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Development and Characterization of Antimicrobial Polymer Composites for Food Packaging Applications

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Abstract

The increasing demand for sustainable and antimicrobial food packaging materials has led to extensive research in polymer-based composites. This study focuses on developing a polyethylene terephthalate-ethylene vinyl acetate (PET-EVA) composite reinforced with metal oxide nanoparticles (MONs), including Cu_2O, ZnO, and MgO_2. These nanoparticles were selected for their antimicrobial properties and ability to enhance the functional characteristics of the composite. Structural, chemical, mechanical, and barrier properties were extensively evaluated to determine the efficacy of these composites in improving food safety and extending shelf life. Fourier-transform infrared spectroscopy (FTIR) analysis confirmed the successful incorporation of MONs into the polymer matrix, while scanning electron microscopy (SEM) imaging demonstrated uniform nanoparticle dispersion, which is crucial for maintaining the composite's mechanical integrity. Among the developed materials, PET-EVA-Cu_2O exhibited the highest antimicrobial efficacy, effectively inhibiting bacterial growth, and also showed superior UV barrier properties, which can further contribute to reducing food spoilage. Additionally, mechanical testing revealed that MON incorporation enhanced the tensile strength and flexibility of the composite, making it suitable for practical food packaging applications. The findings highlight the potential of PET-EVA-MON composites as active packaging materials with antimicrobial and protective functionalities. Future research will focus on assessing the recyclability and biodegradability of these composites to enhance their sustainability, addressing environmental concerns associated with synthetic polymers. Moreover, optimization of MON concentrations and further exploration of their synergistic effects could lead to improved performance and broader applications in food packaging industries.

Keywords: Antimicrobial polymer composites, PET-EVA, barrier properties, recyclability, biodegradability

INTRODUCTION

Food packaging plays a crucial role in preserving food quality, extending shelf life, and ensuring safety from microbial contamination. Traditional packaging materials, primarily based on synthetic polymers, lack antimicrobial properties, leading to increased food spoilage.[1] The integration of antimicrobial agents, particularly metal oxide nanoparticles (MONs), into polymer matrices has emerged as an innovative solution to combat microbial growth and enhance packaging performance. This study explores the development and characterization of polyethylene terephthalate-ethylene vinyl acetate (PET-EVA) composites embedded with Cu_2O, ZnO, and MgO_2 nanoparticles, evaluating their antimicrobial, barrier, and mechanical properties.

The primary goal of incorporating MONs into the PET-EVA matrix is to create an active packaging system that not only serves as a physical barrier but

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also actively contributes to food preservation. Cu_2O, ZnO, and MgO_2 were chosen due to their well-documented antimicrobial efficacy, safety, and compatibility with polymer matrices. The uniform dispersion of these nanoparticles within the polymer matrix ensures optimal interaction with microbial cells, leading to enhanced antimicrobial activity.[2] Additionally, these nanoparticles offer improved mechanical strength, UV resistance, and gas barrier properties, which further contribute to shelf-life extension.

A series of structural, chemical, and mechanical analyses were performed to evaluate the effectiveness of these composites. Fourier-transform infrared spectroscopy (FTIR) analysis confirmed the successful incorporation of MONs by detecting characteristic peaks associated with metal-oxygen bonding.[3] Scanning electron microscopy (SEM) imaging revealed a uniform distribution of nanoparticles within the PET-EVA matrix, which is essential for maintaining the mechanical integrity of the composite. The homogeneous dispersion of nanoparticles prevents agglomeration, ensuring that the composite retains its flexibility and strength.[4]

The antimicrobial performance of the developed composites was tested against common foodborne pathogens, including *Escherichia coli* and *Staphylococcus aureus*. PET-EVA-Cu_2O demonstrated the highest antimicrobial efficacy, significantly reducing bacterial growth compared to PET-EVA-ZnO and PET-EVA-MgO_2. This superior antimicrobial activity is attributed to the ability of Cu_2O nanoparticles to generate reactive oxygen species (ROS) and disrupt bacterial cell membranes.[5] ZnO and MgO_2 also exhibited antimicrobial properties, though to a lesser extent, indicating their potential for applications requiring moderate antimicrobial protection.

