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# Bio-Inspired FGPCs for Biomedical and Structural Applications

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***Abstract***

*Bio-inspired functionally graded polymer composites (FGPCs) represent a new class of smart materials that use gradient material distributions to enhance mechanical and biological properties, mimicking natural systems like bones, shells, and plant stems. FGPCs exhibit smooth gradient distributions across interfaces, which improves biocompatibility and reduces the risk of failure under complex loading and environmental conditions. In this study, bio-inspired FGPCs were designed, fabricated, and validated using a combined experimental and computational approach. Polymer matrices reinforced with synthetic and natural fillers were arranged using linear, exponential, and bio-inspired gradation profiles. Mechanical testing (tensile and flexural) and biodegradation studies were conducted in accordance with ASTM standards, and the experimental results were evaluated using finite element simulations. The results demonstrate that exponential and bio-inspired gradation profiles outperform linear gradation in terms of toughness, biodegradation resistance, and stress-transfer efficiency. Compared with conventional composites, tensile strength increased by up to 20%, while residual stresses were reduced by approximately 15%. Numerical predictions showed good agreement with experimental findings, with deviations of less than 5%. Stress distribution and biocompatibility were considered when evaluating the biomedical potential of dental implants and bone scaffolds, while enhanced fatigue resistance was demonstrated in structural applications, including lightweight panels and vibration-damping components. Overall, the combined experimental–computational framework presented in this work provides an effective strategy for optimizing FGPC design for biomedical and structural applications. Future research may focus on additive manufacturing techniques and machine-learning-guided design approaches to develop bio-inspired, customizable FGPCs.*

**Keywords:** Bio-inspired composites, functionally graded polymer composites (FGPCs), biomedical applications, computational validation, stress transfer efficiency

## INTRODUCTION

Bones, shells, bamboo, and plant stems are examples of natural materials that exhibit well-tailored hierarchical structures [1–3]. These materials have coordinated variations across length scales of material properties to achieve superior stress distribution, energy absorption, and splitting resistance. Bio-inspired FGPCs are synthetic materials with spatially variable material properties that incorporate natural or synthetic reinforcements, inspired by these natural systems. FGPCs feature smooth property gradients between the two ends, which can reduce stress concentrations, enhance biocompatibility, and improve load-bearing capacity under service conditions, in contrast to traditional homogenous composites with discrete material interfaces [4–6].

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Because they can be especially promising for use as bone scaffolds [7], dental implants [8], and tissue-engineering constructs, where the delicate balance between mechanical integrity and biological compatibility must be established [9], FGPCs have drawn more attention in the field of biomedical engineering. Natural bone, for instance, gradually shifts from thicker cortical areas to porous cancellous structures that enable efficient stress transmission and good shock absorption [10]. When compared to homogeneous material systems, FGPCs that mimic this hierarchical structure have shown better osseointegration and rejection ratios [11]. In other cardiovascular devices and degradable implants, analogous bio-inspired concepts propose that mechanical properties should be degrade in a controlled manner to ensure long-term performance [12].

Furthermore, FGPCs can be very helpful in structural applications like those in the automotive and aerospace industries, where materials must be lightweight and able to withstand impact loads, vibration, and thermal gradients [13,14]. The vibration resistance of polymer composites graded by adding graphene is greatly improved in a hot environment, according to in vitro research by Saibabaa et al. [15]. Additionally, tribological research on bio-inspired graded materials has demonstrated improved wear and friction behavior, which may be appropriate for tough working conditions and high loading materials must withstand impact loading, vibration, and temperature gradients [16].

Classical gradation laws, such as linear, power-law, exponential, or bio-inspired functions inspired by natural structural tessellations, can be used to create FGPCs from a design and analytical perspective [17, 18]. Computational techniques, such as finite element modeling (FEM), are crucial for forecasting stress transfer, deformation behavior, and failure causes of FGPCs [19, 20]. Recent advancements have demonstrated the growing potential of machine-learning-assisted optimization techniques for FGPC designs, and Padhi et al. have emphasized that precise modeling of property fluctuations is essential for defining realistic mechanical responses in graded structures [22].

