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Design and Development of Bioactive Scaffold for the Repair of Bone Fracture by 3D Printing

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***Abstract*—Bone defects caused by trauma or disease pose significant challenges in orthopaedictreatment, with traditional grafts limited by donor site morbidity and availability. This study develops 3D-printed scaffolds using a novel polylactic acid-calcium composite filament, termed Simubone, to enhance bone regeneration. Scaffolds were designed via computer-aided design, fabricated using fused deposition modeling 3D printing, and tested for mechanical properties at infill density of 40 percent, 50 percent, and 80 percent. Tensile testing showed peak strength at 50 percent infill with 2.49 megapascals for the triangle pattern, while impact testing indicated optimal energy absorption at 80 percent infill with 1.79 kilojoules per meter for the octo-gram pattern. Compression tests revealed higher resistance at 80 percent infill with 43.34 megapascals. Auxetic structures improved flexibility and crack resistance. The calcium reinforcement enhances osteoconductivity, making Simubone a promising material for bone repair. Future work includes biocompatibility testing and clinical validation to translate this technology into orthopaedic applications.**

***Keywords*—Bone Tissue Engineering, 3D Printing, Polylactic Acid-Calcium Composite, Scaffolds.**

I. INTRODUCTION

Bone defects resulting from trauma, degenerative diseases, or surgical interventions pose significant challenges in orthopaedic treatment. Traditional bone grafting methods, such as auto grafts and allografts, are limited by donor site morbidity, immune rejection, and supply constraints.

Auto grafts, considered the gold standard, require dual surgeries, increasing patient morbidity, while allografts carry risks of disease transmission and immune responses. These limitations necessitate engineered alternatives that can mimic the structural and biological properties of native bone, offering patient-specific solutions with minimal complications.

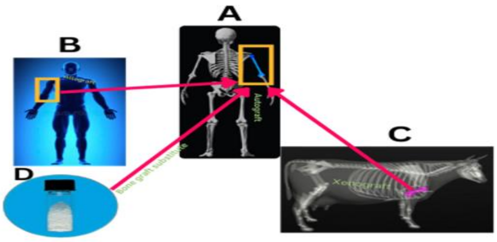

Fig 1 Three main categories of bone grafts namely autograft taken from the patient's body itself, allograft taken from another body of the same species, and xenograft taken from another body of a different species.

Additive manufacturing, specifically three-dimensional printing, has emerged as a transformative approach in bone tissue engineering. It enables the fabrication of scaffolds with tailored porosity, geometry, and mechanical properties, addressing the shortcomings of conventional grafts. This study introduces a novel polylactic acid-calcium composite filament, termed Simubone, which integrates calcium fillers to replicate bone's mineral composition. Unlike standard polylactic acid, Simubone enhances osteoconductivity and mechanical strength, making it a promising material for bone repair scaffolds. The incorporation of auxetic structures further improves flexibility and load distribution, mimicking the hierarchical architecture of bone.

The objectives of this study are to: (1) design three-dimensional-printed scaffolds using computer-aided design based on bone defect models, (2) fabricate scaffolds via fused deposition modelling with varying infill density, (3) evaluate mechanical properties through tensile, compression, and impact testing, and (4) assess the potential of Simubone scaffolds for bone regeneration.

II. LITERATURE SURVEY

The development of effective solutions for bone defect repair has been a focal point in orthopaedic research, driven by the limitations of traditional bone grafting methods. Auto grafts, while osteoinductive and osteoconductive, are hindered by donor site morbidity and limited availability [1]. Allografts, conversely, pose risks of immune rejection and disease transmission, necessitating alternatives that can replicate bone's structural and biological properties [2]. Recent advancements in bone tissue engineering have focused on biomimetic scaffolds to address these challenges, with additive manufacturing emerging as a promising approach.

