Advanced Sr-HT-Gahnite bioceramic scaffolds: Integrating 3D printing, microstructural modelling, and machine learning toward functional bone regeneration

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1. Introduction

Developing bioceramic scaffolds that simultaneously provide mechanical robustness, interconnected porosity, and biological functionality remains a major challenge in bone tissue engineering. Sr-HT-Gahnite ($Sr_2ZnSi_2O_7$–$Ca_2ZnSi_2O_7$), an emerging bioactive ceramic, has shown strong potential because of its superior mechanical performance, controlled ionic release, and high osteoconductivity compared with conventional clinical bioceramics.[1-3] This study presents an integrated digital–experimental strategy that combines 3D printing, microstructural analysis, and machine learning to design Sr-HT-Gahnite scaffolds for enhanced bone regeneration.

An integrated workflow was developed to convert micro-CT images of bone into 3D models that reproduce trabecular architecture and porosity with high fidelity. Raw image datasets were first preprocessed to reduce artefacts, followed by segmentation of bone and pore regions and alignment along a normalised depth axis extending from the cartilage surface to the trabecular interior. Depth-dependent structural features, including local porosity and curvature, were then extracted from the processed datasets. Machine-learning models were trained on these descriptors to identify geometric and connectivity patterns across depth, providing design guidance for new scaffold architectures and vascular networks. The optimised scaffold designs were fabricated using an Sr-HT-Gahnite ceramic slurry via LCD-based 3D printing.[4] After sintering, the resulting constructs exhibited dense microstructures with well-interconnected pores. This workflow establishes a data-driven bridge between imaging, machine learning, and fabrication, enabling the reproducible design of biomimetic scaffolds for bone regeneration.

2. Sr-HT Gahnite powder synthesis

Sr-HT-Gahnite ceramic powder was prepared using a controlled sol–gel process to ensure compositional homogeneity and good processability. TEOS hydrolysis and acidification were first carried out under an ice bath to control precursor reactivity, after which the dissolved metal salt solution was slowly introduced to achieve uniform mixing. The resulting sol was then subjected to sequential ageing at room temperature for 5 hours, 60°C for 24 hours, and 120°C for 3 days. This stepwise treatment promoted gel formation, solvent evaporation, and precursor network consolidation, while helping to minimise cracking and inhomogeneity during drying.

The dried gel was subsequently transferred to a crucible and sintered at 1200°C for 3 hours to form the ceramic phase. Ball milling and sieving were then applied to break down agglomerates and obtain a more uniform powder fraction. These steps were critical for improving powder dispersity and ensuring compatibility with ceramic slurry preparation and LCD-based 3D printing. The overall fabrication route therefore enabled the production of Sr-HT-Gahnite powder with suitable structural uniformity and processing characteristics for scaffold manufacture.



Figure 1 Schematic of Sr-HT Gahnite ceramic powder synthesis

3. Design and modeling of the bone section of scaffold

Micro-CT image stacks of native bone were processed to reconstruct trabecular architecture and pore organisation in 3D. After artefact reduction, bone and pore regions were segmented and aligned along a normalised depth axis from the cartilage surface to the trabecular interior. Structural descriptors, including local porosity, curvature, and pore distribution, were then extracted to quantify depth-dependent variations in bone microarchitecture. These datasets were used to train machine-learning models that captured geometric and connectivity patterns, providing design rules for biomimetic scaffold and vascular network generation.

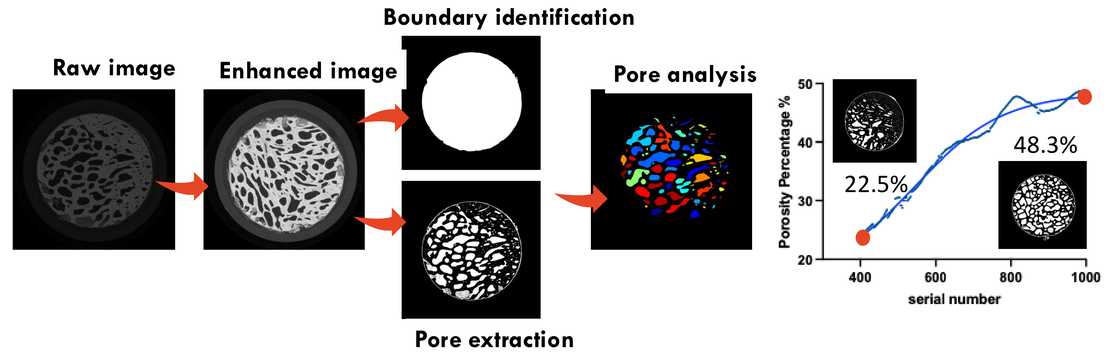


Figure 2 (a) image processing of Micro CT images; (b.) Porosity trend from cartilage layer to the trabecular bone section.