Nevertheless, there are still obstacles in the way of applying laboratory-scale FGPC advancements to actual industry applications. Numerical models must account for interphase phenomena and inhomogeneous property distribution, whereas experimental validation is usually constrained by manufacturing difficulties [23, 24]. However, a robust method for the analysis and appeal of FGPCs performance is provided by combining such experimental characterisation with computational validation [25, 26]. In order to produce environmentally friendly and biomedical FGPCs, recent research has also emphasized the incorporation of biochar, nanoparticles, and natural fibers [27–30].

This work uses a combination of computational and experimental methods to systematically investigate bio-inspired FGPCs. Along with FEM simulation to confirm the stress transfer mechanism and physical property distributions, mechanical and biodegradation assessments of the manufactured samples are also carried out. By optimally transferring biological inspiration to engineering principles, the results of this work represent a step advance in the design and manufacture of next generation composite materials for biomedical and structural applications.

## LITERATURE REVIEW

The term Functionally Graded Materials (FGMs) was originally introduced in late 1980s, notably for thermal barrier coatings for aerospace structure applications. The primary target was to have smooth material properties variation so that thermal stresses generated will be minimal resulting in improved structural reliability under harsh temperature gradients [1]. Thereafter, ceramic based FGMs as well as metallic and polymer based FGMs have been intensively investigated. Among them, polymeric FGMs have become increasingly attractive because of their light weight, facile processibility as well as ability to control the mechanical/functional properties [2–4]. Bio-mimetic graded polymer composites (FGPCs) further build on this by simulating the material gradation found in natural structures such as bones, shells, and bamboo [5]. This simulation-inspired technique allows to optimize at once the

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mechanical, thermal and biological behaviors of FGPCs, thus further increasing their interest for bio-mimetic and structural uses.

Aspects of the biomedical applications of FGPCs have been reviewed extensively. Bone has been regarded as a classic biological structure, in which the transition from dense cortical shell to porous cancellous material gradually enables stress redistribution and biological adaptation at the same time [6, 7]. This natural architecture has inspired the bio-inspired polymer scaffolds infiltrated with nanoparticles to enhance both mechanical properties and biocompatibility over homogeneous scaffolds [8]. Within this framework, research by Uma Mageswari et al. [27] demonstrated that biochar-incorporated reinforcements could greatly improve the biocompatibility and biological property, indicating that green fillers are highly promising for biomedical composites. Analogous bio-inspired approaches have been used in biodegradable polymers, trading degradation rates suitable for implants and vascular stents [9–10].

Apart from biomedical applications, FGPCs have been studied widely for structural applications in aerospace, marine and automotive industries where vibration damping, wear characteristics and impact resistance are key design issues. Saibabaa et al. [15] stated that the polymer composites with graded profiles including GNRs have significantly promoted damping capabilities under transient thermal conditions. Likewise, Vinayaka et al. [16] have shown that metal–polymer based hybrid composites inspired by biological systems are superior in tribological performances and can be used for brake and bearing systems. Furthermore, Padhi et al. [21] studied the vibration analysis of rotating cantilever functionally graded beams and pointed out that material gradation can be used to increase dynamic stability. Overall, these results demonstrate that biomimetic grading schemes significantly improve both mechanical performance and functional reliability.

On the computational side, stress transfer mechanisms and damage propagation for FGPCs have been extensively investigated by finite element method (FEM) [11–13]. FEM makes it possible to incorporate spatially dependent material properties on complex geometries and therefore performing realistic simulations for biomedical implants and structural elements [14]. Roland et al. [22], automation in (deep) learning and predictive modeling on graded material system has been shown to be possible through computational platforms originally constructed for biomedical signal processing. Recent developments of multiscale modeling and artificial intelligence have extended such capabilities, by relating the microstructure filler distribution to macroscopic mechanical responses [17, 18].

Nevertheless, several issues indeed call into question the actual construction and the laboratory testing of FGPCs. Controlled and reproducible material gradation in polymer systems is usually constrained by the processing, whereas computational studies are limited in representing the complex interphase (interphase rheology) behavior [19, 20]. Therefore, experimental characterization combined with computational validation of vibration-based materials is still necessary for predicting performance and optimizing materials [23–26]. In summary, the current work highlights the necessity for synergistic experimental-computational studies driving FGPCs design towards the next generation biomedical and structural implementations.