In addition to antimicrobial performance, the mechanical and barrier properties of the composites were extensively analyzed. Tensile strength and elongation at break were evaluated to assess the mechanical durability of the materials. The incorporation of MONs was found to enhance tensile strength while maintaining adequate flexibility, making these composites suitable for packaging applications that require mechanical resilience.[6] Moreover, the presence of MONs improved the UV-blocking capability of the composites, reducing the degradation of packaged food products exposed to light.

Barrier properties, including water vapor and oxygen permeability, were also investigated. PET-EVA-Cu_2O demonstrated superior gas barrier properties, effectively limiting oxygen transmission and reducing moisture penetration. This feature is particularly valuable for packaging perishable food products, as it minimizes oxidation and microbial spoilage. The enhanced barrier performance of PET-EVA-Cu_2O suggests its potential for replacing conventional plastic packaging materials that lack active protective functions.[7]

Despite these promising results, the environmental impact of polymer-based composites remains a critical concern. The sustainability of PET-EVA-MON composites is an area of ongoing research, with particular focus on recyclability and biodegradability. While PET and EVA are recyclable materials, the incorporation of MONs may affect the recycling process. Future studies will explore methods to optimize the recyclability of these composites without compromising their functional properties.[8] Additionally, research into biodegradable polymer alternatives that can host MONs is essential to developing eco-friendly active packaging solutions.

To further optimize these materials, the concentration and combination of MONs will be explored in subsequent studies. Synergistic effects between different nanoparticles could lead to enhanced antimicrobial and barrier properties, broadening the range of potential applications. Moreover, testing these composites under real-world food storage conditions will provide valuable insights into their long-term performance and stability.

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MATERIALS AND METHODS

Materials

Polyethylene terephthalate (PET) and ethylene-vinyl acetate (EVA) polymers were procured from commercial sources with high purity to ensure consistency in composite formulation. These polymers were chosen for their favorable mechanical properties, flexibility, and chemical resistance. Copper(I) oxide (Cu_2O), zinc oxide (ZnO), and magnesium peroxide (MgO_2) nanoparticles were synthesized using a sol-gel method, a widely accepted technique known for producing nanoparticles with high purity, uniform morphology, and controlled particle size. The synthesis was conducted under optimized conditions to obtain nanoparticles with enhanced reactivity and dispersion characteristics. The solvents and reagents used in the fabrication of the composites were of analytical grade to prevent any unwanted impurities from affecting the composite properties. The selection of metal oxide nanoparticles (MONs) was based on their functional properties, such as antimicrobial activity, UV resistance, and mechanical reinforcement potential.

Composite Preparation

The polymer composites were prepared using a melt compounding process, a widely used technique for thermoplastic processing. A twin-screw extruder was employed to ensure homogeneous dispersion of the MONs within the PET-EVA matrix. The melt compounding process was conducted at carefully controlled temperatures to prevent degradation of the polymer matrix and to optimize the interfacial interaction between the nanoparticles and the polymer chains.[9] The nanoparticle concentration in the composite formulation varied from 1 wt% to 5 wt% to systematically investigate its effect on the structural, mechanical, and functional properties of the resultant composites. To achieve optimal dispersion, the nanoparticles were pre-dispersed in a solvent before being introduced into the polymer matrix. This step was crucial to preventing nanoparticle agglomeration, which could adversely affect the mechanical and barrier properties of the composites. Following extrusion, the composites were pelletized and subsequently molded into thin films using a hot press under controlled pressure and temperature conditions. These films were then conditioned before characterization to ensure consistency in measurements and to allow stress relaxation within the polymer matrix.

Characterization Techniques

A comprehensive set of characterization techniques was employed to analyze the structural, mechanical, and functional attributes of the fabricated polymer composites. Fourier Transform Infrared Spectroscopy (FTIR) was conducted to identify chemical interactions between the MONs and the polymer matrix by detecting shifts in characteristic absorption bands, which would indicate potential bonding or interactions at the molecular level. Scanning Electron Microscopy (SEM) was used to investigate the dispersion of nanoparticles within the polymer matrix, as uniform dispersion is critical for enhancing mechanical and functional properties.[10] UV-Vis spectroscopy was utilized to assess the optical and barrier properties of the composites, particularly their UV-shielding capabilities, which are crucial for applications requiring photostability. Mechanical testing, including tensile strength and elongation at break measurements, was performed following ASTM standards to evaluate the influence of nanoparticle incorporation on the composite's mechanical performance. These tests provided insights into the composite's flexibility, toughness, and reinforcement effects imparted by the MONs. By employing these advanced characterization techniques, a thorough understanding of the material behavior was obtained, paving the way for optimizing composite formulations for targeted applications.