Three-dimensional (3D) printing, particularly fused deposition modeling (FDM), enables the fabrication of patient-specific scaffolds with controlled porosity and geometry. Hollister [3] highlighted the importance of scaffold architecture, noting that porosity levels of 60–90% and pore sizes of 100–500 micrometers are critical for cell infiltration and nutrient diffusion. However, achieving mechanical

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properties comparable to native bone (e.g., 2–12 megapascals for trabecular bone) remains a challenge [4]. Polylactic acid (PLA) is widely used in 3D-printed scaffolds due to its biodegradability and ease of processing, but its limited bioactivity restricts its efficacy in bone regeneration [5].
To enhance scaffold performance, researchers have explored composite materials incorporating bioactive fillers. Bose et al. [6] demonstrated that calcium-based additives, such as hydroxyapatite, improve osteoconductivity by mimicking bone's mineral composition, though challenges in uniform dispersion persist. Auxetic structures, characterized by a negative Poisson's ratio, have also gained attention for their ability to enhance flexibility and load distribution. Rosetti et al. [7] reported that auxetic scaffolds reduce stress shielding, improving long-term integration with host tissue. Despite these advances, few studies have combined calcium-reinforced composites with auxetic designs in FDM-printed scaffolds, particularly for optimizing both mechanical and biological properties.
Current literature underscores the need for scaffolds that balance mechanical strength, biocompatibility, and manufacturability. While PLA-based composites show promise, their mechanical performance often falls short of cortical bone requirements, and biocompatibility testing remains limited [8]. Additionally, the scalability of 3D printing for clinical applications is underexplored, with most studies focusing on prototype development rather than translational outcomes. This study addresses these gaps by developing a novel PLA-calcium composite filament (Simubone) for FDM-printed scaffolds, incorporating auxetic structures to enhance mechanical and biological performance, and evaluating their suitability for bone defect repair through comprehensive mechanical testing.

III. METHODOLOGY

A. Materials The scaffold material is a novel polylactic acid-calcium composite filament, termed Simubone, with a diameter of 1.75 millimetres. Simubone was selected for its biocompatibility and ability to mimic bone's mineral content, combining the biodegradability of polylactic acid with calcium fillers to enhance osteoconductivity and mechanical strength. This addresses the limitations of standard polylactic acid, which lacks sufficient bioactivity for bone repair applications.

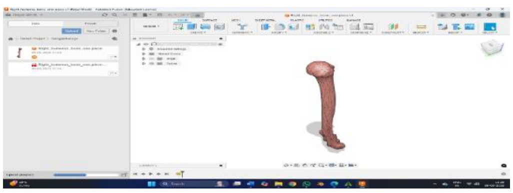

Fig:2,3,4, Bone design using Autodesk Fusion

B. Scaffold Design

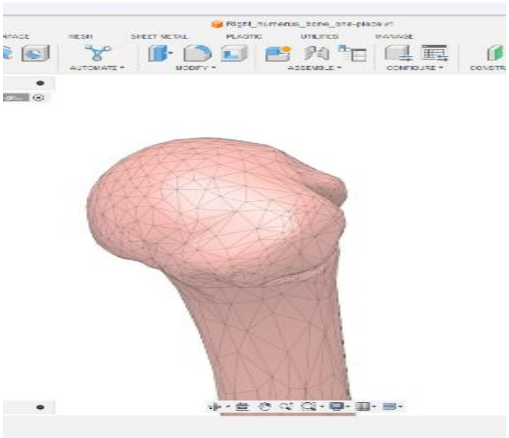

Fig:3

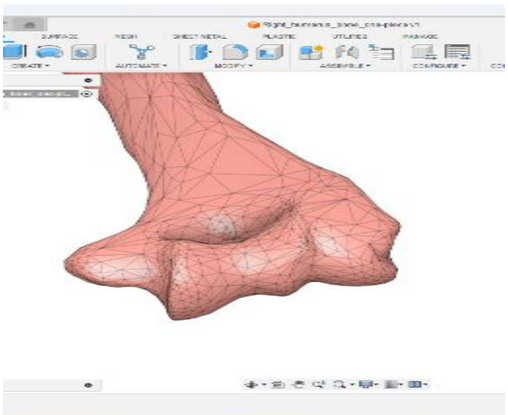

Fig:4

Scaffolds were designed using AutoCAD software, based on bone defect models derived from computed tomography or magnetic resonance imaging scans. The designs incorporated auxetic structures with a negative Poisson's ratio to improve flexibility and load distribution under mechanical stress. Porosity was maintained at 70 to 90 percent, with pore sizes ranging from 100 to 500 micrometers, to facilitate cell infiltration and nutrient flow. The models were exported in STL format for three-dimensional printing.

