



Computational Design and Multi-Physics Simulation of 3D Printed Nypa Fruticans-shell Powder Biocomposite Scaffolds for Tissue Engineering

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Abstract. Scaffold design for tissue engineering requires an optimal balance between mechanical strength, permeability and biocompatibility. In this study, a sustainable bio-composite scaffold was developed by using Nypa fruticans-shell powder as the base material and optimized through computational design and multi-physics simulation. Various scaffold architectures (gyroid, diamond and cubic) and porosity levels (40-80%) were modeled to evaluate their mechanical and transport behavior. Finite Element Analysis (FEA) was employed to assess compressive stiffness and stress distribution. The results indicate that gyroid scaffolds porosity offers the best balance between structural integrity. It was effective modulus suitable for bone tissue engineering application. This study highlights the potential of natural bio-composites in additive manufacturing for sustainable biomedical applications.

Introduction

Tissue engineering scaffolds must combine mechanical stability with sufficient load bearing to support cell growth and body weight. Additive manufacturing enables precise control of geometry and porosity, which directly influence these properties. Recent studies have shown that optimizing scaffold architecture can enhance both mechanical strength and biological performances [1, 2]. Natural biomaterials have emerged as suitable and biocompatible alternatives to synthetic polymers. For instance, alginate scaffolds have been shown to promote bone regeneration through improved porosity and bioactivity [3,4]. The cuttlefish bone-derived bio-composites demonstrated good mechanical strength and cyto-compatibility [5]. Similarly, hybrid PLA/PCL scaffolds combining computational and experimental approaches have provided valuable insights into the relationships between structure and performance [6]. Natural based biomaterials have attracted growing interest because of their sustainability, low cost and inherent biocompatibility [7-9]. Nypa fruticans fiber has good structural integrity and biodegradability, while shell powder is rich in calcium carbonate and can enhance mechanical strength and osteo-conductivity. These materials offer a sustainable alternative to synthetic polymer in bone scaffold fabrication. However, the computational study of Nypa fruticans shell powder bio-composite scaffolds has not been reported yet. Multi physics of finite element analysis (FEA) can accelerate design iteration and predict structure function relationships before fabrication [10]. Therefore, the objective of this study is to explore the potential of natural bio-composites (Nypa fruticans + shell powder) as an alternative material for tissue engineering scaffold and other purposes of biomedical application.

Methods

The architecture of scaffold design was modeled using parametric computer-aided design (CAD) software. Unit cell size was fixed at 2 mm with variable porosities of 50%, 60% and 70%. Scaffold dimensions were set at $10 \times 10 \times 10 \text{ mm}^3$ for simulation consistency. The material properties for this studies, *Nypa fruticans* shell powder bio-composites were derived from preliminary mechanical characterization. Whereas the elastic modulus 120 MPa, Poisson's ratio 0.3 and density 1.2 g/cm^3 . The biomaterial composition from *Nypa fruticans* and shell powder was arranged by randomized design (CRD) method. The composition of the additional ingredients (solution of glycerol, and sorbitol) was designed at four concentration levels: 3%, 5%, 10%, and 15%. Mechanical simulation was performed using a static compression load of 10 MPa applied on the top surface while the bottom face was fixed. Mesh convergence analysis ensured less than 5% error in stress-strain values. A computer model (represented by a volume model) is sliced into a few layers by CAD software, and each layer of the original model is produced in succession as shown in Fig. 1

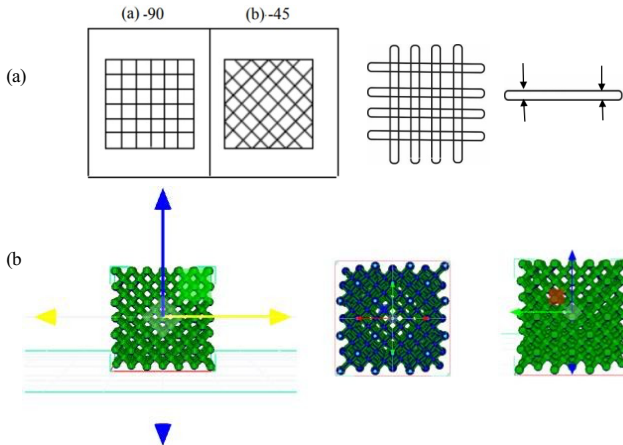


Figure 1. Tissue scaffold CAD parametric models. (a) scaffold patterns (b) CAD Model

Figure 2 depicts a schematic illustration of the 3D porous bio-composite scaffold preparation and characterization as well as the computational design and multi-physics simulation of 3D printed