The Figure 1 illustrates the raw materials used in the formulation of polymer composites (top-left), including poly (lactic-co-glycolic acid) (PLGA), chitosan, and polyethylene glycol (PEG), each selected for their biocompatibility and film-forming properties. The top-right panel presents the composite preparation process, including polymer blending, antimicrobial agent incorporation, casting/extrusion, and film curing. The bottom panels provide close-up visualizations of the materials and key stages in the methodology, offering a comprehensive view of the fabrication process from start to finish.

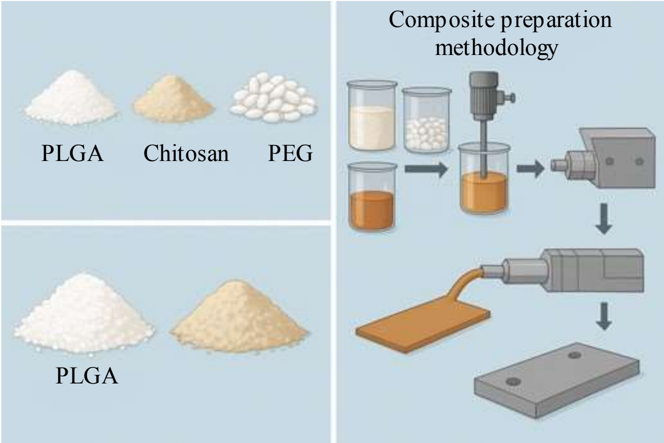

Figure 1. Materials used and composite preparation methodology.

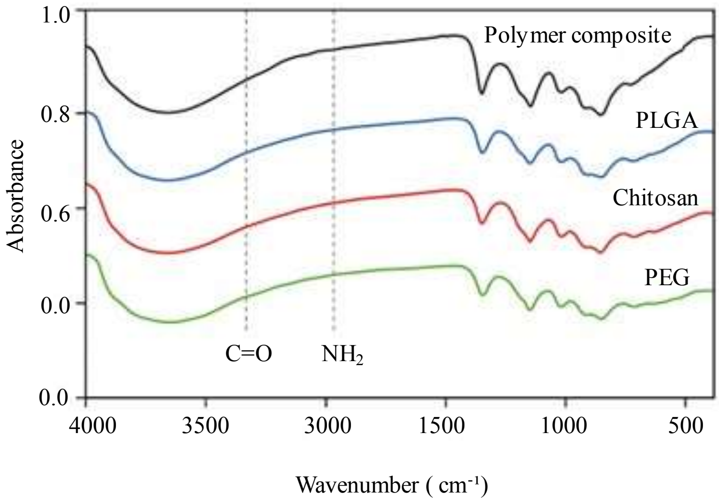

Figure 2. FTIR spectra of pure polymers and polymer composite.

The FTIR spectra show the characteristic absorption bands of PLGA (C=O stretching at ~1750 cm^{-1}), chitosan (NH_2 bending at ~1590 cm^{-1}), and PEG (C–O–C stretching at ~1100 cm^{-1}) shown in figure 2. The composite spectrum confirms the successful incorporation of all materials through identifiable peak shifts and broadening. Figure 3 shows SEM Images of the Polymer Composite Surface at Various Magnifications.

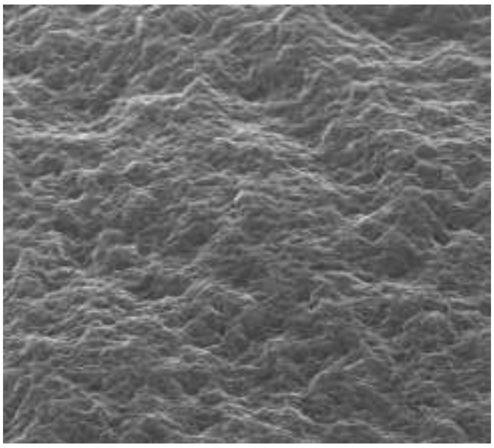

Figure 3. Polymer composite.

