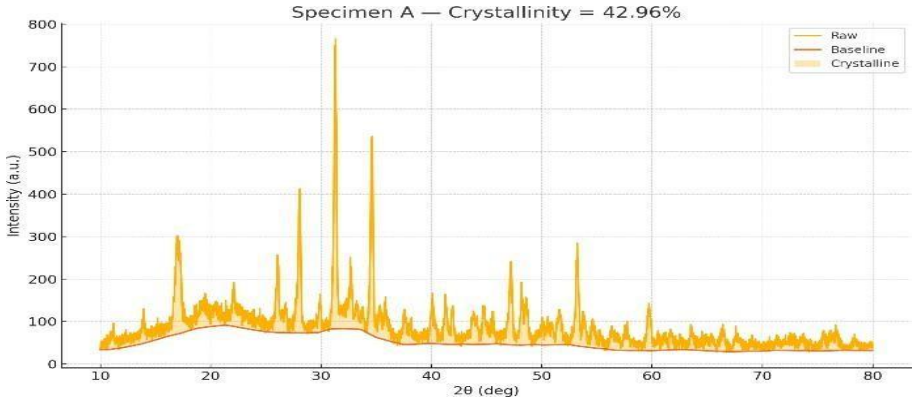
A.Crystalline Pattern

XRD analysis revealed distinct diffraction patterns for both specimens, plotted as intensity (a.u.) against diffraction angle 2θ. The bone allograft (DFDBA) exhibited a broad maximum peak at approximately 32° (2θ) with a peak intensity of ~330 a.u. shown in graph 1.



GRAPH 1 : INTENSITY VS 2Θ GRAPH OF DFDBA

reflecting greater lattice strain and a predominantly amorphous or disordered atomic arrangement. In contrast, the bioresorbable synthetic graft matrix (BSGM, PowerBone®) showed a sharp, well-defined maximum peak at 31.5°–32° (2θ) with a substantially higher intensity of ~760–770 a.u. as shown in Graph 2,
indicative of a highly ordered, repetitive crystal lattice producing strong constructive interference.



GRAPH 2 : INTENSITY VS 2Θ GRAPH OF POWERBONE®

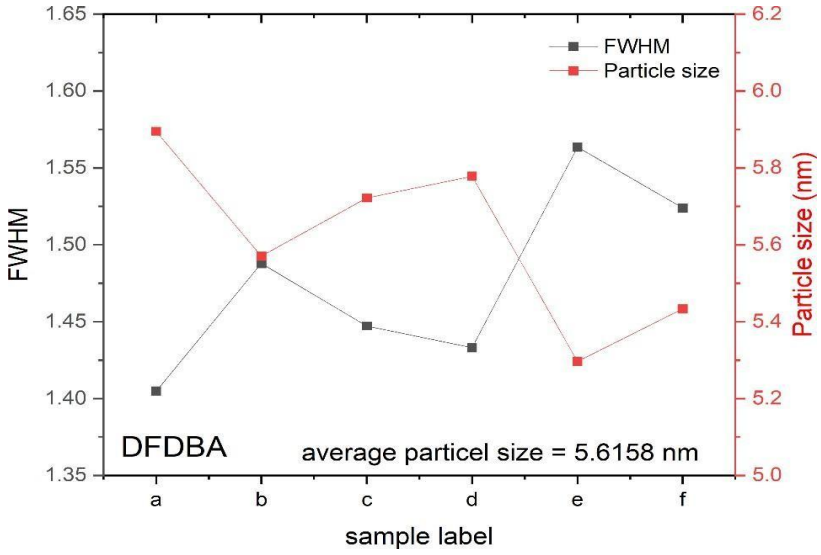
TABLE 1 : COMPARISON OF MAXIMUM XRD PEAK INTENSITY

SPECIMEN	MAX PEAK POSITION (2Θ)	MAX PEAK INTENSITY	INTERPRETATION
DFDBA (Bone Allograft)	~32°	~330 a.u.	Lower crystallinity; natural, disordered bone mineral
PowerBone® (BSGM)	~31.5°–32°	~760 a.u.	Highly crystalline β-TCP/HA synthetic phase

In our table 1, graph 1 & 2 we have found that, the peak intensity of BSGM was more than double that of DFDBA, indicating a significantly stronger and more organized atomic structure in the synthetic graft compared to the biologically derived allograft.