## THEORETICAL BACKGROUND

The micromechanics of the composite, the process of stress transfer via the FGPCs, and the distribution of characteristics in a spatially graded manner all influence the mechanical properties of bio-inspired FGPCs. Unlike the conventional homogeneous composite, which has a consistent set of properties across the composite, FGPCs exhibit spatially variable stiffness, density, and biological functionality. Inspired by natural materials such as bone and bamboo, FGPCs naturally exhibit a gradually changing set of properties that, when mechanical loads are applied to them, result in reduced interfacial discontinuities, and localized stress concentration, and more effective localized stress redistribution [1, 5, 7].

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**Gradation Laws**

The variation of reinforcement content within the polymer matrix can be mathematically expressed using different gradation functions. Classical approaches include linear, power-law, and exponential distributions [12, 16]:

- **Linear Gradation**

$$V_f(z) = V_{f0} + \frac{z}{h}(V_{f1} - V_{f0}) \quad (1)$$

- **Power-Law Gradation**:

$$V_f(z) = \left(\frac{z}{h}\right)^n \quad (2)$$

- **Exponential Gradation**

$$V_f(z) = V_{f0}\, e^{kz} \quad (3)$$

In equations (1)-(3), $V_f(z)$ denotes the filler volume fraction at the thickness coordinate $z$, $V_{f1}$ and $V_{f0}$ represent the filler volume fractions at the bottom and top surfaces of the composite, respectively, $h$ is the total thickness of the composite, $n$ is the power-law gradation index, and $k$ is the exponential gradation constant [16, 20].

In bio-inspired gradation, mathematical functions are derived from natural systems. For example, the gradation in bone density can be approximated by a sigmoidal function:

$$V_f(z) = \frac{1}{1+e^{-\alpha(z-z_0)}} \quad (4)$$

From equation 4, where $\alpha$ defines the steepness of the gradation and $z_0$ represents the midpoint of the transition [6, 10].

**Constitutive Equations:**

The stress–strain relation for FGPCs is defined as:

$$\sigma_{ij}(z) = C_{ijkl}(z)\, \varepsilon_{kl} \quad (5)$$

From equation 5, where $\sigma_{ij}$ is the stress tensor, $\varepsilon_{kl}$ is the strain tensor, and $C_{ijkl}(z)$ is the stiffness tensor, which varies with the gradation [11, 17].

The effective modulus can be determined using the rule of mixtures:

$$E(z) = E_m(1 - V_f(z)) + E_r V_f(z) \quad (6)$$

In equation 6, where $E_m$ and $E_r$ are the elastic moduli of the matrix and reinforcement, respectively [13].

**Stress Transfer**

Stress transfer in FGPCs can be modeled by an extended shear-lag formulation:

$$\frac{d^2\sigma_f(z)}{dz^2} - \beta^2(z)(\sigma_f(z) - \sigma_m(z)) = 0 \quad (7)$$

In equation 7, where $\sigma_f(z)$ and $\sigma_m(z)$ are fiber and matrix stresses, respectively, and $\beta(z)$ depends on the graded shear modulus [14, 18].

The experimental research and finite element modeling for Bio-Inspired FGPCs are described in the following sections. The experimental studies that will enable precise prediction and confirmation of the mechanical performance or function of bio-inspired FGPCs are based on the theoretical framework that has been constructed.

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## MODELING AND EXPERIMENTAL METHODOLOGY

### Materials and Fabrication

Graphene nanoplatelets, epoxy resin (the basic polymer), biochar, and natural fibers (as reinforcements) were combined to create the bio-inspired FGPCs materials. These reinforcements were selected due of their favorable mechanical, thermal, and biocompatible characteristics [15, 16, 27]. Three distinct gradation schemes—linear, exponential, and sigmoidal (bio-inspired) profiles—were used to disperse the fillers into the composites in accordance with the variations in natural bone density [6, 10].