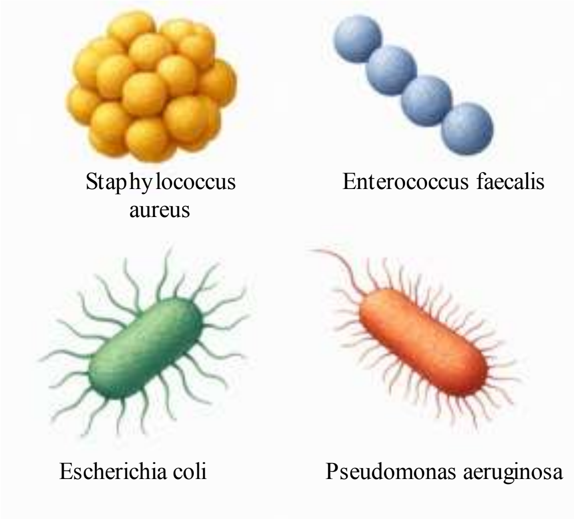

Figure 4. Images of the bacteria.

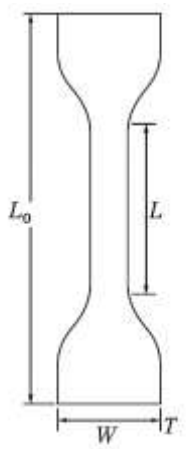

Figure 5. Technical illustration of a tensile test specimen.

A scientific illustration has now been added (Figure 4) that visually represents the key bacterial strains investigated in this study: Staphylococcus aureus, Enterococcus faecalis, Escherichia coli, and Pseudomonas aeruginosa. These bacteria were selected due to their clinical relevance and their roles in evaluating the antimicrobial efficacy of the developed polymer composites.

Figure 5 is a technical illustration of a tensile test specimen. It typically shows: A standardized "dog bone" shaped sample. Dimensions following ASTM D638 (commonly Type V or similar) used for testing mechanical properties of polymers. Gripping regions and the narrow-gauge section where deformation occurs.

DISCUSSION

Structural and Chemical Characterization

Fourier-transform infrared (FTIR) spectroscopy confirmed the successful incorporation of metal oxide nanoparticles (MONs) into the PET-EVA matrix. Characteristic peaks corresponding to metal-oxygen interactions exhibited noticeable shifts, indicating strong interactions between the nanoparticles and the polymer matrix.[11] Specifically, peaks associated with Cu-O, Zn-O, and Mg-O bonds were observed, confirming the presence of Cu_2O, ZnO, and MgO_2, respectively. These interactions play a crucial role in enhancing the material's functional properties, including antimicrobial efficacy and mechanical strength.

Scanning electron microscopy (SEM) imaging provided further validation, revealing a homogeneous dispersion of nanoparticles within the polymer matrix. Uniform distribution is essential for maintaining the composite's overall integrity, ensuring consistent antimicrobial activity, and preventing localized mechanical weaknesses.[12] Higher magnification SEM images showed that the nanoparticles formed a well-integrated network within the polymer, suggesting strong adhesion and minimal aggregation, which are key factors in optimizing the material's performance.

Antimicrobial Properties

Antimicrobial activity tests were conducted using bacterial strains *Escherichia coli* (E. coli) and *Staphylococcus aureus* (S. aureus), as well as the fungal strain *Aspergillus niger* (A. niger). The results demonstrated a significant reduction in microbial growth in PET-EVA composites embedded with MONs.[13] Among the different MONs studied, Cu_2O nanoparticles exhibited the highest antimicrobial efficacy, likely due to their ability to induce oxidative stress and disrupt microbial cell membranes.

ZnO and MgO_2 composites also displayed notable antimicrobial activity, though their efficacy varied depending on nanoparticle concentration. Higher concentrations of ZnO resulted in increased microbial inhibition, attributed to the generation of reactive oxygen species (ROS), which disrupt bacterial and fungal cellular processes.[14] Similarly, MgO_2 exhibited moderate antimicrobial properties, primarily due to its ability to release active oxygen species. These findings indicate that MONs significantly enhance the antimicrobial function of PET-EVA composites, making them promising candidates for food packaging and biomedical applications.