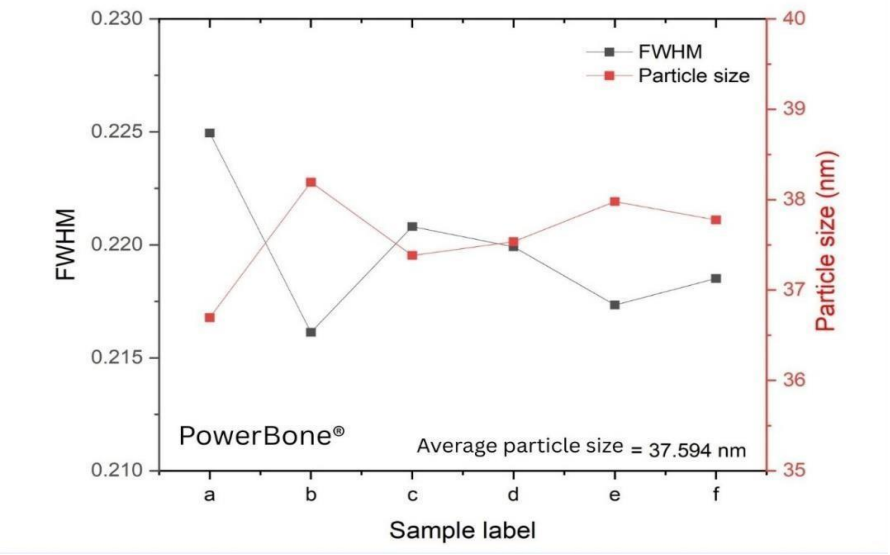
B.Particle size Evaluation

Crystallite (particle) size was estimated by isolating the most prominent diffraction peak and applying the Debye–Scherrer equation, $D = K\lambda / \beta\cos\theta$. The average particle size for DFDBA was calculated as 5.6 nm as shown in graph 3,



GRAPH 3 : PARTICLE SIZE OF DFDBA

consistent with the broadened peak profile observed. The average particle size for BSGM was calculated as 37.6 nm as shown in graph 4, consistent with its sharper diffraction peak.



GRAPH 4 : PARTICLE SIZE OF POWERBONE®

TABLE 2 : COMPARISON OF PARTICLE SIZE

SPECIMEN	AVERAGE PARTICLE SIZE (nm)	PEAK CHARACTERISTIC
DFDBA (Bone Allograft)	5.6	Broad Peak → Smaller Crystal Dimension
PowerBone® (BSGM)	37.6	Sharp Peak → Larger Crystal Dimension

Table 2, graph 3 &4 shows that , The particle size of DFDBA was markedly smaller than that of BSGM, an approximately 6.7-fold difference, reflecting the fundamentally different crystallization mechanisms of biologically demineralized bone versus synthetically manufactured ceramic material.

C.Crystalline Percentage

Crystallinity was quantified in OriginLab software by calculating the ratio of the area under the crystalline peaks to the total area under the diffraction curve, expressed as: Crystallinity (%) = (Sum of crystalline peak areas / Total curve area) × 100. The average crystallinity was 39.67% for DFDBA and 43.13% for BSGM (Graph 7), indicating a comparatively more tightly packed and organized mineral arrangement in the synthetic graft matrix relative to the bone allograft.

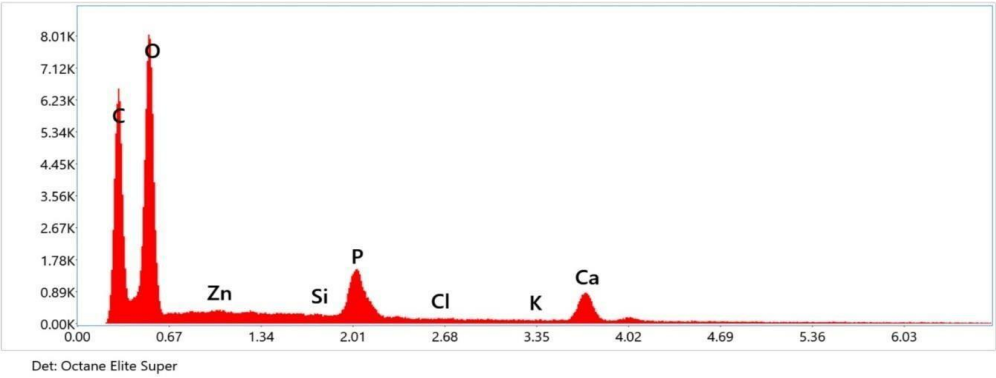
2.EDS Mapping

A.DFDBA

EDS mapping of DFDBA identified carbon, oxygen, calcium, and phosphorus as the primary constituent elements, confirming its identity as a calcium phosphate–based biomaterial with an organic collagenous component. Calcium and phosphorus were sparsely and non-uniformly distributed throughout the sample.