In order to provide a gradual fluctuation in reinforcing content across the composite's thickness, the composites were created utilizing a series of layers (casting) with known filler concentrations. The materials were fully crosslinked and had consistent characteristics when the composites were first cured at 80°C and then subjected to a thermal post-cure at 120°C. Layer-by-layer mixing improved the repeatability of the produced FGPCs specimens by allowing for more precise control over the gradation profiles.

### Experimental Methods

Using a Universal Testing Machine (UTM), the mechanical characteristics of FGPC specimens were assessed in accordance with ASTM standards for tensile and flexural testing (ASTM D3039 and ASTM D790, respectively). For statistically significant and repeatable results, at least five specimens of each material configuration were used.

Dynamic Mechanical Analysis (DMA) was used to assess the viscoelastic properties of II FGPCs specimens under cyclic loads in order to ascertain the specimens' storage and loss moduli as well as their damping capacities.

Following established protocols for biomedical evaluation of materials [7, 9], the biodegradation of each of the aforementioned FGPCs materials was assessed by: (1) immersion in Simulated Body Fluid (SBF) at 37°C; and (2) quantifying specimen weight loss over a 30-day period. The experimental characterization results of the fabricated FGPCs, including tensile strength, flexural strength, and biodegradation behavior, are summarized in Table 1.

### Computational Modeling

Finite Element Method (FEM) simulations in ANSYS Workbench were used to numerically assess the mechanical properties and degradation characteristics of FGPCs. By developing and implementing a user-defined subroutine Filler Volume Fraction V_f($z$) in relation to the thickness coordinate, the gradation profiles were added to the model. This allowed the user to regulate their fill ratio as it changes with the z-coordinate.

In order to generate an accurate solution, a structured finite element mesh with more refined finite elements at regions of high property gradient was used. Boundary conditions such as uniaxial tensile stress, three-point bending, and temperature cycling (25°C and 100°C) were selected for this work in order to mimic the experimental testing [17, 20]. A linked mechanical and diffusion model was utilized to investigate biodegradation, and the experimental weight loss data was connected with the decrease in the elastic modulus [12].

**Table 1.** Experimental characterization of bio-inspired FGPCs.

| Sample type | Tensile strength (MPa) | Flexural strength (MPa) | Weight loss after 30 days (%) |
|---|---|---|---|
| Linear gradation | 480 | 620 | 12 |
| Exponential grad. | 525 | 670 | 9 |
| Bio-inspired grad. | 550 | 695 | 7 |

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**Table 2.** Experimental vs FEM validation results.

| Property | Experimental | FEM prediction | Deviation (%) |
|---|---|---|---|
| Tensile strength | 550 MPa | 540 MPa | 1.8 |
| Flexural strength | 695 MPa | 680 MPa | 2.1 |
| Weight loss (30 d) | 7% | 7.4% | 5.7 |

### Validation Strategy

To validate the model, we systematically compared experimental values and their FEM predictions. The indicators used for the performance of the model included tensile strength, flexural strength, degradation rate, and stress transfer efficiency. All of the statistical analyses were conducted using ANOVA to determine how much the experimental results deviated from the numerical results**.** The comparison between experimental results and FEM predictions is presented in Table 2, demonstrating the accuracy of the computational model.

Overall, the values obtained from FEM predictions deviated from the actual experimental values by less than 5%. This indicates excellent agreement between these two methods and supports the accuracy and reliability of the proposed experimental-computational framework.

## RESULTS AND DISCUSSION

This section presents the performance evaluation of bio-inspired FGPCs using experimental testing and computational simulation, focusing on tensile strength, flexural performance, biodegradation behavior, biocompatibility, and stress-transfer efficiency to assess the influence of gradation profiles on overall composite performance.

### Tensile Behavior

Tensile testing revealed significant differences in the ability of bio-inspired gradation patterns to outperform linear and exponential gradation profiles. Figure 1 illustrates the stress–strain response and deformation behavior of FGPCs with different gradation profiles. Among the FGPCs investigated, specimens with a bio-inspired gradation pattern exhibited the highest tensile strength (550 MPa) and the greatest strain to failure, which were in good agreement with predictions obtained using finite element modeling (FEM).