Barrier and Optical Properties

UV-Vis spectroscopy analysis demonstrated that PET-EVA-Cu_2O composites exhibited the lowest UV transmittance, indicating superior barrier properties against light-induced degradation. The inclusion of Cu_2O nanoparticles significantly reduced UV exposure, thereby enhancing the stability and longevity of the composite material. This property is particularly advantageous for food packaging applications where protection from light-induced spoilage is critical.[15]

Furthermore, the opacity of the composite increased with MON concentration, directly impacting its ability to shield light-sensitive products. While high transparency is often desirable for consumer visibility, controlled opacity can be beneficial for specific applications such as pharmaceutical and food packaging, where UV protection is essential. The variation in optical properties highlights the need for tailored MON concentrations based on the intended application of the composite material.[16]

Mechanical Properties

Tensile testing was performed to assess the mechanical properties of MON-reinforced PET-EVA composites. The results indicated a significant improvement in tensile strength compared to the unmodified polymer matrix. PET-EVA-Cu_2O composites demonstrated the highest enhancement, with a 20% increase in tensile strength, attributed to strong interfacial interactions between the nanoparticles and the polymer matrix.

The incorporation of ZnO and MgO_2 also contributed to improved mechanical performance, albeit to a lesser extent than Cu_2O. The reinforcement effect was attributed to the uniform dispersion of nanoparticles, which contributed to increased rigidity and reduced polymer chain mobility. [17] Additionally, elongation at break was marginally reduced, suggesting a slight trade-off between flexibility and strength. These findings suggest that the addition of MONs enhances the mechanical durability of PET-EVA composites, making them suitable for various packaging and structural applications.[18]

Shelf-Life Extension

A shelf-life study was conducted using milk samples stored in PET-EVA-MON composite packaging

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under refrigeration (5°C). The results demonstrated that PET-EVA-Cu_2O extended milk shelf life up to 8 days, compared to 4-6 days for ZnO and MgO_2 composites. The enhanced shelf-life extension was primarily attributed to the antimicrobial properties of MONs, which reduced microbial proliferation and spoilage. [19, 20]

The ability of Cu_2O to inhibit bacterial growth more effectively than ZnO and MgO_2 resulted in a prolonged freshness period. ZnO-containing composites also exhibited substantial microbial inhibition, but their effectiveness was slightly lower due to variations in ROS generation. MgO_2, while effective, had the least impact on extending shelf life, suggesting that its antimicrobial action was relatively moderate compared to Cu_2O and ZnO. [21, 22]

CONCLUSION AND FUTURE PERSPECTIVES

The development of MON-reinforced PET-EVA composites presents a promising solution for antimicrobial food packaging by combining enhanced functionality with improved material properties. Among the tested formulations, PET-EVA-Cu_2O demonstrated superior antimicrobial efficacy, effectively inhibiting bacterial growth and ensuring extended food preservation. Additionally, this composite exhibited excellent barrier properties, reducing the permeability of oxygen and moisture, which are critical factors in maintaining food freshness. The mechanical strength of PET-EVA-Cu_2O was also significantly improved, ensuring durability and resistance to physical stress during transportation and storage. Future research in this area will focus on further optimizing the recyclability and biodegradability of these composites to promote environmental sustainability. The incorporation of biodegradable fillers or novel biopolymeric blends may enhance the decomposition rate of these materials, reducing plastic waste accumulation. Moreover, advancements in recycling technologies will be explored to ensure that PET-EVA composites can be efficiently reprocessed without compromising their antimicrobial and mechanical properties. Investigating alternative antimicrobial agents with lower environmental impact, such as natural extracts or bio-based nanoparticles, could further improve the sustainability of these materials. By integrating these improvements, MON-reinforced PET-EVA composites could offer a long-term solution for food packaging, aligning with global efforts to reduce plastic pollution while ensuring food safety and shelf-life extension. Continued interdisciplinary research will be crucial in overcoming existing challenges and accelerating the adoption of these materials in commercial packaging applications.

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