ISSN 0973-2063 (online) 0973-8894 (print)
Bioinformation 22(10): 7503-7507 (2026)
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BIOINFORMATION
Discovery at the interface of physical and biological sciences
BIOMEDICAL INFORMATICS
www.bioinformation.net
Volume 22(10)
Research Article

Received October 1, 2026; Revised October 31, 2026; Accepted October 31, 2026, Published October 31, 2026
DOI: 10.6026/973206300227503

SJIF 2026 (Scientific Journal Impact Factor for 2026) = 8.478
2022 Impact Factor (2023 Clarivate Inc. release) is 1.9

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Citation: Naqvi *et al*. Bioinformation 22(10): 7503-7507 (2026)

3D-printed bioactive scaffold for alveolar bone regeneration: An *in vitro* study

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https://www.trusmiledental.in/

ISSN 0973-2063 (online) 0973-8894 (print)
Bioinformation 22(10): 7503-7507 (2026)
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Abstract:
Three-dimensional printing permits porous scaffolds with controlled geometry, but bioactive reinforcement must enhance osteogenesis without compromising print fidelity or mechanical performance. Therefore, it is of interest to compare the 3D-printed polycaprolactone (PCL), PCL/20% β-tricalcium phosphate (β-TCP) and PCL/20% β-TCP/10% 58S bioactive-glass scaffolds. Dimensional accuracy, porosity, compressive strength, degradation, apatite formation, stromal-cell viability, alkaline phosphatase activity and mineralization were evaluated. The bioactive-glass group maintained approximately 70% porosity, showed the greatest simulated-body-fluid apatite coverage and produced significantly higher ALP activity and mineralization than both controls ($p < 0.001$), while compressive strength remained within a cancellous-bone range. Thus, bioactive-glass reinforcement improved the *in vitro* osteogenic performance of the printable scaffold without an unacceptable loss of geometry or strength.

Keywords: 3D printing, bioactive glass, alveolar bone, scaffold, polycaprolactone, osteogenesis

Background:
Alveolar defects are geometrically complex and can compromise implant positioning and prosthetic rehabilitation **[1, 2]**. Additive manufacturing can reproduce defect-specific pore architecture and interconnectivity that support tissue ingrowth **[3]**. Polycaprolactone is attractive for fused-deposition printing because of its thermoplastic processability and slow degradation, but its relative bioinertness can limit osteogenic stimulation **[4].** β-Tricalcium phosphate contributes osteoconductive calcium-phosphate phases, whereas bioactive glass can release ionic cues that promote apatite formation and osteogenic differentiation **[5, 6]**. Combining polymer printability with ceramic bioactivity is therefore a rational strategy for craniofacial scaffold design **[7]**. Therefore, it is of interest to determine whether bioactive-glass reinforcement improves the biological performance of a PCL/β-TCP scaffold while preserving print accuracy and mechanical competence.

Materials and Methods:
Scaffold fabrication:
Cylindrical scaffolds were designed with nominal 500-µm interconnected pores and fabricated by fused deposition modelling. Three compositions were evaluated: neat PCL, PCL containing 20% β-TCP and PCL containing 20% β-TCP plus 10% 58S bioactive glass. The ceramic phases were incorporated into the polymer feedstock before printing and the same scaffold geometry and deposition settings were maintained across the three groups to minimize manufacturing-related variability. Thirty specimens were produced per group. After printing, specimens were visually inspected for strand continuity, gross deformation and pore patency before allocation to physical or biological testing.

Material characterization:
External dimensions, pore size and interconnected porosity were quantified from micro-computed-tomography reconstructions using the same acquisition and analysis settings for all groups. Compressive testing was performed along the principal scaffold axis and peak stress was used to characterize compressive strength. For degradation assessment, specimens were dried to a constant baseline mass, immersed for 28 days, re-dried and the percentage mass change was calculated. Bioactivity was assessed after immersion in simulated body fluid by quantifying apatite-covered surface area. Scanning electron microscopy was used to evaluate surface morphology, while energy-dispersive spectroscopy confirmed calcium- and phosphate-rich deposits and enabled estimation of the surface Ca/P ratio.

Cell response:
Human mesenchymal stromal cells were seeded onto sterilized scaffolds at a standardized density under identical culture conditions. Cell viability and proliferation were assessed through day 7 to evaluate early cytocompatibility. Osteogenic response was then examined by measuring alkaline phosphatase activity on days 7 and 14 and by quantifying mineral deposition on day 21. Assays were performed using the same incubation times and readout conditions across groups and values were normalized according to the corresponding assay protocol so that the three scaffold compositions could be compared directly.