C. Fabrication Scaffolds were fabricated using fused deposition modeling on a three-dimensional printer. Printing parameters included a nozzle temperature of 200 to 220 degrees Celsius, a bed temperature of 60 to 70 degrees Celsius, a layer height of 0.2 millimeters, and infill density of

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40 percent, 50 percent, and 80 percent. Two infill patterns, triangle and octo-gram, were tested to evaluate their impact on mechanical properties. Post-processing steps included support removal, cleaning with isopropyl alcohol, and sterilization via ultraviolet treatment to ensure biocompatibility.

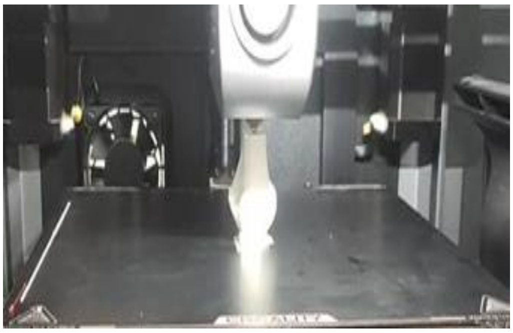

Fig:5 Fused deposition modeling process for Simubone scaffolds, illustrating layer-by-layer deposition of the polylactic acid-calcium filament.

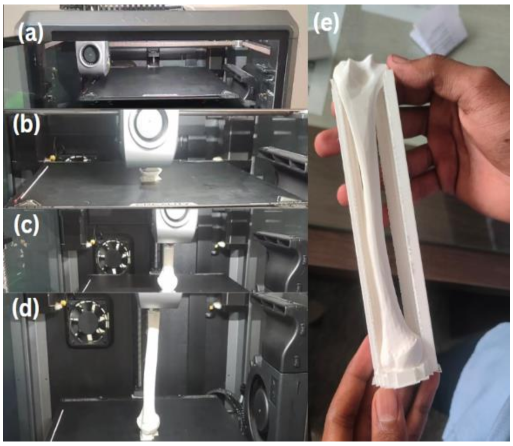

Fig:6 Printing Process

Fig:7 3D printing machine with model

D. Mechanical Testing Mechanical properties were evaluated according to ASTM standards. Tensile tests, per ASTM D638, used Type I specimens measuring 165 millimeters by 13 millimeters by 3.2 millimeters, with a loading rate of 4 millimeters per minute. Impact tests, per ASTM D256, used Izod specimens measuring 63.5 millimeters by 12.7 millimeters by 3.2 millimeters. Compression tests used cubic specimens of 2.5 centimeters by 2.5 centimeters by 2.5 centimeters. Tests were conducted for each infill pattern and density, with three specimens per group to ensure statistical reliability.

IV. RESULTS AND DISCUSSION

A. Tensile Strength

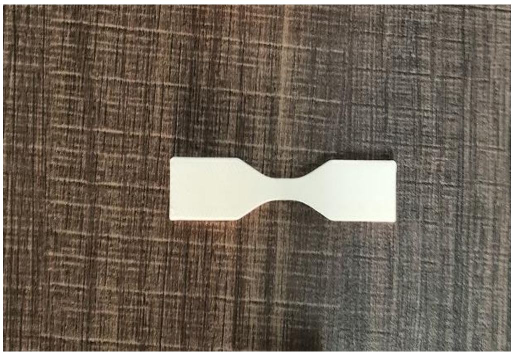

Fig:8 Tensile Specimen

Tensile tests were conducted to evaluate the influence of infill density and pattern on the mechanical performance of Simubone scaffolds. Results are summarized in Table I. The triangle infill pattern at 50 percent infill achieved the highest tensile strength of 2.49 megapascals, with a percent elongation of 1.93. The octo-gram pattern peaked at 50 percent infill with 2.24 megapascals and 1.12 percent elongation. At 80 percent infill, both patterns exhibited reduced strength, likely due to internal stress concentrations caused by denser filament packing.