TABLE 3 : ELEMENTAL COMPOSITION OF DFDBA

ELEMENT	WEIGHT %	ATOMIC %	ERROR %
C K	46.6	58.1	8.6
O K	38.0	35.5	9.2
Si K	0.3	0.1	16.8
P K	5.4	2.6	3.9
Cl K	0.2	0.1	54.4
K K	0.2	0.1	59.0
Ca K	9,1	3.4	5.0
Zn L	0.3	0.1	27.8



GRAPH 5 : EDS ANALYSIS OF DFDBA

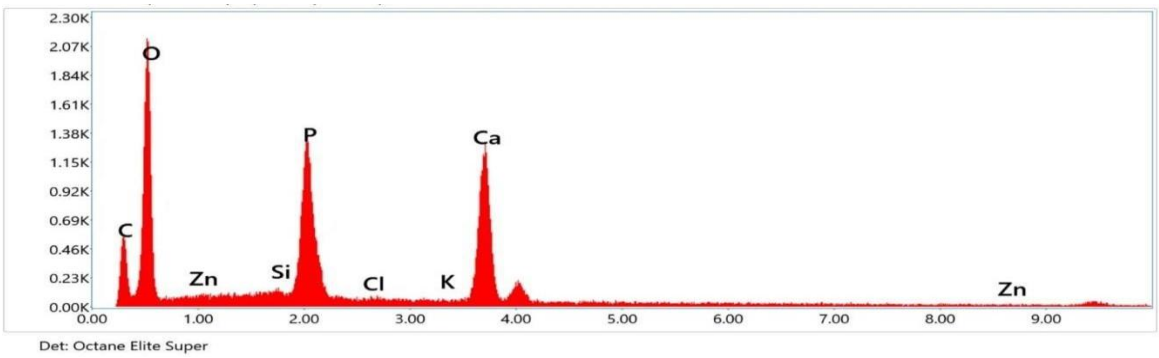
According to table 3 & graph 5, the calculated calcium-to-phosphorus (Ca/P) ratio for DFDBA was 1.31 (3.4/2.6 atomic %), which is lower than the stoichiometric ratio of pure hydroxyapatite (1.67). A Ca/P ratio below 1.67 is characteristic of a calcium-deficient apatite, a feature considered clinically favorable for DFDBA since it promotes faster resorption and bioactivity rather than mere passive space maintenance. The predominance of carbon (46.6 wt%) and oxygen (38.0 wt%) confirmed the organic, collagenous nature of the demineralized matrix, while the comparatively low calcium and phosphorus content reflected the substantial mineral reduction achieved through the demineralization process. Trace amounts of silicon (0.3 wt%), chlorine (0.2 wt%), and potassium (0.2 wt%) were also detected, likely representing processing artifacts of no clinical significance; magnesium and sodium were not identified.

B.Bioresorable Synthetic Graft Matrix

EDS mapping of BSGM revealed markedly elevated calcium and phosphorus content alongside minimal carbon, confirming its composition as a synthetic, inorganic calcium-phosphate ceramic, distinct in nature from the organic-mineral composite structure of DFDBA.

TABLE 4 : ELEMENTAL COMPOSITION OF BSGM

ELEMENT	WEIGHT %	ATOMIC %	ERROR %
C K	5.5	9.3	27.9
O K	55.4	69.5	10.5
Si K	0.2	0.1	60.3
P K	12.3	8.0	4.3
Cl K	0.1	0.0	63.9
K K	0.1	0.0	67.9
Ca K	25.1	12.6	3.4
Zn L	1.3	0.4	21.9



GRAPH 6 : EDS ANALYSIS OF POWERBONE®

According to table 4 & graph 6, the calculated Ca/P ratio for BSGM was 1.58 (12.6/8.0 atomic %), closely approximating the stoichiometric hydroxyapatite ratio, indicative of higher crystallinity and a composition optimal for volume preservation and defect stability in implant and periodontal regenerative procedures. Oxygen (55.4 wt%) was the most abundant element, consistent with a ceramic apatite matrix, while calcium (25.1 wt%) and phosphorus (12.3 wt%) were distributed uniformly and densely across the sample. A trace but evenly dispersed zinc content (1.3 wt%) was noted, suggesting intentional bioactive doping, while the minimal carbon content (5.5 wt%) confirmed the absence of an organic matrix. Neither potassium nor chlorine was detected in this specimen.