Statistical analysis:
Ten independent scaffold specimens per group were analysed for each physical or material-characterization outcome and six independent specimens per group were evaluated for each cell-assay time point. Results were summarized as mean ± standard

deviation. Group differences were tested with one-way analysis of variance, followed by Tukey multiple-comparison testing when the omnibus test was significant. Statistical testing was two-sided and the significance threshold was set at α=0.05.

Results:

All groups printed without strand collapse. Bioactive particles increased surface roughness and mineral precipitation while preserving interconnected pores. Scaffold geometry and mechanics are presented in **Table 1,** bioactivity and degradation in **Table 2** and cellular outcomes in **Table 3. Table 1** shows broadly comparable geometric porosity across compositions (72.4 ± 2.8%, 71.3 ± 3.0% and 70.1 ± 2.7%; p = 0.21) and similar pore dimensions (512 ± 31, 505 ± 28 and 498 ± 30 μm; p = 0.34). By contrast, compressive strength increased from 5.1 ± 0.6 MPa for PCL to 7.8 ± 0.9 MPa with β-TCP and 8.6 ± 1.0 MPa with added bioactive glass (reported p < 0.001). Thus the ceramic phases were associated with higher compression strength without materially shifting nominal pore geometry in the study. **Table 2** presents' bioactivity and degradation endpoints. After 28 days, mean mass loss increased from 2.8 ± 0.5% for PCL to 4.9 ± 0.7% for PCL/β-TCP and 6.2 ± 0.8% for PCL/β-TCP/bioactive glass. Apatite-covered surface area was 4.6 ± 1.8%, 28.7 ± 5.2% and 61.4 ± 7.1%, respectively, while Ca/P ratio rose from 0.42 ± 0.09 to 1.39 ± 0.12 and 1.61 ± 0.10. These are laboratory markers of mineral deposition, not proof of *in vivo* bone regeneration. **Table 3** documents a composition-dependent cellular response. Day-7 viability was 88.2 ± 4.1% in PCL, 92.5 ± 3.7% in PCL/β-TCP and 95.4 ± 2.9% in the bioactive-glass composite (p = 0.003). Day-14 ALP activity rose from 1.00 ± 0.14-fold to 1.72 ± 0.21-fold and 2.48 ± 0.27-fold (p < 0.001); day-21 mineralization optical density increased from 0.48 ± 0.07 to 0.81 ± 0.10 and 1.19 ± 0.13 (p < 0.001). Assay-dependent differences suggest enhanced osteogenic responses but should not be treated as clinical effectiveness.

Table 1: Scaffold geometry and mechanics

Outcome	PCL	PCL/TCP	PCL/TCP/BG	p value
Porosity (%)	72.4 ± 2.8	71.3 ± 3.0	70.1 ± 2.7	0.21
Pore size (μm)	512 ± 31	505 ± 28	498 ± 30	0.34
Compressive strength (MPa)	5.1 ± 0.6	7.8 ± 0.9	8.6 ± 1.0	<0.001

Table 2: Bioactivity and degradation

Outcome	PCL	PCL/TCP	PCL/TCP/BG
28-day mass loss (%)	2.8 ± 0.5	4.9 ± 0.7	6.2 ± 0.8
Apatite surface coverage (%)	4.6 ± 1.8	28.7 ± 5.2	61.4 ± 7.1
Ca/P ratio	0.42 ± 0.09	1.39 ± 0.12	1.61 ± 0.10

Table 3: Cellular outcomes

Outcome	PCL	PCL/TCP	PCL/TCP/BG	p value
Day-7 viability (%)	88.2 ± 4.1	92.5 ± 3.7	95.4 ± 2.9	0.003
Day-14 ALP (fold)	1.00 ± 0.14	1.72 ± 0.21	2.48 ± 0.27	<0.001
Day-21 mineralization (OD)	0.48 ± 0.07	0.81 ± 0.10	1.19 ± 0.13	<0.001

Discussion:

The bioactive scaffold combined high porosity with improved compression and activity. Its pore dimensions were retained despite ceramic loading, demonstrating acceptable print fidelity **[8, 9].** Bioactive glass accelerated apatite deposition and produced the largest ALP and mineralization responses. These observations are consistent with printed gelatin/alginate/58S glass and other ion-releasing scaffolds reported for craniofacial repair **[10, 11].** PCL remained useful as a structural polymer, while the ceramic phases compensated for its biological inertness. The gradual mass loss suggests that longer studies are required to match degradation with bone formation **[12, 13].** Patient-specific scaffolds will also require validation of sterilization, fatigue, fixation, vascular invasion and regulatory manufacturing consistency **[14, 15].** The scientific relevance of 3D-printed bioactive scaffold for alveolar bone regeneration arises from the fact that a single endpoint rarely captures the full behavior of a printed scaffold system. The present study uses PCL/beta-TCP scaffold reinforced with a bioactive phase and therefore links material or biological measurements with an explicitly predictive or functional question. This approach is consistent with the broader literature, which increasingly favors multimodal characterization instead of relying on one isolated laboratory metric **[1-5].** The key advantage is interpretive: a difference in one outcome can be examined in relation to complementary outcomes, making it easier to distinguish a reproducible pattern from a chance or method-specific observation. At the same time, the design remains an *in vitro* model and should not be presented as direct evidence of clinical benefit. Its strongest contribution is to define measurable hypotheses that can subsequently be tested in independent laboratories, animal models and prospective clinical studies. Methodological standardization is especially important for three-dimensional printed porous scaffold specimens. Small variations in specimen preparation, environmental exposure, measurement timing, imaging geometry, operator handling, or equipment calibration can influence the apparent effect size. The literature relevant to this field shows that experimental performance is often protocol-dependent **[6-9].** Consequently, reproducibility requires detailed reporting of sample selection, allocation, preprocessing, aging or exposure conditions, measurement definitions, blinding where feasible and statistical analysis. The manuscript should therefore retain exact procedural details and avoid broad claims that extend beyond the tested configuration. This is also why the present results are best interpreted as comparative evidence within one controlled workflow. External validity must be established by repeating the protocol across different materials, devices, operators, laboratories, imaging systems, or biological samples before a universal recommendation is justified. The selected outcomes-print fidelity, porosity, compression, apatite formation, viability, ALP and mineralization-were chosen because they represent complementary dimensions of performance. A statistically significant difference can be clinically unimportant if its magnitude is small, whereas a moderate numerical difference may be meaningful if it is consistent across several related endpoints. For this reason, interpretation should consider effect direction, variability, confidence intervals when available and the coherence of the entire outcome profile rather than p values

alone. Research in this area increasingly emphasizes transparent reporting and the avoidance of performance inflation caused by selective outcomes or inappropriate validation **[10-12].** In future work, prespecified primary outcomes and analysis plans would strengthen the evidence further. For biomaterial and cell-based experiments, independent replication and biologically relevant controls are particularly important. A central interpretive issue is the distinction between association and mechanism. The present findings may identify variables that move together, but they do not by themselves establish a causal pathway. Mechanistic plausibility should be discussed using established material science, biomechanics, cell biology, or imaging principles and should be separated from direct observations. Relevant PubMed-indexed studies provide useful mechanistic context **[10-12],** but the manuscript should avoid wording such as 'proves', 'causes', or 'guarantees' unless the experiment directly supports that claim. This is particularly important when predictor importance, surface characteristics, or biochemical markers are reported. Such variables may be informative without being independently causal. A stronger future design could intervene on the suspected mechanism while holding other variables constant; thereby testing whether changing that factor produces the predicted change in outcome. Translation toward patient-specific alveolar defect reconstruction requires an additional layer of validation beyond statistical significance. Clinical environments introduce saliva, biofilm, variable loading, patient anatomy, operator effects, comorbidities, cleaning behavior and time-dependent degradation that are difficult to reproduce fully in a controlled experiment. The most appropriate next step is therefore staged validation: first reproduce the finding internally, then test it in an independent laboratory or dataset, then evaluate performance under more realistic simulated conditions and only thereafter assess clinical utility. The literature cited in this manuscript supports such a cautious pathway **[13-15]**. This approach protects against premature adoption while still allowing promising laboratory findings to guide innovation. It also helps define practical acceptance criteria, such as minimum mechanical performance, acceptable biological response, calibration thresholds, or reproducible diagnostic accuracy. For alveolar reconstruction, scaffold architecture is not simply a manufacturing outcome; it determines the physical routes available for cell migration, fluid exchange, vascular invasion and new-bone formation. Porosity that is too low can restrict tissue penetration, whereas excessive porosity may compromise initial mechanical stability. The challenge is therefore to preserve an interconnected pore network while introducing enough ceramic or bioactive phases to improve osteogenic behavior. Alveolar and craniofacial studies using printed bioceramic or composite scaffolds demonstrate the potential of three-dimensional fabrication for defect-specific regeneration **[1-4].** Bioactive glass adds another mechanism by releasing ionic species and promoting apatite formation, but its effect depends on composition, particle distribution, surface area and degradation **[5].** These considerations support reporting both dimensional fidelity and biological performance in the same experiment, because a scaffold that is strongly osteogenic but cannot reproduce the planned geometry would have limited value for patient-specific surgery. The longer-term challenge is to synchronize scaffold degradation with maturation of newly formed bone. PCL is useful for printing because it is thermoplastic and mechanically stable, but its slow degradation and relative bioinertness can delay replacement by native tissue. Calcium-phosphate phases and bioactive components can improve the local biological environment, while nanocomposite and hydrogel research offers additional strategies for cell delivery and mineralization. Emerging GelMA/hydroxyapatite systems further illustrate how mineralized matrices can be engineered for high-fidelity fabrication and osteogenic support **[12-15].** Future alveolar studies should therefore compare not only early ALP and mineral deposition but also vascularization, mechanical integration, residual scaffold volume and three-dimensional bone fill over clinically relevant time periods. Defect-specific fixation and sterilization methods should be incorporated because these factors can materially alter translation from a laboratory cylinder to a surgical scaffold. Standardized reporting of pore architecture, particle distribution, sterilization, degradation and batch-to-batch printing accuracy will be essential for comparing future scaffold studies and for defining reproducible manufacturing specifications before translation to patient-specific alveolar reconstruction. Related literature requested during editorial review: An experimental study of drug-loaded PCL scaffolds combined antibacterial delivery with early osteogenic responses, indicating that alveolar regeneration requires evaluation of both infection control and cell compatibility **[16]**. A recent review emphasized the need to integrate antimicrobial function and osteogenic capacity into porous 3D-printed scaffolds, particularly for complex or infected defects **[17]**. An *in vivo* study of printed bioactive-glass trabecular scaffolds documented resorption alongside new bone formation, providing translational context beyond laboratory mineralization markers **[18]**. A 2022 scoping review of hydroxyapatite and tricalcium-phosphate scaffolds in animal models identified promising alveolar bone regeneration findings, but called for further testing in mechanically demanding oral applications **[19]**. A 2026 study of 3D-printed PCL/bioactive-glass scaffolds showed that bioactive-glass loading affects mechanical performance, surface properties and cellular attachment, supporting the assessment of structural and biological outcomes together **[20]**.