4. Design and optimising of lattice section

Lattice topology had a strong effect on both the thickness needed to maintain 65% porosity and the simulated mechanical response. Strut-based lattices such as BCC, FCC, and simple cube generally required thicker members, while TPMS lattices including Gyroid, Schwarz, and Lidinoid maintained the target porosity with thinner continuous walls. Larger and cylindrical cell mappings increased stress response in several strut-based lattices, especially BCC and FCC, indicating higher sensitivity to geometric variation. By comparison, TPMS lattices showed a more stable response while preserving smooth, highly interconnected pore networks. These features make TPMS-based designs more suitable for biomimetic scaffold development.

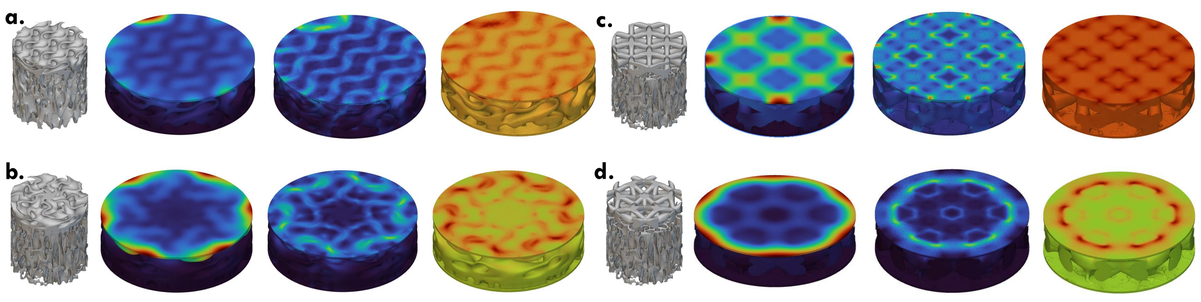


Figure 3 Scaffold preview (porosity consisted with 65%), FEA simulation results of deformation, strain, and stress illustration of Gyroid model with (a) rectangular cell mapping (b) cylinder cell mapping, Body Centered Cubic model with (a) rectangular cell mapping (b) cylinder cell mapping.

5. LCD based scaffold 3D printing

Sr-HT-Gahnite powder was dried, sieved (~5 µm) and dispersed into a photocurable resin system containing Aqua Clear resin and Darvan 811 surfactant to prepare a printable ceramic slurry. The mixture was homogenised by ball milling to ensure stable dispersion and suitable rheology for LCD-based printing. Scaffolds were then fabricated by layer-by-layer LCD vat photopolymerisation on a silanised glass-supported build platform.

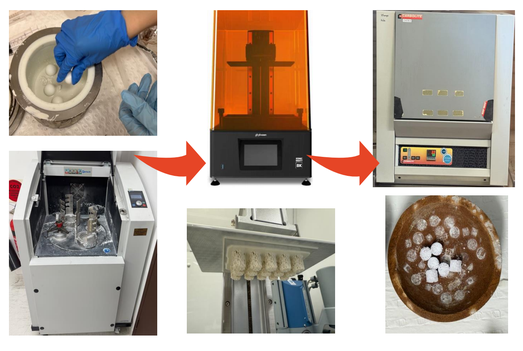


Figure 2 Schematic of Sr-HT Gahnite ceramic scaffold 3D printing

5. Conclusion & future experiments

An integrated workflow combining micro-CT bone modelling, machine learning, and LCD-based 3D printing was developed to design and fabricate biomimetic Sr-HT-Gahnite scaffolds. This approach enabled the translation of native trabecular bone features into scaffold architectures with controlled porosity and structural relevance, while establishing a reproducible route from ceramic powder processing to sintered scaffold fabrication. Future studies will refine the machine-learning design framework by incorporating more advanced descriptors of pore connectivity and vascular organisation, and will further evaluate scaffold performance through mechanical, physicochemical, and biological testing.

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