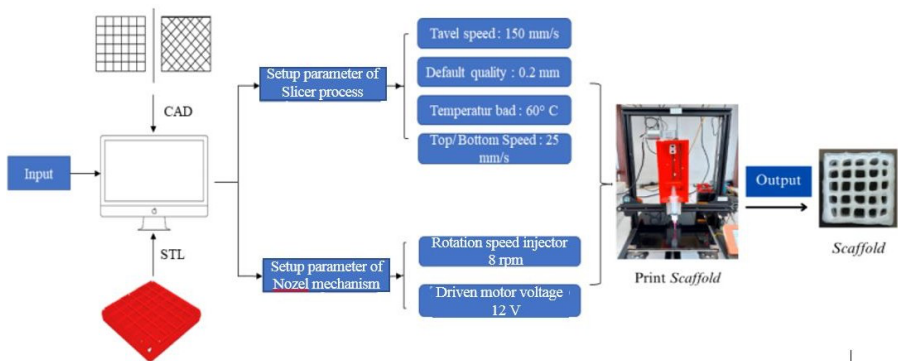


Figure 2. Schematic illustration of the method used to fabricate 3D porous bio-composite scaffolds.

Results and Discussion

The structure scaffolds demonstrated the highest compressive strength across all porosities. At 50% porosity, the maximum stress reached 0.8 MPa with minimal deformation. It indicates that uniform load deformation. The other scaffold structure showed localized stress concentration, particularly near strut joint. A prototype scaffold has a porous structure arranged in a cubic pore pattern. Figure 3 presented the scaffolds in different architecture patterns (90 and 45) that affected physical characteristics.

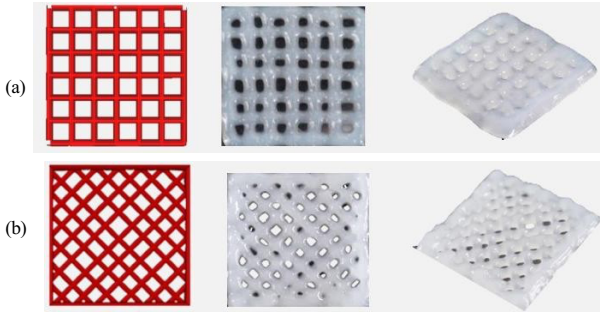


Figure 3. The CAD images of generated scaffold assemblies (a) and fabricated counterparts (b).

The density and porosity test results shown a consistent trend of increasing density bio-composite material concentration. This indicates that the addition of bio-composite material significantly improves the physical properties of the scaffold by increasing its density. Thus, bio-composite material plays a crucial role in strengthening and improving the quality of the scaffold, making it more solid and potentially suitable for use in various biomedical applications.

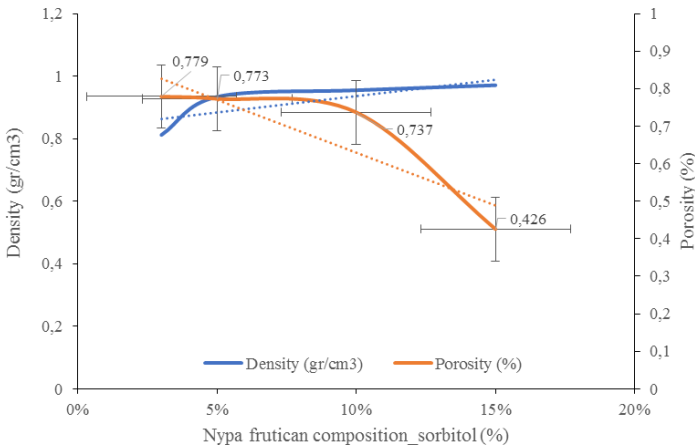


Figure 4. Bio-composite concentration to density and porosity of tissue scaffold

The stress-strain curve shown that bio-composite concentration provides balanced mechanical properties, shown in Fig. 4. A maximum stress of 3.65 MPa and a maximum strain of approximately 19%. The analysis results shown that the mechanical properties prefer cartilage implant applications, as supported by the research of Zhou et al. (2009), tensile strength 3,57 MPa and 12% strain [11].

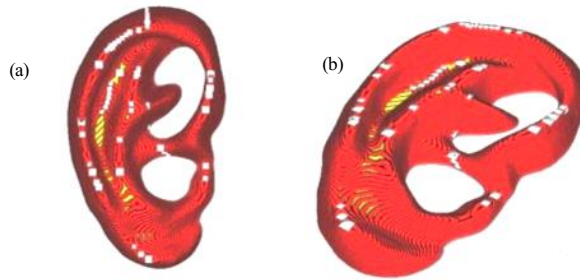


Figure 5. 3D model of human-ear-shaped cartilage. (a) front view, (b) isometric view.