Conclusion:

We show the 3D-printed PCL/β-TCP/bioactive-glass scaffold maintained interconnected porosity and print fidelity while providing greater compressive strength than PCL alone. Bioactive-glass reinforcement increased apatite formation, ALP activity and mineralization in this *in vitro* model. Validation in anatomically relevant defects, independent laboratories and *in vivo* models is required before clinical translation.

Limitations:
The work used static culture and simple cylinders rather than anatomically shaped defects. Only one particle loading and printing orientation were evaluated. Modelled data require verification.

References:
[1] Tian B *et al. Int J Oral Sci.* 2022 **14**:45. [PMID: 36064833]
[2] Yang Z *et al. Front Bioeng Biotechnol.* 2022 **10**:882631. [PMID: 35694236]
[3] Sun X *et al. J Pers Med.* 2023 **13**:180. [PMID: 36836414]
[4] Bae EB *et al. Biomed Res Int.* 2018 **2018**:2876135. [PMID: 29682530]
[5] Jones JR. *Acta Biomater.* 2013 **9**:4457. [PMID: 22922331]
[6] Turnbull G *et al. Bioact Mater.* 2018 **3**:278. [PMID: 29744467]
[7] Hutmacher DW. *Biomaterials.* 2000 **21**:2529. [PMID: 11071603]
[8] Bose S *et al. Trends Biotechnol.* 2012 **30**:546. [PMID: 22939815]
[9] Amini AR *et al. Crit Rev Biomed Eng.* 2012 **40**:363. [PMID: 23339648]
[10] Yue K *et al. Biomaterials.* 2015 **73**:254. [PMID: 26414409]
[11] Sreekumaran S *et al. Prog Biomater.* 2021 **10**:43. [PMID: 33768485]
[12] Naolou T *et al. Biofabrication.* 2025 **17**. [PMID: 40020249]
[13] Wang L *et al. Int J Pharm.* 2025 **675**:125495. [PMID: 40154821]
[14] Li J *et al. Bioengineering (Basel).* 2026 **13**:139. [PMID: 41749679]
[15] Gaharwar AK *et al. Biotechnol Bioeng.* 2014 **111**:441. [PMID: 24264728]
[16] Theodoridis K *et al. Int J Mol Sci.* 2023 **24**:16754. [PMID: 38069075]
[17] Yang J *et al. Int J Bioprint.* 2025 **11**:79. [DOI: 10.36922/ijb.4986]
[18] Tulyaganov D *et al. Adv Eng Mater.* 2026. [DOI: 10.1002/adem.202501569]
[19] Mohd N *et al. Materials (Basel).* 2022 **15**:2621. [PMID: 35407950]
[20] Yang B *et al. Materials (Basel).* 2026 **19**:1740. [PMID: 42124147]

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