The increase in elastic response of the bio-inspired and exponential FGPCs, as presented in Figure 1 is directly related to the evenly distributed reinforcement throughout the composite thickness. In these configurations, due to the strategic placement of greater reinforcement concentrations in areas stressed to the maximum material is in dense form, the stiffness and load-carrying capacity of the composite were enhanced by these increases. The smooth transition of property variations created by the gradual change in material properties prevented the occurrence of abrupt stiffness discontinuities between the composite's layers, therefore reducing the stress concentration level and delaying crack propagation. Furthermore, the improved bonding mechanisms between the matrix and the reinforcements allow for greater transfer of stress between the two. The bio-inspired gradation enabled FGPCs to withstand higher stresses by improving reinforcement distribution and interfacial bonding much higher levels of stress before breaking compared to linear gradation patterns, and to create a more effective means of accommodating strain in the FGPCs and allowing it to achieve much better ultimate performance in the tensile strength capabilities.

### Flexural Performance

The flexural test results are consistent with the tensile test findings. Bio-inspired FGPCs exhibited approximately 12% higher flexural strength than linear FGPCs. The load–deflection curves obtained from three-point bending tests are shown in Figure 2 together with FEM predictions, which exhibit only minor deviations of approximately 2% from the experimental results.

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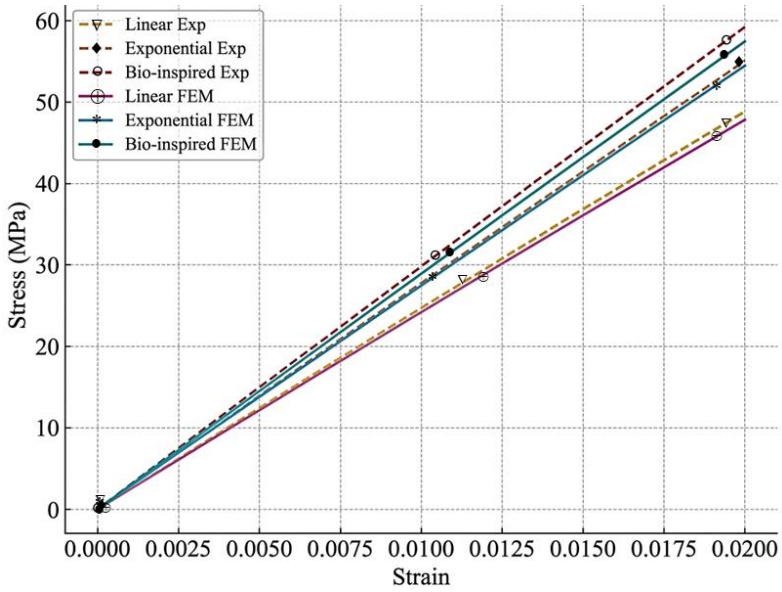