B. Impact Strength

Fig:9 Impact test Specimen

Impact tests assessed the energy absorption capacity of the scaffolds,
The octo-gram pattern at 80 percent infill demonstrated the highest impact strength of 1.79 kilojoules per meter, absorbing 0.89 joules of energy. The triangle pattern at 80 percent infill followed closely with 1.63 kilojoules per meter. Lower infill density resulted in reduced energy absorption, indicating that denser scaffolds better withstand sudden impacts.

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C. Compression Strength

Fig:10 Compression test Specimen

Compression tests evaluated the scaffolds' resistance to compressive forces. At 80 percent fill, the triangle pattern exhibited the highest compressive strength of 43.34 megapascals, with a 2.36 percent reduction in length. The octo-gram pattern at 80 percent infill achieved 37.41 megapascals. Lower infill density samples showed greater deformation, suggesting that higher infill density enhances structural integrity under compressive loads.

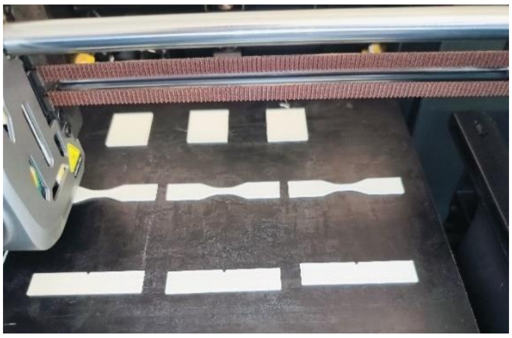

Fig:11 Process and finished 3D model

Materials	Infill pattern	Infill density	Tensile strength MPa	% of Elongation
PLA-Calcium	Triangle	40%	1.9023	1.0214%
PLA-Calcium	Triangle	50%	2.4921	1.9262%
PLA-Calcium	Triangle	80%	2.3012	0.99%
PLA-Calcium	Octo-gram	40%	1.7562	0.92%
PLA-Calcium	Octo-gram	50%	2.2439	1.12%
PLA-Calcium	Octo-gram	80%	1.9431	0.94%

Table I Tensile Testing Results for Simubone Scaffolds

Materials	Infill pattern	Infill density	Energy absorption in J	Impact strength J/mm^2
PLA-Calcium	Triangle	40%	0.2144	0.7157
PLA-Calcium	Triangle	50%	0.4914	0.9928
PLA-Calcium	Triangle	80%	0.8057	1.6278
PLA-Calcium	Octo-gram	40%	0.2054	0.6823
PLA-Calcium	Octo-gram	50%	0.5364	1.1829
PLA-Calcium	Octo-gram	80%	0.8946	1.7914

Table II Impact Testing Results for Simubone Scaffolds

Materials	Infill pattern	Infill density	Compression strength MPa	% of Reduction in Length
PLA-Calcium	Triangle	40%	29.32	2.78%
PLA-Calcium	Triangle	50%	35.91	2.49%
PLA-Calcium	Triangle	80%	43.34	2.36%
PLA-Calcium	Octo-gram	40%	27.61	3.17%
PLA-Calcium	Octo-gram	50%	32.85	2.70%
PLA-Calcium	Octo-gram	80%	37.41	2.58%

Table III Compressive Strength Testing Results for Simubone Scaffolds

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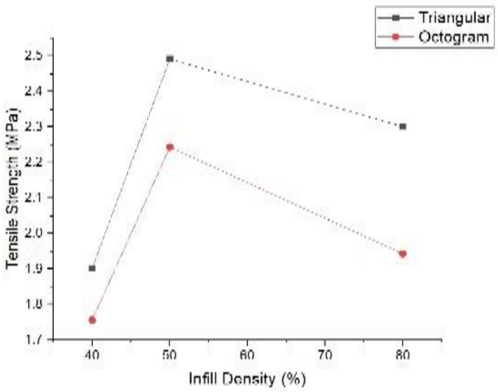

Fig. 12 Tensile Strength of Simubone Scaffolds Across Infill Densities for Triangle and Octo-gram Patterns