TABLE 5 : COMPARATIVE ANALSYIS

PARAMETER	DFDBA	POWER BONE ® (BSGM)
Carbon (C)	Very high (46.6 wt%)	Very low (5.5 wt%)
Calcium (Ca)	9.1 wt%	25.1 wt%
Phosphorus (P)	5.4 wt%	12.3 wt%
Ca/P ratio	~1.31	~1.58
Crystallinity	39.67%	43.13%
Average particle size	5.6 nm	37.6 nm
Nature	Organic + mineral	Fully inorganic ceramic
Resorption rate	Faster	Slower
Space maintenance	Limited	Excellent
Osteoinduction	Present	Absent
Osteoconduction	Moderate	High

We have found that according to table 5, XRD and EDS findings demonstrate that DFDBA is characterized by a calcium-deficient, amorphous apatite phase embedded within an organic collagenous matrix, features consistent with its natural biological origin and clinical role as a rapidly resorbable, osteoinductive graft material. In

contrast, BSGM presents as a highly crystalline, fully inorganic calcium-phosphate ceramic with a Ca/P ratio approaching stoichiometric hydroxyapatite, larger particle size, and intentional zinc doping, properties that favor slower resorption, superior space maintenance, and enhanced osteoconductive potential. These compositional and structural differences highlight the complementary but distinct clinical applications of the two graft materials in periodontal and implant regenerative therapy.

DISCUSSION

The present study demonstrated that the bioresorbable synthetic graft matrix (BSGM, PowerBone®) exhibited a sharper, more intense XRD peak (~760 a.u.) and a higher crystallinity percentage (43.13%) compared to the bone allograft (DFDBA), which showed a broader, lower-intensity peak (~330 a.u.) and reduced crystallinity (39.67%). This finding aligns closely with previous comparative XRD studies of bone substitute materials, where synthetic hydroxyapatite (SHA) and β-TCP-based grafts consistently displayed sharper, narrower diffraction peaks indicative of high crystallinity, whereas bovine-derived xenografts like Bio-Oss® showed broader peaks matching calcium-deficient carbonate apatite, reflecting a more amorphous structural character (Wüster et al., 2024; Tabatabaei, et al.,2017). Similarly, a comparative crystallographic study of synthetic IngeniOs HA particles versus Bio-Oss® bone substitute reported sharper HA peaks for the synthetic material, attributed to a more regular crystalline lattice and higher percentage crystallinity (Greenspan 2012), directly corroborating the pattern observed between BSGM and DFDBA in the present study. These convergent findings across multiple graft material comparisons support the biological rationale that synthetic ceramics, manufactured under controlled sintering conditions, achieve a more ordered atomic lattice than biologically processed, demineralized allogenic bone, which retains inherent structural disorder from the demineralization process itself. Moreover, the particle size findings in the present study showed 5.6 nm for DFDBA while 37.6 nm for BSGM which also mirror trends reported in comparable investigations of natural & synthetic apatite sources (Montesissa et al., 2024). A study synthesizing hydroxyapatite from egg-shell biogenic sources while commercial xenografts from biogenic synthetic apatite which achieved a crystallite size of 43.73 nm with high crystallinity (Xc 0.92), reinforcing that engineered or controlled-synthesis materials tend to yield larger, more defined crystallite domains than naturally processed bone-derived materials (Dumitrescu et al., 2021). In addition to above, comparable Debye-Scherrer-based crystallite size evaluations of doped versus non-doped hydroxyapatite also demonstrated that lattice modifications (whether through doping or biological demineralization) reduce crystallite dimensions and correspondingly broaden diffraction peaks, consistent with the mechanistic explanation offered for the smaller DFDBA particle size in this study. Notably, a directly comparable Indian dental research study evaluating DFDBA against synthetic mineralized collagen and other matrices using an identical XRD-EDS methodology reported similarly patterned Ca/P findings, lending strong external validity to the present study's protocol and analytical approach (M. Khairnar et al., 2025).

