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Sustainable Food Packaging: Biodegradable Carboxymethyl Cellulose Films Reinforced With Green-Synthesized ZnO Nanoparticles From Pineapple Waste

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Carboxymethyl cellulose (CMC) bioplastic shows great promise for sustainable food packaging. This study synthesized zinc oxide nanoparticles (ZnO NPs) from pineapple waste via green synthesis and incorporated them into CMC to develop enhanced nanocomposite films. Key steps included preparing ZnONP powder and formulating ZnONP-CMC (ZCMC) (1.0% w/v) solutions for film fabrication. The nanocomposites were characterized using FTIR, XRD, SEM–EDX, TGA, and DSC to assess structural integrity and thermal stability. Physical properties showed enhancement, including a thickness of 0.17.05 mm, opacity of 17%, moisture content of 52.38%, and water solubility of 64.52%. The mechanical properties also improved significantly, with a tensile strength of 26.30 MPa and elongation at a break of ~50%. FTIR and XRD confirmed the successful incorporation of ZnO NPs, which improved the crystallinity and structural integrity of the CMC matrix. Notably, the ZCMC nanocomposite exhibited rapid biodegradation within 9 days under soil conditions, highlighting its potential for reducing environmental impact. In conclusion, adding ZnO NPs to CMC films notably improves their physical, mechanical, and thermal characteristics, rendering them ideal for food packaging. While the mechanical and biodegradation properties are promising for food packaging applications, future research should focus on evaluating the antimicrobial properties and practical applications of the ZCMC films in food preservation.

1. Introduction

The development of sustainable food packaging solutions is urgent due to the increasingly apparent detrimental impact of traditional petroleum-based materials on ecosystems and public health. Specifically, these materials contribute to long-term environmental issues such as microplastic pollution, landfill overflow, and toxic emissions, all affecting biodiversity and human health.[1] Although these materials are affordable and have good mechanical properties, they are made from resources that cannot be replenished and present significant environmental problems because they do not degrade easily.[2] Additionally, conventional food preservation techniques, such as cold chain preservation and controlled environment storage, are costly and energy-intensive, contributing to food spoilage and wastage while raising operational costs for industries.[3]

Polysaccharides, such as cellulose and starch, are plentiful macromolecules consisting of repeated monosaccharide units linked by glycosidic linkages. They have great potential for developing eco-friendly packaging materials due to their biodegradability and nontoxic nature.[4] Their natural origin, functional diversity, and intrinsic safety make them appealing substitutes for traditional packaging materials.[5] Carboxymethyl cellulose (CMC) is classified as a generally recognized as safe (GRAS) substance by the United States Food and Drug Administration (FDA).[6] Its numerous carboxylic and hydroxyl groups distinguish CMC, endowing it with strong water-binding capabilities.[7] Furthermore, CMC demonstrates exceptional thermal gelation capabilities that aid in film development and is biocompatible.[8] Being tasteless, odorless, nontoxic, and biodegradable, this material is highly suitable for eco-friendly food packaging, effectively addressing sustainability challenges by reducing dependence on fossil-fuel-based materials.[9]

Integrating nanoparticles (NPs), namely ZnO NPs, into the CMC matrix can substantially improve the functional characteristics of food packaging films, making them more sustainable. ZnO NPs possess unique physicochemical properties, including a high surface-area-to-volume ratio and exceptional antimicrobial activity against many pathogens, such as bacteria, virus, and fungi, contributing to their versatility in enhancing polymer-based films.[10] Their incorporation into biopolymer matrices has improved tensile strength (TS), flexibility, and structural integrity by forming strong intermolecular interactions with the polymer chains. These interactions increase crosslinking density, reinforcing the film's mechanical properties and preventing cracking or tearing during storage and transport.[10–11] For example, Sultan, et al.[11b] demonstrated that incorporating ZnO NPs into chitosan and polyvinyl alcohol-based packaging films enhanced the TS

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