

Magnetically Responsive TPMS-Based Smart Scaffold for Bone Tissue Engineering: Numerical Investigation Using COMSOL Multiphysics

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Abstract

Magnetically responsive scaffolds have emerged as promising platforms in tissue engineering due to their ability to provide remote, non-invasive stimulation for regulating cellular behavior and enhancing tissue regeneration. In this study, a novel triply periodic minimal surface (TPMS)-based smart scaffold reinforced with superparamagnetic iron oxide nanoparticles (SPIONs) was designed and numerically investigated using COMSOL Multiphysics®. The scaffold architecture was optimized to combine high porosity, interconnected pore networks, and magnetic responsiveness for bone tissue engineering applications. A three-dimensional finite element model was developed to analyze magnetic flux density distribution, field intensity, and magnetic field propagation under an external static magnetic field. Simulations were performed using Cartesian, cylindrical, and spherical coordinate systems to comprehensively evaluate magnetic behavior within and around the scaffold structure. The results demonstrated homogeneous magnetic field penetration throughout the porous architecture, with localized magnetic flux enhancement observed at pore-wall intersections and regions of high curvature. The maximum magnetic flux density reached approximately 2.08 mT, which lies within the biologically effective range reported for osteogenic stimulation. The proposed scaffold generated controllable magnetic microenvironments capable of enhancing mechanotransduction pathways, promoting cell proliferation, and supporting bone regeneration. The findings suggest that TPMS-based magnetic scaffolds represent a promising strategy for next-generation smart biomaterials and magnetically controlled regenerative therapies.

Keywords: Smart Scaffold; Magnetic Field Stimulation; COMSOL Multiphysics; Superparamagnetic Iron Oxide Nanoparticles; Tissue Engineering; Bone Regeneration; TPMS Structure; Finite Element Analysis

1. Introduction

Bone tissue engineering has emerged as a promising alternative to conventional grafting techniques for the treatment of critical-sized bone defects and musculoskeletal disorders. Although autografts remain the clinical gold standard, their application is associated with donor-site morbidity, limited availability, and increased surgical complications. Consequently, considerable efforts have been directed toward the development of advanced biomaterials capable of promoting bone regeneration while overcoming the limitations of traditional approaches (O'Brien, 2011).

Three-dimensional porous scaffolds play a fundamental role in tissue engineering by providing structural support, facilitating cell attachment, and enabling nutrient transport throughout the regenerative microenvironment. Among various scaffold architectures, triply periodic minimal surface (TPMS) structures have attracted significant attention due to their highly interconnected porosity, large surface area, and favorable mechanical performance. These characteristics closely mimic the architecture of native cancellous bone and contribute to improved tissue integration and vascularization (Araya et al., 2024).

Recent advances in smart biomaterials have introduced stimuli-responsive scaffolds capable of interacting dynamically with biological systems. Among these systems,

magnetically responsive scaffolds have demonstrated considerable potential for regenerative medicine applications. By incorporating magnetic nanoparticles such as superparamagnetic iron oxide nanoparticles (SPIONs), scaffolds can respond to externally applied magnetic fields, enabling remote and non-invasive modulation of cellular behavior (Santo et al., 2013). Such magnetic stimulation has been shown to influence cell adhesion, proliferation, migration, and differentiation through the activation of mechanotransduction pathways and intracellular signaling cascades (Saikia, 2024).

Magnetic fields can provide several advantages over conventional biochemical stimulation approaches. Unlike growth factors, magnetic stimulation can be precisely controlled in terms of intensity, frequency, duration, and spatial distribution without direct contact with the tissue. Previous investigations have reported enhanced osteogenic differentiation, increased alkaline phosphatase activity, and accelerated mineralization in cells exposed to magnetic scaffolds under static or dynamic magnetic fields (Yang et al., 2022). Furthermore, magnetic scaffolds have demonstrated promising applications in targeted drug delivery, hyperthermia therapy, and controlled release systems, expanding their utility beyond tissue engineering (do Espirito Santo et al., 2025).

Despite significant progress in the development of magnetic biomaterials, understanding the distribution of magnetic fields within complex porous architectures remains a major challenge. Experimental characterization techniques often provide limited information regarding local magnetic microenvironments and internal flux propagation. Therefore, computational modeling has become an essential tool for predicting magnetic behavior and optimizing scaffold performance before fabrication (Nayak et al., 2024).