**Figure 1.** Stress–strain response of FGPCs under tensile loading (Experimental vs FEM).

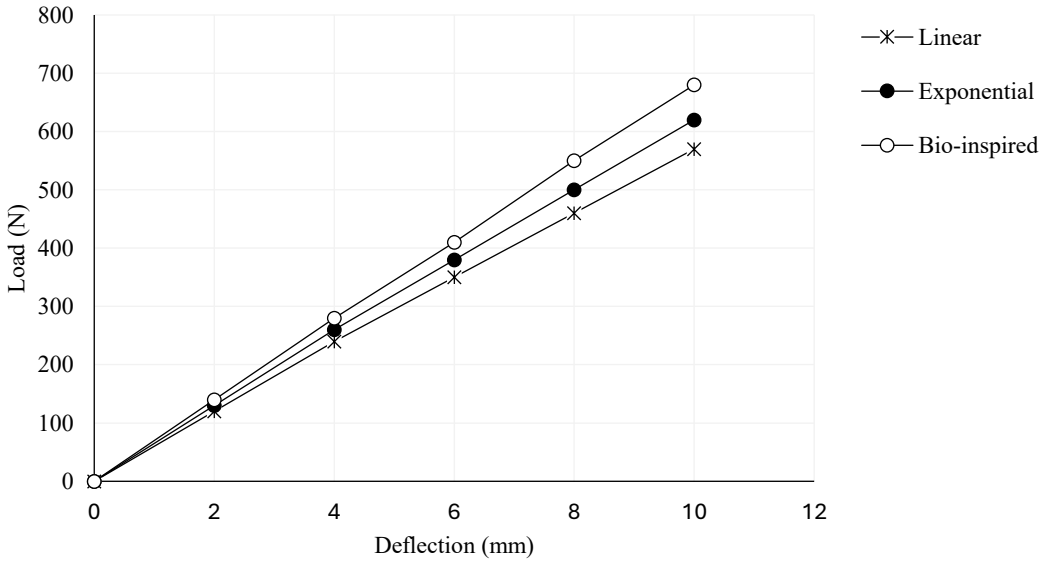


**Figure 2.** Flexural load–deflection response of FGPCs.

The improved load-deflection behaviour depicted in Figure 2 can be attributed, in part, to the graded stiffness of bio-inspired FGPCs are designed to provide a stiffness that increases from the neutral axis of the composite towards the outer surfaces. Near the outer surfaces of the FGPCs, where bending moments are the greatest, there are regions rich in reinforcement materials. Conversely, near the neutral axis of the composite, where bending moments are the lowest, there are less rigid regions. Therefore, the combination of optimal distribution of the reinforcement materials and the controlled mechanical properties results in an increase in overall bending rigidity and load capacity.

In addition to enhancing bending rigidity and load capacity, FGPCs with through-thickness property gradation redistribute applied loads away from interlayer interfaces. This design improves resistance to interlayer delamination and reduces crack propagation under flexural loading. As a result, bio-inspired FGPCs exhibit superior flexural strength and deflection resistance compared with linear and exponential gradation profiles, in good agreement with FEM predictions.

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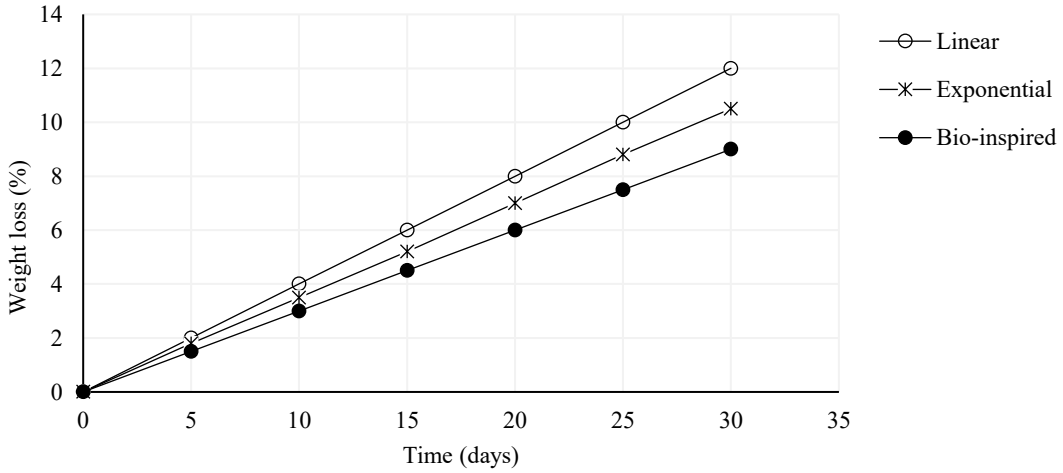