The 3D fabricated bio-composites in which reinforcements are uniformly distributed through the matrix. To optimize amount of filler should be selected, as shown in fabrication 3D bio-printing human ear cartilage based *Nypa fruticans* material (see. Fig. 5 and Fig. 6). 3D-bioprinted ear shaped scaffold with bio composite ink enabling the creation of complex anatomical structure with suitable mechanical strength and biocompatibility for tissue engineering application,

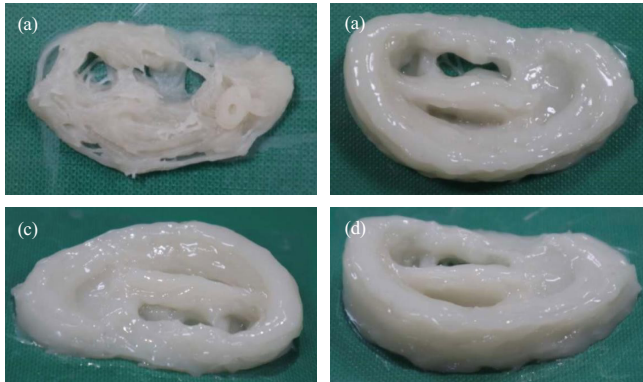


Figure 6. The fabricated 3D bio-printing human ear cartilage based *Nypa fruticans* material. (a) the defect shape, (b) top-view, (c) front-view and (d) side-view after processing.

Conclusion

This study demonstrates the potential of *Nypa fruticans* shell powder as a sustainable biomaterial for 3D printing tissue engineering scaffolds. Multi-physics simulation presenting that architecture of scaffold structure and porosity significantly affects both mechanical strength and fluid transport. The scaffold architecture provides mechanical isotropy and permeability. Intermediate scaffold porosity offers a favorable balance for bone scaffold applications.

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References

- [1] C.I. Codrea, D. Lincu, V.L. Ene, et al., A. Three-Dimensional-Printed Composite Scaffolds Containing Poly- ϵ -Caprolactone and Strontium-Doped Hydroxyapatite for Osteoporotic Bone Restoration. *Polymers*, 16, 1511. (2024).
- [2] F. Liu, T. Li, Z. Jia, and L. Wang, Combination of Stiffness, Strength, and Toughness in 3D Printed Interlocking Nacre-Like Composites, *Extreme Mech. Lett.* 35, 100621. (2020).
- [3] N. Sahai and M. Gogoi, 3D tissue scaffold library development from medical images for bioprinting application, *Materials Today: Proceedings*. Vol. 26, Part 2, pp. 399-404, (2020).
- [4] J. Hatton, G.R.Davis, A-H.I. Mourad, N. Cherupurakal, R.G. Hill, and S. Mohsin. Fabrication of Porous Bone Scaffolds Using Alginate and Bioactive Glass. *Journal of Functional Biomaterials*.10(1):15, (2019).
- [5] V.R. Sivaperumal, S, Sadhasivam, R. Manikandan, I. Pugazhendhi, S. Sekar, Y. Lee, and S. Lee. Cuttlefish-Bone-Derived Hybrid Composite Scaffolds for Bone Tissue Engineering. *Nanomaterials*. 15(3):196. (2025).
- [6] S.V. Kallivokas, L.C. Kontaxis, S. Psarras, M. Roumpi, et al. A Combined Computational and Experimental Analysis of PLA and PCL Hybrid Nanocomposites 3D Printed Scaffolds for Bone Regeneration. *Biomedicines*,12, 261. (2024).
- [7] H. Salleh, M. Hussin, A. Dom, A. Zakaria, and Jufriadi. Natural Hydroxyapatite from Fish Bones and Scales for Biomedical Applications - A Review on Current Progress. *Journal of Power and Energy Engineering*, 14, 1-14. (2026).
- [8] A.T. Guduru, S. Sankaranarayanan, and D. Bhatia. Plant-Based Biodegradable and Biocompatible Polymers for Tissue Engineering Applications. *Carbohydrate Research*. Vol. 558,109699, (2025).
- [9] O. Amponsah, P.S.A. Nopuo, F.A. Manga, N.B. Catli, and K. Labus. Future-Oriented Biomaterials Based on Natural Polymer Resources: Characteristics, Application Innovations, and Development Trends. *Int. J. Mol. Sci.* 26, 5518, (2025).
- [10] D. Calneryte, R. Barauskas, D. Milasiene, et al. Multi-scale finite element modeling of 3D printed structures subjected to mechanical loads. *Rapid Prototyping Journal*, Vol. 24 No. 1 pp. 177–187, (2018).
- [11] J. Zhou, C. Cao, and X. Ma, A novel three-dimensional tubular scaffold prepared from silk fibroin by electrospinning. *International Journal of Biological Macromolecules*, 45(5), 504 - 510. (2009).

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