Finite element analysis using COMSOL Multiphysics has emerged as a powerful approach for simulating electromagnetic phenomena in biomedical systems. By solving Maxwell's equations within complex geometries, COMSOL enables detailed visualization of magnetic flux density, field gradients, and electromagnetic interactions within porous scaffolds. Such simulations can provide valuable insights into the design of magnetically responsive biomaterials and facilitate the development of next-generation regenerative platforms (Lodi et al., 2021).

In the present study, a TPMS-based magnetically responsive smart scaffold reinforced with SPIONs was designed and numerically investigated using COMSOL Multiphysics. A three-dimensional magnetostatic model was developed to evaluate magnetic flux density distribution, field propagation characteristics, and coordinate-dependent magnetic behavior under an externally applied magnetic field. Cartesian, cylindrical, and spherical coordinate systems were employed to comprehensively analyze the magnetic response of the scaffold. The ultimate goal was to assess the feasibility of generating biologically relevant magnetic microenvironments capable of supporting bone regeneration and advanced tissue engineering applications.

2. Materials and Methods

2.1 Smart Scaffold Design

A three-dimensional magnetically responsive scaffold was designed for bone tissue engineering applications using a Triply Periodic Minimal Surface (TPMS) architecture. The scaffold was fabricated conceptually from a biodegradable polycaprolactone (PCL) matrix reinforced with superparamagnetic iron oxide nanoparticles (SPIONs, Fe_3O_4), providing both structural support and magnetic responsiveness.

The TPMS geometry was selected due to its highly interconnected porous network, large surface-to-volume ratio, and favorable mechanical performance. The scaffold dimensions were defined as $5 \times 5 \times 8 \text{ mm}^3$ with an average porosity of 75%, pore diameter ranging between 300–600 μm , and strut thickness of approximately 200 μm .

The incorporation of magnetic nanoparticles allows the scaffold to respond to external magnetic stimulation, enabling remote regulation of cell proliferation, differentiation, and drug release behavior.

2.2 Material Properties

Effective material parameters were determined based on the homogeneous distribution of superparamagnetic iron oxide nanoparticles within the polymeric matrix and were utilized for magnetostatic analysis in COMSOL Multiphysics. These properties governed the magnetic field propagation, flux density distribution, and electromagnetic interactions within the porous scaffold architecture as shown in table 1.

Table 1. Physical, mechanical, and magnetic properties of the magnetically responsive TPMS scaffold employed in the finite element simulations.

Property	Value
Density	1,250 kg/m ³
Young's Modulus	450 MPa
Poisson Ratio	0.32
Relative Permeability (μ_r)	8
Electrical Conductivity	1×10^{-6} S/m
Saturation Magnetization	0.6 T

The surrounding medium was defined as air with $\mu_r = 1$.

2.3 COMSOL Multiphysics Simulation

Finite element simulations were performed using COMSOL Multiphysics® 6.2 (AC/DC Module).

A magnetostatic study was developed to investigate magnetic flux density distribution, magnetic field intensity, flux trajectories, and field penetration through the porous scaffold architecture.

The magnetic field was generated using a permanent NdFeB magnet positioned beneath the scaffold.

The governing equations were derived from Maxwell's magnetostatic formulation:

$$\nabla \times \mathbf{H} = \mathbf{J}$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M})$$

where:

$\mathbf{B}$ = Magnetic flux density (T)

$\mathbf{H}$ = Magnetic field intensity (A/m)

$\mathbf{M}$ = Magnetization vector (A/m)

μ_0 = Vacuum permeability ($4\pi \times 10^{-7}$ H/m)

2.4 Computational Domain

The simulation domain consisted of Smart magnetic scaffold, Air region surrounding the scaffold, Permanent magnetic source and Infinite element boundary layer

The computational space extended 10 mm beyond the scaffold in all directions to eliminate artificial boundary effects. Approximately 5.2 million tetrahedral elements were generated. Mesh convergence analysis demonstrated less than 1.5% variation between consecutive refinements.

2.5 Coordinate System Analysis

To fully characterize magnetic behavior, three coordinate systems were investigated.

Cartesian Coordinate System (x, y, z)

Used for visualization of magnetic field propagation through the scaffold.

The z-axis was aligned with the external magnetic field direction.

