Development of Sustainable Self-Healing PLGA Biopolymers Loaded with ZnO and TiO2 Nanoparticles for Enhanced Tissue Regeneration

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Abstract

Poly(lactic-co-glycolic acid) (PLGA) is a widely used polymer in regenerative engineering and prosthetics; however, like most materials, it is susceptible to degradation, and its cracking limits its lifespan. This project aimed to determine the optimal structure of PLGA polymer to ensure maximum sustainability, longevity, excellent mechanical properties, and high biocompatibility by comparing the effectiveness of zinc oxide and titanium dioxide. This was achieved through: (1) the preparation of zinc oxide nanoparticles, resulting in a heterogeneous structure with varying sizes and shapes, yet the nanoscale dimensions were suitable for high reactivity and good crystallinity; (2) the preparation of titanium dioxide nanoparticles using the sol-gel method, which exhibited spherical nanostructures in the chemical composition, with suitable size and properties; and (3) the fabrication of PVP/PLGA films loaded with zinc oxide (ZnO) and titanium dioxide (TiO2) nanoparticles at different concentrations (2% and 5% of each). Self-healing tests showed that adding 2% zinc oxide (ZnO) or titanium dioxide (TiO2) nanoparticles significantly improved these properties. Notably, the samples showed no toxicity to either healthy or diseased human cells. Subsequently, the resulting composite nanopolymer was analyzed and tested, comparing its mechanical properties, biocompatibility, self-healing capabilities, and microstructure. Applications of the composite can be expanded to include the fabrication of prosthetics, wound dressings, and braces .

Introduction

Cartilage and the musculoskeletal system are key components of human movement and physical function, playing a pivotal role in maintaining health and quality of life. One of the risks threatening these components is musculoskeletal disorders, defined as conditions affecting bones, joints, muscles, tendons, and ligaments, leading to reduced mobility and impaired physical function (National Academies of Sciences, Engineering, and Medicine, 2020). A 2022 World Health Organization report revealed that approximately 1.71 billion people in more than 160 countries worldwide suffer from these serious disorders (World Health Organization, 2022).

Despite research advancements in developing polymers for tissue and cartilage repair, significant challenges remain regarding their effectiveness and durability. Among smart materials, poly(lactide-co-glycolide) (PLGA) is one of the most widely used polymers in biomedical applications; however, this compound suffers from high susceptibility to cracking and deterioration, which limits its functional performance (Makadia & Siegel, 2011).

current research focuses on studying polymeric and nanomaterials to extend the shelf life of therapeutic compounds. Among these nanoparticles, zinc oxide and titanium dioxide have emerged as promising possibilities due to their unique properties and robust structure. In this study, these two types of particles were incorporated into a PLGA polymer matrix to compare the efficacy of a PLGA polymer incorporating zinc oxide nanoparticles versus a PLGA polymer incorporating titanium oxide nanoparticles. Their optical properties, internal structure, self-repair capabilities, and mechanical properties were evaluated to determine the optimal compound composition for maximum sustainability and extended shelf life.

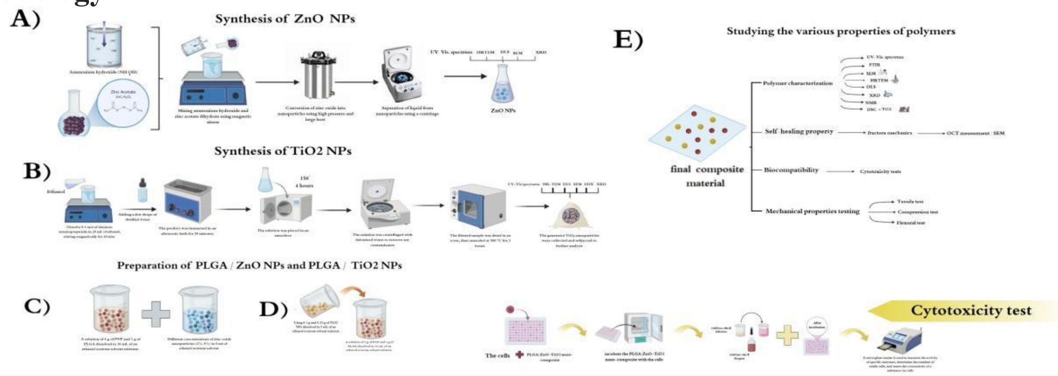
Literature Review

Greco, Leonetti, and Lonetti (2013) studied crack initiation and propagation in composite materials and found that they strongly influence structural failure. They also highlighted the risks of cracks, noting that they can accumulate and lead to catastrophic damage, reducing material lifespan and causing structural failure (Greco et al.,2013)

Numerous studies have been conducted to identify factors that enhance the self-healing efficiency of polymers. For example, Choi et al. (2023) highlighted that one of the factors influencing regeneration is the nature of the polymer. The nature of the cracks is also an influential factor, including their size, shape, and location, as well as the accessibility of repair materials and the available surface area for repair (Choi et al.,2023).

Furthermore, the principles and mechanisms of polymer self-healing have been analyzed. Burhan et al. (2020) addressed this topic in a chapter titled "Self-Healing Composite Materials" (pp. 193-208), The study explained that self-repair in polymers depends on physical and chemical reactions that go through two stages: the proximity of damaged surfaces and the activation of repair processes (Burhan et al.,2020).

Methodology



Synthesis of Zinc Oxide & Titanium Dioxide nanoparticles

To prepare zinc oxide (ZnO) nanoparticles, ammonium hydroxide was added to a zinc acetate solution. After treatment, the compound underwent UV-Vis spectroscopy to confirm the success of the preparation process(Singh et al.,2008). Additionally, titanium dioxide nanoparticles were prepared by adding titanium isopropoxide to 20 mL of ethanol solution(Sui et al.,2019). After ultrasonic treatment, the solution was placed in a steam sterilizer and washed. Finally, the resulting titanium dioxide nanoparticles were collected and subjected to further analysis.

Preparation of PVP/PLGA Membranes Loaded with ZnO and TiO2 Nanoparticles

We used a mixture of acetone and ethanol to dissolve the PVP and PLGA polymers. This process then involved incorporating 2% zinc oxide (ZnO) and 2% titanium dioxide (TiO_2) nanoparticles into the polymer matrix at varying weight ratios. The resulting nanocomposite solutions were then cast into thin films. The prepared films were labeled and stored under dry conditions for further analysis.

Self healing property method & Cytotoxicity assay

A sharp scalpel was used to make scratches on the polymers, and the healing process of the resulting scratches was recorded using a light microscope, a digital camera MU800, and AmScope software(Supramaniam et al.,2022;Xu et al.,2025). A cytotoxicity assay was performed to verify that the compound was not toxic to living cells.

Conclusion

The study showed that incorporating zinc oxide and titanium dioxide nanoparticles can improve the mechanical, optical, and intrinsic properties of the PLGA polymer matrix. making it a promising and sustainable material for many medical applications. This indicates the importance of studying more durable materials for tissue regeneration and prosthetics in the future.

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