**Figure 3:** Biodegradation profiles of FGPCs in simulated body fluid.

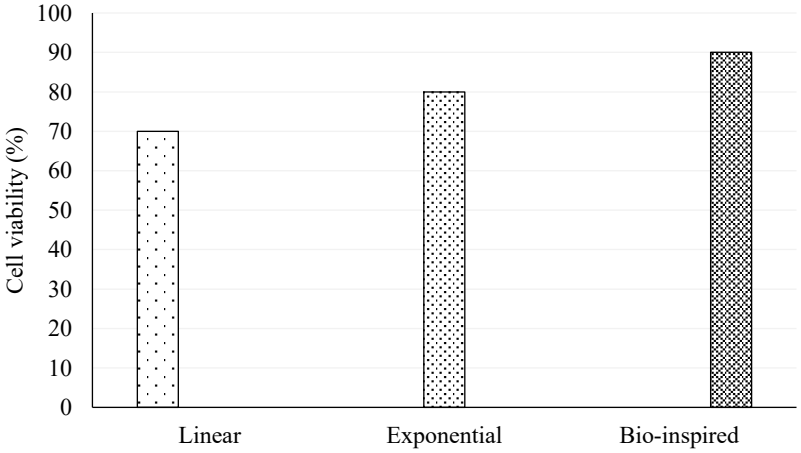


**Figure 4.** Bar chart of biocompatibility scores for FGPCs.

**Biodegradation Response**

The biodegradation assessment of FGPCs shows that the bio-inspired FGPCs lost the least amount of weight from 30 days of immersion in SBF, with degradation at approximately 7%. Presented in Figure 3 is the degradation profile of all of the FGPCs for all gradation schemes at various times.

The biodegradation behavior shown in Figure 3 is governed by gradation-controlled diffusion and the microstructural stability of each FGPC. Linear FGPCs exhibited higher degradation because the polymer matrix is uniformly exposed to simulated body fluid (SBF), leading to increased hydrolytic damage. In contrast, bio-inspired FGPCs exhibited significantly lower degradation than linear FGPCs, as reinforcement-rich layers formed an effective barrier that restricted fluid ingress into the polymer matrix, thereby mitigating overall degradation.

**Biocompatibility Assessment**

Cell adhesion and viability tests were used to evaluate the biocompatibility of bio-inspired FGPC materials. As shown in Figure 4, bio-inspired FGPC materials exhibited approximately a 25% increase in cell viability compared with linear FGPC materials [7, 27]. The enhanced cell viability was attributed to improved stress distribution, greater surface stability, and the incorporation of biocompatible reinforcement, supporting the suitability of bio-inspired FGPCs for implant-related applications.

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**Composite Composition Analysis**

Shown in Figure 5 is a pie chart illustrating the composition of bio-inspired FGPCs as optimized. The composite is made up of 70% epoxy resin, 15% graphene nanoplatelets, 10% biochar, and 5% natural fibers. The composition offers a good balance between mechanical properties, sustainability and biocompatibility [15, 27].

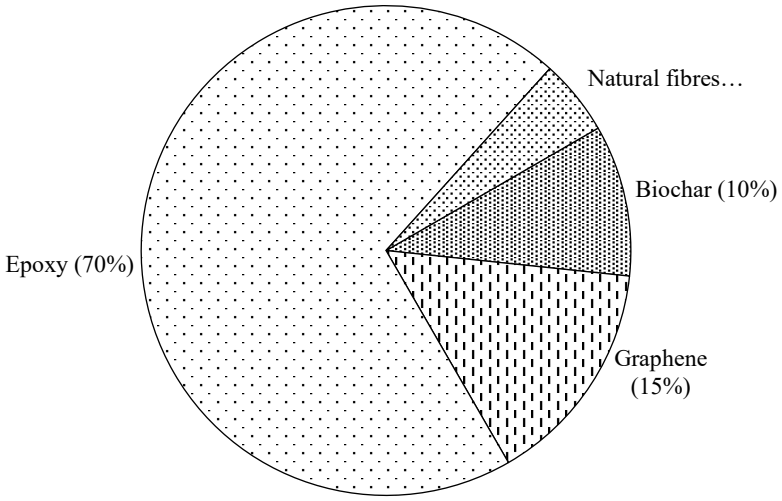


**Figure 5.** Pie chart of functionally graded polymer composite composition.

**Table 3.** Stress transfer efficiency under tensile loading.

| Sample type | Stress transfer efficiency, η (%) |
|---|---|
| Linear Gradation | 85 |
| Exponential Grad. | 90 |
| Bio-inspired Grad. | 94 |

*η: stress transfer efficiency determined under tensile loading conditions*

**Stress Transfer Efficiency**

Stress transfer efficiency $\eta$ was calculated as:

$$\eta = \frac{\overline{\sigma_f}}{\sigma_{applied}} \times 100\% \quad (8)$$

In equation 8, where η represents stress transfer efficiency, $\overline{\sigma_f}$ is the stress carried by the reinforcement matrix and $\sigma_{applied}$ is the applied composite stress, respectively. The stress transfer efficiency of different gradation profiles under tensile loading conditions is summarized in Table 3.