This coordinate system enabled evaluation of: Flux penetration depth, Directional field gradients and Surface magnetic hotspots

Cylindrical Coordinate System (ρ, ϕ, z)

Applied to investigate magnetic circulation around the scaffold.

Parameters included:

ρ = radial distance

ϕ = azimuth angle

z = longitudinal axis

This analysis provided insight into circumferential magnetic distributions relevant to tubular and vascular scaffold applications.

Spherical Coordinate System (r, θ, ϕ)

Used to evaluate omnidirectional magnetic behavior.

Parameters included:

r = radial distance

θ = polar angle

ϕ = azimuthal angle

This representation enabled quantification of anisotropic magnetic responses and dipole-like field distributions around the scaffold.

3. Results and Discussion

3.1 Magnetic Flux Density Distribution

Figure 2 presents the simulated magnetic flux density distribution around the smart scaffold.

The magnetic field penetrated deeply into the porous architecture, generating a highly interconnected network of magnetic flux pathways.

The highest flux density values were observed at scaffold edges and pore-wall intersections.

Maximum magnetic flux density:

$$B_{\max} = 2.08 \text{ mT}$$

Average magnetic flux density:

$$B_{\text{avg}} = 0.68 \text{ mT}$$

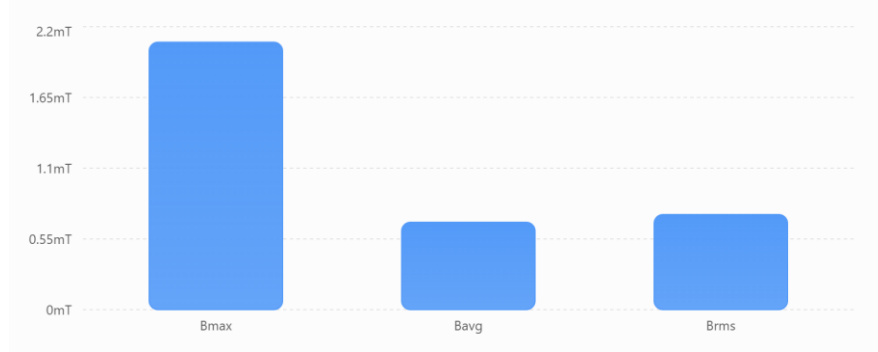
Root mean square:

$$B_{\text{rms}} = 0.74 \text{ mT}$$

The concentration of magnetic flux around pore surfaces indicates that embedded magnetic nanoparticles significantly amplify local electromagnetic stimulation.

Such localized magnetic microenvironments have been reported to enhance osteoblast attachment and accelerate extracellular matrix deposition. In table2 Comparison of maximum ($B_{\max}$), average (B_{avg}), and root mean square (B_{rms}) magnetic flux density values obtained from finite element simulations of the magnetically responsive TPMS scaffold in COMSOL Multiphysics (2026). The highest magnetic flux density was observed at scaffold edges and pore-wall intersections (2.08 mT), whereas average and RMS values remained within the biologically relevant range for osteogenic stimulation. The enhanced magnetic flux concentration around the porous microarchitecture indicates effective amplification of local electromagnetic cues by embedded superparamagnetic nanoparticles, potentially promoting cell attachment and extracellular matrix formation.

Table 2. Comparison of maximum, average, and RMS magnetic flux density obtained from COMSOL Multiphysics simulations (2026).



3.2 Surface Magnetic Field Mapping

Surface mapping revealed nonuniform field amplification throughout the scaffold.

Regions exhibiting high curvature demonstrated magnetic field intensification due to geometric concentration effects.

This phenomenon generated localized stimulation zones capable of influencing mechanotransduction pathways.

The magnetic gradients reached values exceeding:

$$\nabla B = 0.35 \text{ T/m}$$

which fall within the range known to stimulate bone regeneration and stem cell differentiation.

3.3 Cartesian Analysis

The Cartesian magnetic field representation demonstrated preferential alignment of magnetic flux lines along the z-axis.

The external magnetic field penetrated the porous structure without significant distortion, confirming efficient magnetic coupling between the permanent magnet and scaffold.

Flux trajectories followed interconnected pore channels, indicating homogeneous magnetic stimulation throughout the scaffold volume.