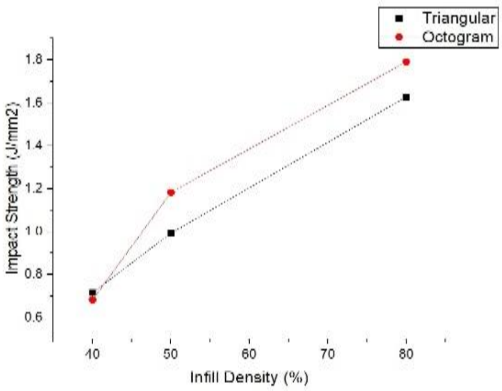

Fig:13 Compressive Strength of Simubone Scaffolds Across Infill Densities for Triangle and Octo-gram Patterns

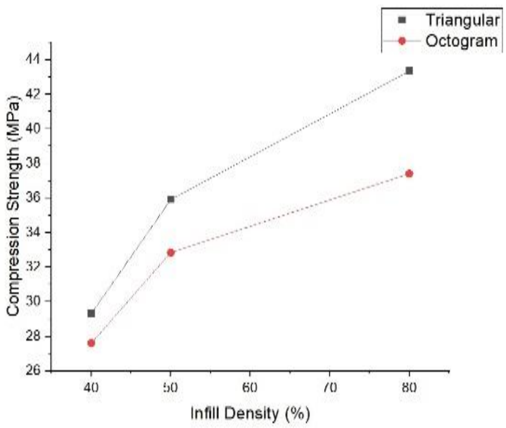

Fig:14 Compressive Strength of Simubone Scaffolds Across Infill Densities for Triangle and Octo-gram Patterns

D. Discussion

The mechanical testing results indicate that Simubone scaffolds with 50 to 80 percent infill density balance strength and flexibility, making them suitable for trabecular bone applications, which typically exhibit compressive strengths of 2 to 12 megapascals. The incorporation of auxetic structures enhanced crack resistance and load distribution, aligning with studies on biomimetic scaffold designs. Compared to standard polylactic acid, which has a tensile strength of 2.5 to 3.5 megapascals, Simubone's calcium reinforcement maintains comparable mechanical performance while improving Osteoconductivity, as the calcium fillers mimic bone's mineral phase. The scaffolds' porosity of 70 to 90 percent and pore sizes of 100 to 500 micrometres support nutrient flow and cell infiltration, critical for bone regeneration. However, the lack of biocompatibility testing limits conclusions about in vivo performance. Future work should include cell viability assays and vascularization studies to validate Simubone's clinical potential.

V. CONCLUSION

This study developed and evaluated three-dimensional (3D)-printed scaffolds using a novel polylactic acid-calcium composite filament, termed Simubone, for bone defect repair. Mechanical testing demonstrated that scaffolds with 50 percent infill density achieved optimal tensile strength of 2.49 megapascals for the triangle infill pattern, while 80 percent infill scaffolds exhibited superior impact strength of 1.79 kilojoules per meter for the octo-gram pattern and compressive strength of 43.34 megapascals for the triangle pattern. These properties align with the mechanical requirements of trabecular bone, which typically ranges from 2 to 12 megapascals in compressive strength [4]. The incorporation of auxetic structures enhanced flexibility and crack resistance, improving load distribution under mechanical stress [7].

The Simubone filament's calcium reinforcement significantly enhances osteoconductivity compared to standard polylactic acid, addressing a critical limitation in bone tissue engineering scaffolds [6]. With porosity levels of 70 to 90 percent and pore sizes of 100 to 500 micrometres, the scaffolds support nutrient flow and cell infiltration, essential for bone regeneration. However, the absence of biocompatibility testing limits current conclusions about in vivo performance. Future work will focus on conducting cell viability assays, vascularization studies, and in vivo trials to validate Simubone clinical applicability. Additionally, optimizing printing parameters to reduce fabrication time and exploring scalability for clinical production are critical next steps.

This work advances personalized orthopaedic solutions by demonstrating the feasibility of 3D-printed Simubone scaffolds for bone repair, offering a promising alternative to traditional grafting methods. By addressing mechanical and biological requirements, Simubone scaffolds pave the way for translational research in bone tissue engineering.

VI. ACKNOWLEDGEMENTS

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