Regarding elemental composition, the Ca/P ratio of 1.31 obtained for DFDBA in this study is consistent with the well-established concept that demineralized, freeze-dried bone allografts exhibit a calcium-deficient apatite phase relative to the stoichiometric hydroxyapatite ratio of
1.67. Comparative characterization studies of allogenic bone apatite have confirmed that Ca/P ratios and mineral content in allograft-derived material vary depending on donor factors, degree of demineralization, and processing protocols, but consistently remain below the stoichiometric HA benchmark, supporting the compositional deficiency observed in the present DFDBA sample (Wang & Kang, 2025 ; Graziani et al., 2020). Conversely, the BSGM Ca/P ratio of 1.58 obtained here closely parallels an earlier report comparing synthetic IngeniOs HA (Ca/P = 1.62) and Bio-Oss (Ca/P = 1.58), both of which approximated the human bone reference ratio of 1.67, reinforcing that synthetic ceramic grafts are engineered to closely mimic natural stoichiometric hydroxyapatite for optimized volume stability. This near-stoichiometric ratio, combined with higher crystallinity, has been clinically linked in prior work to slower resorption rates and superior long-term space maintenance, properties reflected in the current comparative table between BSGM and DFDBA and consistent with established literature on β-TCP and HA-based synthetic grafts showing excellent volume retention but limited osteoinductive capacity relative to allografts (Greenspan, 2012). Furthermore, zinc incorporation detected in BSGM (1.3 wt%) also finds support in the broader biomaterials literature, where trace element doping (zinc, strontium, silicon) of synthetic calcium phosphate ceramics is a well-documented strategy to enhance bioactivity, though such substitutions can simultaneously alter crystallite size and crystallinity depending on ionic radius and substitution site, as demonstrated in strontium- and silicon-zinc-doped hydroxyapatite studies (Diputra et al., 2025).

Overall, the concordance between the present XRD-EDS findings and the described comparative literature strengthens the validity of the study's central conclusion where BSGM represents a highly crystalline, compositionally stoichiometric, and intentionally doped inorganic ceramic optimized for structural stability, whereas DFDBA retains a naturally disordered, calcium-deficient, and organically embedded mineral phase that favors faster resorption and osteoinductive potential, a distinction with direct clinical implications for graft selection in periodontal regenerative therapy depending on whether space maintenance or biological turnover is the primary treatment objective.

CONCLUSION

Within the limitations of this in-vitro comparative study, XRD and EDS analysis demonstrated distinct mineral and structural profiles between the bioresorbable synthetic graft matrix (BSGM) and bone allograft (DFDBA). BSGM exhibited a sharper diffraction peak, higher crystallinity (43.13%), larger particle size (37.6 nm), and a Ca/P ratio (1.58) closely approximating stoichiometric hydroxyapatite, confirming its identity as a highly crystalline, fully inorganic calcium-phosphate ceramic. In contrast, DFDBA showed a broader peak, lower crystallinity (39.67%), smaller particle size (5.6 nm), and a calcium-deficient Ca/P ratio (1.31), reflecting its naturally disordered, organically embedded mineral phase typical of demineralized bone. These findings indicate that BSGM offers superior structural stability and space-maintenance capacity, favorable for defect preservation, while DFDBA retains inherent biological reactivity conducive to faster resorption and osteoinduction. Thus, the two materials are not interchangeable but rather complementary, each suited to distinct clinical objectives within periodontal and implant regenerative therapy. Material selection should therefore be guided by the specific requirements of the osseous defect, balancing the need for volumetric stability against the demand for biological turnover.