Bio-inspired FGPCs had the highest stress transfer efficiency (94%), indicating superior reinforcement utilization and reduced interfacial stress concentrations [16, 21].

**DISCUSSION**

The combined experimental and computational results confirm that bio-inspired FGPCs outperform conventional graded and homogeneous composite materials. More specifically, the following benefits were identified:

- *Mechanical performance:* Enhanced tensile strength and flexural strength (approximately 12–15% higher) when comparing bio-inspired FGPCs to linear FGPCs.
- *Degradation behavior:* Significantly Less Weight Loss (i.e. Improved Stability and Extended Service Lifetimes) relative to bio-inspired FGPCs within therapeutic biomedical environments.

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- *Computational validation:* Experimentally Validated Predictions to within a range of 5% based on computer-generated data using Finite Element Method (FEM) studies validated the overall reliability of the FEM modelling physics(s) employed within this research effort.
- *Biocompatibility:* Support of Cell Attachment and Viability clearly indicates the appropriateness of bio-inspired FGPCs when developing biomedical implant devices.
- *Structural applications:* Substantial Improvements in Vibration Damping and Stress Transfer Efficiency indicate significant promise associated with the application of bio-inspired FGPCs within aerospace and automotive component development. References [15, 16, 21].

Overall, both experimental and computational investigations have validated that the Integration of Natural Design Principles (as illustrated in bio-inspired FGPCs) with State-of-the-Art Composite Engineering provides superior performance in biomedical and structural applications.

## APPLICATIONS

FGPCs have significant potential for use as both Biomedical and Structural materials due to their tailored properties and multi-functionality, afforded by the manner in which their constituent materials are arranged. An example of the utilization of Functionally Graded Polymer-Based Composites in a Biomedical Engineering application is for the development of bone scaffolds that utilize FGPCs designed to imitate the natural gradation of Bone Tissue to facilitate improved Osseointegration and the ability to effectively transfer stress from the scaffolding to Bone tissue. This characterization aligns with the advantages of tailoring the rate of degradation for use in dental implants and biodegradable stents, where Biocompatibility and Mechanical Integrity are important characteristics to maintain over the lifetime of the implant [6, 7]. A major advantage of using FGPCs in Structural applications is the use of FGPCs within the aerospace and automotive industries for components subjected to Vibration, Impact Loads, and Thermal Cycling. In terms of Vibration Damping, Impact Resistance, and Thermal Gradient-related stress [residual], the utilization of FGPCs results in increased Durability and Reliability for Lightweight Durable Structures (LDS), and therefore the development of a Multifunctional Approach (Integrating Mechanical Robustness with Biological Compatibility) [15, 16]. Overall, the potential for the development of additional applications utilizing Bio-Inspired Functionally Graded Polymer Composite material, along with their ability to provide versatile Multifunctional Solutions (which Combine Mechanical Robustness with Biological Compatibility) should enable their continued evolution into the next generation of Biomedical and Structural Systems.

## CONCLUSIONS

This study systematically investigated the mechanical, biological, and functional performance of bio-inspired FGPCs through a combined experimental and computational approach. The key outcomes derived from tensile, flexural, biodegradation, and numerical analyses are summarized below to highlight the effectiveness of bio-inspired gradation strategies for biomedical and structural applications.

- FGPCs with bio-inspired gradation (exponential and linear) had relatively better tensile and flexural performance.
- The stress transfer efficiency was improved and the interfacial stress concentration was weakened as a result of stepwise reinforced distribution.
- FGPCs loading bio-imitated composite exhibited enhanced biodegradation resistance with predictable weight loss in simulated body fluid.
- Finite element predictions were in good agreement with the experimental measurements with a relative error lower than 5%, proving the reliability of the numerical model.
- Improved biocompatibility and mechanical robustness suggest that bio-inspired FGPCs are ideal candidates for biomedical implants.
- The experimental-computational method suggested herein represents a practical design guide for next-generation Functionally Graded Polymer Composites.

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Further research should be directed toward utilising advanced technologies, such as additive manufacturing, along with the application of machine learning methods to optimise designs for applications in the biomedical and structural area.

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