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MECHANO-BIOLOGICAL RESPONSE OF POLYLACTIC ACID-BASED BIOCOMPOSITES IN THE CONTEXT OF STRUCTURAL MATERIAL DESIGN

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Abstract

Polylactic acid (PLA)-based biocomposites represent a promising class of materials for biomedical applications due to their biodegradability, biocompatibility, and structural tunability. In the present study, PLA biocomposites are analyzed from the perspective of mechano-biological response governed by material structural organization. The objective of this work is to establish the relationship between filler morphology, matrix phase structure, and interfacial interactions, and the resulting mechanical and biological behavior of the composite. It is demonstrated that mechanical characteristics of PLA-based biocomposites may act as active regulators of biological response rather than passive performance indicators. A structure–function design framework for PLA biocomposites intended for biomedical applications is proposed.

Keywords: Polylactic acid; biocomposites; mechano-biological response; structural design; biomaterials.



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1. Introduction

The growing demand for sustainable and biocompatible materials has significantly intensified research on biodegradable polymers. Polylactic acid (PLA) is among the most widely utilized biopolymers due to its renewable origin, established biocompatibility, and compatibility with conventional polymer processing technologies. PLA has been extensively applied in temporary implants, tissue engineering scaffolds, fixation devices, and regenerative medicine systems.

Despite these advantages, the practical application of neat PLA is limited by its relatively low impact resistance, inherent brittleness, and sensitivity of mechanical properties to service conditions. Consequently, the development of PLA-based biocomposites has emerged as an effective strategy for expanding the functional range of this material. However, the performance of such systems is strongly governed by their structural organization, which necessitates a systematic and concept-driven analysis.

In recent years, increasing attention has been devoted to the mechano-biological response of materials, reflecting the coupling between mechanical behavior and biological interaction. For PLA-based biocomposites, this relationship remains insufficiently structured and conceptually unified, which defines the relevance of the present study.

2. Objective of the Study

The objective of this study is to establish the relationship between the structural organization of PLA-based biocomposites and their mechano-biological response. Particular emphasis is placed on identifying structural parameters that govern the alignment of mechanical performance with biological functionality, including filler morphology, matrix phase structure, and interfacial interactions.

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3. Scientific Novelty

The scientific novelty of this work lies in the integrative interpretation of PLA-based biocomposites as mechano-biologically active systems whose properties arise from the coupled interaction between structure, mechanical behavior, and biological response. Unlike conventional approaches, mechanical characteristics of PLA biocomposites are interpreted not as isolated performance metrics but as functional regulators of biological interaction.

For the first time, filler morphology, matrix crystallinity, and interfacial architecture are introduced as controllable design variables enabling the targeted formation of mechano-biological response. On this basis, a structure–function design framework for PLA-based biocomposites intended for biomedical applications is proposed.

4. Structural Parameters of PLA-Based Biocomposites

The structural organization of PLA-based biocomposites is formed across multiple length scales and is governed by filler type, morphology, and dispersion within the polymer matrix. Fillers with high aspect ratios and developed surface areas can effectively participate in load transfer, enhancing stiffness and strength while maintaining structural efficiency at low filler contents. Uniform dispersion is a critical requirement for achieving structural stability, as insufficient dispersion may lead to stress localization and premature failure. In addition, the phase structure of the PLA matrix plays a decisive role in defining composite behavior. Matrix crystallinity influences stiffness, deformability, and fracture mechanisms. Fillers may act as heterogeneous nucleation sites, modifying crystallization behavior and enabling structural control over mechanical response.

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5. Mechanical Response and Structure Dependence

The mechanical behavior of PLA-based biocomposites arises from interactions between the polymer matrix and reinforcing phases. Interfacial interactions govern load transfer efficiency and structural integrity under mechanical loading. Increased stiffness is commonly accompanied by changes in deformation mechanisms and stress redistribution, which become particularly significant under cyclic or complex loading conditions.

Mechanical response should therefore not be considered solely in terms of strength and modulus, as local deformations and microstructural heterogeneities play a critical role in defining material performance and subsequent biological interaction.

6. Biological and Mechano-Biological Response

From a biomedical perspective, PLA-based biocomposites operate under continuous mechanical interaction with living tissues. Biological response is determined not only by chemical composition but also by mechanical characteristics such as stiffness, surface microstructure, and local deformation fields. These parameters influence cell adhesion, orientation, proliferation, and differentiation.

The mechano-biological response manifests in the ability of the material to modulate biological processes in response to mechanical stimuli. Structural control enables synchronization of material degradation with tissue regeneration, providing temporary mechanical support followed by gradual biological integration.

7. Technological Aspects of Structural Formation

Processing methods, including extrusion and additive manufacturing, play a critical role in shaping the structural organization of PLA-based biocomposites.

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Processing parameters influence filler orientation, density, and structural heterogeneity, thereby affecting both mechanical and biological performance. Limitations associated with processability at elevated filler contents necessitate optimization of composition and processing conditions, highlighting the importance of an integrated engineering approach to material design.

8. Conclusions

The mechano-biological response of PLA-based biocomposites is governed by their hierarchical structural organization. Filler morphology, matrix phase structure, and interfacial interactions collectively define mechanical behavior and biologically relevant mechanical cues.

Mechanical properties of PLA-based biocomposites should therefore be regarded as active contributors to biological functionality rather than secondary performance indicators. The proposed structure–function design framework provides a rational basis for engineering PLA-based biocomposites with tailored mechano-biological behavior, expanding their applicability in biomedical and tissue engineering systems.

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