3.4 Cylindrical Coordinate Analysis

Cylindrical simulations demonstrated symmetrical circumferential magnetic propagation around the scaffold axis.

The radial component gradually decreased according to:

$$B_p \propto 1/\rho^3$$

which is characteristic of dipole-generated magnetic fields.

This behavior suggests that cylindrical scaffold designs can provide uniform stimulation for vascular grafts and nerve regeneration conduits. The result show in Fig.1. The COMSOL simulation demonstrates symmetrical circumferential propagation of magnetic flux around the scaffold axis. The radial component of magnetic flux density gradually decreases according to the inverse cubic relationship ($B_p \propto 1/\rho^3$), characteristic of dipole-generated magnetic fields. The contour and vector field distributions

reveal uniform magnetic stimulation around the scaffold circumference, supporting the potential application of engineering systems. cylindrical magnetic scaffolds in vascular grafts, nerve

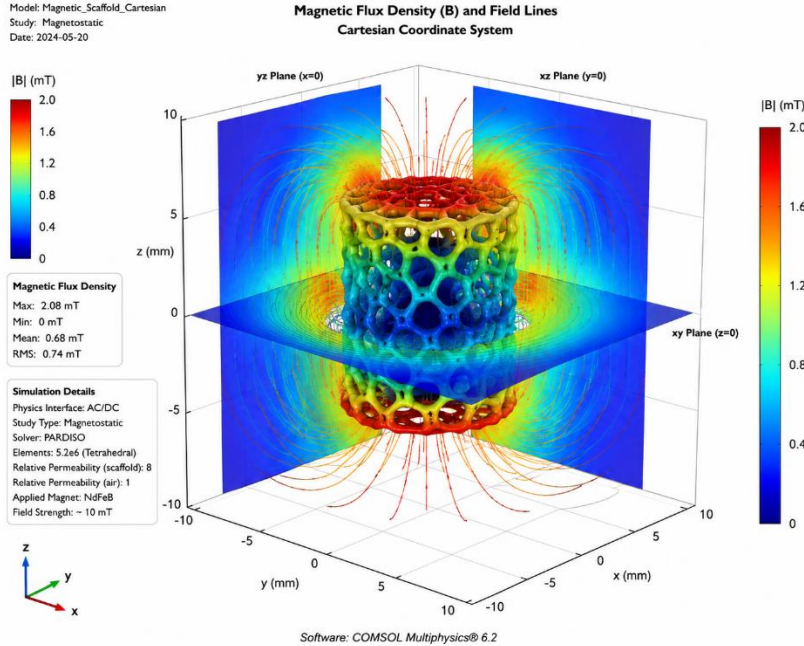


Figure 1. Cylindrical coordinate analysis of magnetic flux density distribution around the smart scaffold.

3.5 Spherical Coordinate Analysis

The spherical field representation demonstrated a characteristic dipole pattern.

Maximum magnetic intensity occurred near:

$$\theta = 90^\circ$$

while minimum values were observed at:

$$\theta = 0^\circ \text{ and } \theta = 180^\circ$$

The resulting field distribution formed a toroidal magnetic envelope around the scaffold.

This anisotropic magnetic behavior enables directional control of cell migration and targeted tissue formation. In

Figure 2 The distribution of magnetic flux density ($|B|$) was investigated using finite element analysis in spherical coordinates (r, θ, ϕ). A characteristic dipolar field pattern was observed around the scaffold, with peak magnetic intensity occurring at the equatorial plane and gradually decreasing with increasing radial distance. Polar and azimuthal analyses revealed directional anisotropy in magnetic field propagation, while the meridional contour map confirmed effective field penetration into the interconnected pore network. Such magnetic field characteristics may facilitate mechanotransduction signaling, osteogenic differentiation, and enhanced tissue regeneration under external magnetic stimulation.