REFERENCES

1. Marian, D., Toro, G., D'Amico, G., Trotta, M. C., D'Amico, M., Petre, A., ... & Fratila, A. (2024). Challenges and innovations in alveolar bone regeneration: a narrative review on materials, techniques, clinical outcomes, and future directions. Medicina, 61(1), 20.
2. Reynolds, M. A., Aichelmann-Reidy, M. E., & Branch-Mays, G. L. (2010). Regeneration of periodontal tissue: bone replacement grafts. Dental Clinics, 54(1), 55-71.
3. Wang, W., & Yeung, K. W. (2017). Bone grafts and biomaterials substitutes for bone defect repair: A review. Bioactive materials, 2(4), 224-247.
4. Jaiswal, Y., Kumar, S., Mishra, V., Bansal, P., Anand, K. R., & Singh, S. (2017). Efficacy of decalcified freeze-dried bone allograft in the regeneration of small osseous defect: a comparative study. National Journal of Maxillofacial Surgery, 8(2), 143.
5. Bowers, G. M., Chadroff, B., Carnevale, R., Mellonig, J., Corio, R., Emerson, J., ... & Romberg, E. (1989). Histologic evaluation of new attachment apparatus formation in humans: Part I. Journal of Periodontology, 60(12), 664-674.
6. Ansari, N., Faraz, F., Lamba, A. K., Tandon, S., Kamal, Z., & Madni, Z. K. (2025). Effect of Demineralization Time on the Release of Bone Morphogenetic Protein in Indigenously Prepared Demineralized Freeze-Dried Bone Allografts: A Comparative In Vitro Study. Cureus, 17(5).
7. Schwartz, Z., Mellonig, J. T., Carnes Jr, D. L., De La Fontaine, J., Cochran, D. L., Dean, D. D., & Boyan, B. D. (1996). Ability of commercial demineralized freeze-dried bone allograft to induce new bone formation. Journal of periodontology, 67(9), 918-926.
8. Mishchenko, O., Yanovska, A., Kosinov, O., Maksymov, D., Moskalenko, R., Ramanavicius, A., & Pogorielov, M. (2023). Synthetic calcium–phosphate materials for bone grafting. Polymers, 15(18), 3822.
9. Rodham, P. L., Giannoudis, V. P., Kanakaris, N. K., & Giannoudis, P. V. (2023). Biological aspects to enhance fracture healing. EFORT open Reviews, 8(5), 264.
10. Kumar, S., Desai, N., Joshi, S., Hirani, T., Gajjar, S., Patel, C., ... & Govindool, S. R. (2022). Biphasic calcium phosphate versus demineralized freeze-dried bone allograft in the treatment of periodontal disease: a clinical and radiographical evaluation. Cureus, 14(9).
11. Wang, H., & Kang, J. (2025). Bone grafts and synthetic substitutes in dental applications: a comprehensive review of molecular mechanisms, materials evolution, and clinical perspective. Frontiers in Bioengineering and Biotechnology, 13, 1759864.
12. Wüster, J., Neckel, N., Sterzik, F., Xiang-Tischhauser, L., Barnewitz, D., Genzel, A., ... & Knabe, C. (2024). Effect of a synthetic hydroxyapatite-based bone grafting material compared to established bone substitute materials on regeneration of critical-size bone defects in the ovine scapula. Regenerative Biomaterials, 11, rbae041.
13. Tabatabaei, F. S., Samadi, R., & Tatari, S. (2017). Surface characteristics of three commercially available grafts and adhesion of stem cells to these grafts. Bio-medical materials and engineering, 28(6), 621-631.
14. Greenspan, D. C. (2012). Comparison of a synthetic and bovine derived hydroxyapatite bone graft substitute. Zimmer Dental Inc, 1-4.
15. Montesissa, M., Sassoni, E., Boi, M., Borciani, G., Boanini, E., & Graziani, G. (2024). Synthetic or natural (bio-based) hydroxyapatite? A systematic comparison between biomimetic nanostructured coatings produced by ionized jet deposition. Nanomaterials, 14(16), 1332.
16. Dumitrescu, C. R., Neacsu, I. A., Surdu, V. A., Nicoara, A. I., Iordache, F., Trusca, R., ... & Andronescu, E. (2021). Nano-hydroxyapatite vs. Xenografts: Synthesis, characterization, and in vitro behavior. Nanomaterials, 11(9), 2289.
17. M. Khairnar, S. ., N, R. ., Porwal, K. B., Vyas, V. ., Rizvi, A. ., & Kamble, A. . (2025). Comparative Evaluation Of Mineral & Crystalline Pattern Of Dfdba & Differnt Cbr Scaffolds. Journal of Neonatal Surgery, 14(27S), 207–215.

18. Graziani, G., Govoni, M., Vivarelli, L., Boi, M., De Carolis, M., Bianchi, M., ... & Dallari, D. (2020). A Comprehensive microstructural and compositional characterization of allogenic and xenogenic bone: Application to bone grafts and nanostructured biomimetic coatings. Coatings, 10(6), 522.
19. Greenspan, D. C. (2012). Comparison of a synthetic and bovine derived hydroxyapatite bone graft substitute. Zimmer Dental Inc, 1-4.
20. Diputra, A. H., Dinatha, I. K. H., & Yusuf, Y. (2025). A comparative X-ray diffraction analysis of Sr2+ substituted hydroxyapatite from sand lobster shell waste using various methods. Heliyon, 11(2).