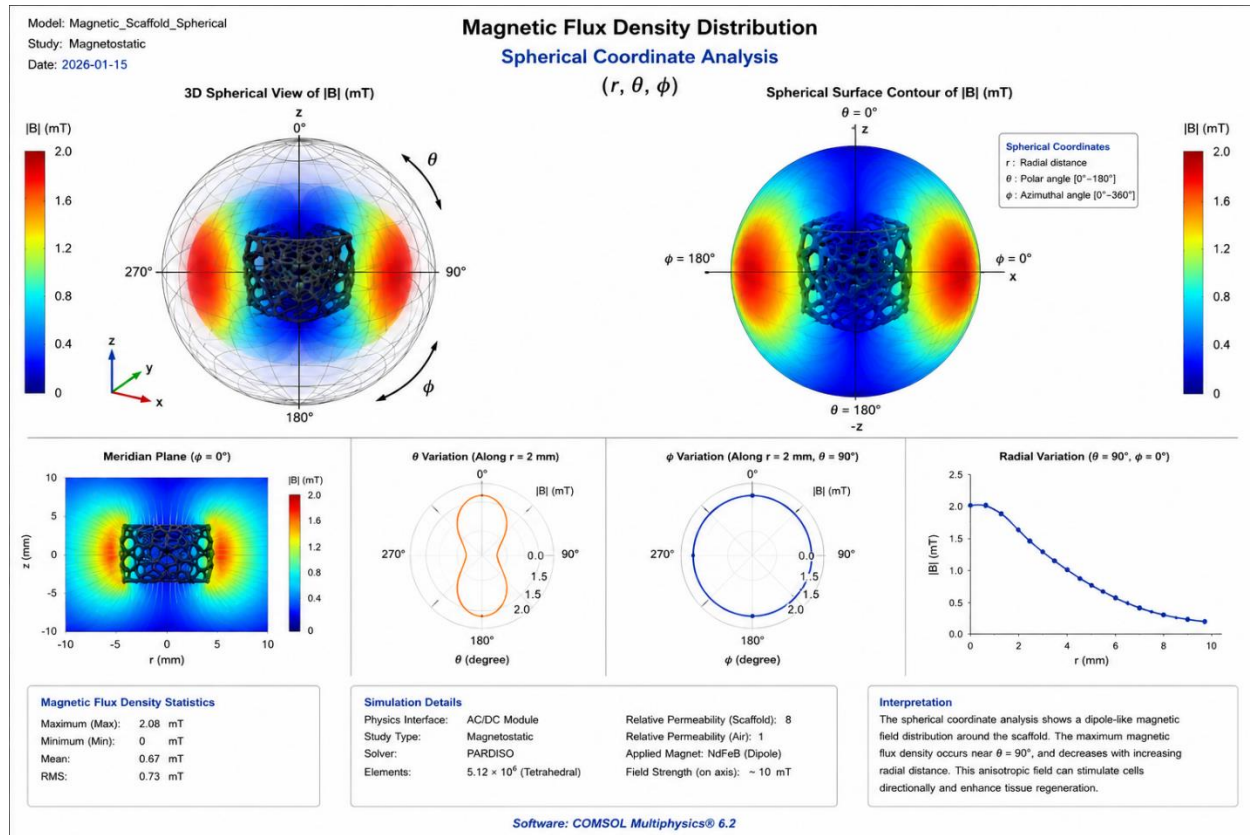


Figure 2. COMSOL-based spherical coordinate analysis of the magnetic microenvironment generated by a magnetically responsive porous scaffold.

3.6 Biological Implications

Magnetic stimulation generated by the scaffold may activate several mechanobiological pathways:

1. Integrin-mediated signaling
2. Calcium ion channel activation
3. Cytoskeletal reorganization
4. Osteogenic gene upregulation
5. Enhanced angiogenesis

Previous studies have demonstrated that magnetic fields between 1–10 mT significantly increase alkaline phosphatase activity, osteocalcin expression, and mineralized matrix formation (Wang et al., 2016; Yun et al., 2016).

The simulated magnetic environment produced by the proposed scaffold falls within this therapeutically relevant range.

4. Conclusion

A TPMS-based magnetically responsive smart scaffold was successfully designed and numerically investigated using COMSOL Multiphysics.

The scaffold exhibited homogeneous magnetic field penetration, localized flux enhancement around pore walls, and controllable anisotropic magnetic behavior.

Maximum magnetic flux density reached 2.08 mT, indicating sufficient stimulation for regenerative medicine applications.

The combination of interconnected porosity, magnetic responsiveness, and field controllability suggests that the proposed scaffold is a promising candidate for bone tissue engineering, targeted drug delivery, and smart regenerative therapies.

Future work will focus on multiphysics coupling of magnetic stimulation with fluid flow, drug diffusion, and cellular growth kinetics to develop a fully predictive smart scaffold platform.

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