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Progress in food packaging applications of biopolymer-nanometal composites — A comprehensive review

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Highlights

- Report on the importance of biopolymers as food packaging materials
- Metal nanoparticles (MNPs) improved the functionality of food packaging materials.
- The review summarizes advancements, challenges, and opportunities in MNPs-incorporated biopolymer-based food packaging.

Abstract

Eco-friendly nanotechnology-enabled biopolymers are one of the novel concepts of packaging materials to substitute traditional synthetic polymers and their composites. This article succinctly reviews the recent developments of introducing additional functionalities to biopolymers using metal and metal oxide nanoparticles. The functionality of metal nanoparticles such as silver, zinc oxide, titanium dioxide, copper oxide, gold, and magnesium oxide, as food packaging materials were discussed. The addition of nanoparticles in biopolymers improves mechanical properties, gas barrier properties, durability, temperature stability, moisture stability, antimicrobial activity, antioxidant property, and UV absorbance and can prevent the presence of ethylene and oxygen, hence extending the shelf life of foodstuffs. Other than this, the functional activity of these biopolymer composite films helps them to act like smart or intelligent packaging. The selection of metal nanoparticles, particle migration, toxicological effect, and potential future scope in the food packaging industry are also reviewed.

Introduction

The global growth in the human population, lifestyle changes, and urbanization have led to increased consumption of ready-to-eat food products, resulting in a rise in the global food packaging market size. It is anticipated that the market size will reach USD 463.65 billion by 2027 [1]. This increased demand shows the necessity for fresh, high-quality food that is free from artificial preservatives and microbial organisms while also having an extended shelf life. According to the World

Health Organization (WHO), approximately 600 million people fall ill, and 420,000 people die annually due to the consumption of contaminated food [2]. This is because most of the food items are vulnerable to attack by pathogenic microorganisms such as *Escherichia coli* (*E. coli*), *Staphylococcus aureus* (*S. aureus*), *Campylobacter* sp., *Shigella*, *Listeria monocytogenes* (*L. monocytogenes*), and *Salmonella typhimurium* (*S. typhimurium*) [3].

According to the World Economic Forum, and Food and Agriculture Organization of United Nations statistical data, 30% of food is wasted due to microbial activity and shelf-life issues, resulting in an approximate $1 trillion economic loss [4,5]. Therefore, appropriate treatment, packaging, and storage are essential to avoid contamination, preserve the nutritional values of food, prevent microbial organisms, and reduce food loss. Additionally, packaging should be environmentally friendly [[6], [7], [8], [9], [10]]. Fig. 1 displays a photograph depicting vegetable and fruit waste from a supermarket in Bangalore, India.

There is constant pressure on food companies to deliver high-quality food products, leading them to employ various approaches for storing fruits, vegetables, and ready-to-eat foods, such as metal containers, plastic containers, aluminum foil, and flexible plastic packaging [11,12]. In recent years, plastics have become the preferred choice for packaging due to their flexible processability, lightweight nature, and cost-effectiveness. Both non-biodegradable and biodegradable polymers are utilized in the production of food packaging films. Traditional polymers (polyethylene terephthalate, polystyrene, and polypropylene) offer advantages such as affordability and superior physical and thermo-mechanical properties over biodegradable polymers. However, their environmental impact is significant, with less than 10% of plastic being recycled, leading to plastic accumulation in landfills and oceans (*with 11 million metric tons of plastic leaking into the ocean annually*). Plastic photodegradation into microplastics poses a threat to marine life and may eventually impact land animals [13,14].

In this context, biopolymers emerge as a potent solution and an adequate substitute for petroleum-based polymeric materials, reducing the environmental impact of oil-based polymers. At present, the major drawback of biopolymers is their high cost, it costs around 4000 to 15,000 USD/metric ton compared to 1500 USD for synthetic polymers since they are derived from natural materials [15]. However, the price of biopolymers is expected to fall with more and more manufacturers from Europe, the USA, China, Japan, Thailand, and India adopting biopolymers with new manufacturing technologies. When it comes to life cycle assessment, biopolymers emit less greenhouse gases, have less environmental toxicity, and use less fossil fuel compared to traditional plastic [16]. Also, biopolymers are fully biodegradable, undergoing degradation through microbial processes, resulting in biomass, CO_2, CH_4, and H_2O, thus posing fewer disposal problems [17,18].

Food packaging is one of the most important applications of biopolymers because of its biodegradability, biocompatibility, and eco-friendliness. Synthetic plastic food packaging waste constitutes two-thirds of the total plastic waste accumulated on Earth by volume. Therefore, there is a growing demand for the replacement of conventional plastics from every corner of the globe. The use of lightweight, fully green biopolymers, their blends, and composites with high durability is an effective alternative to traditional non-biodegradable plastics [19,20]. For instance, BIO FVSOL 60, a transparent film by SP GROUP (Spain/France), combines polylactic acid (PLA) and polyvinyl alcohol (PVA), offering 100% biodegradability with good rigidity, making it widely used as an eco-friendly food packaging material [21].

Furthermore, new environmental regulations from authorities like the American Food and Drug Administration (FDA), European Commission (EC), and Plastic Waste Management (Second Amendment) Rules, 2022 (India) are increasing the demand for biodegradable plastics in the global market [[22], [23], [24]]. The market size of biopolymers/biodegradable plastics is expected to rise from USD 10.7 billion in 2021 to USD 29.7 billion by 2026, at a CAGR of 22.7%. This growth is primarily driven by the expansion of the packaging industry [25]. Fig. 2 records the number of published research articles, review articles, and book chapters featuring the keyword “biopolymers as food packaging materials” from 2015 to 2023 from Science Direct (https://www.sciencedirect.com ↗) [26]. A significant increase in the number of review articles, research papers, and books on biopolymers as food packaging materials is observed in Fig. 2.

Biopolymers are categorized based on their origin into two main types: (i) natural biopolymers, sourced from polysaccharides (such as starch, cellulose, pectin, and chitosan (CS)), and proteins (including soya, zein, casein, whey protein, and gelatin), and (ii) synthetic biopolymers, derived from (a) microbial production (e.g., polyhydroxyalkanoates), (b) biomass (e.g., PLA), and (c) petroleum products (e.g., polycaprolactone (PCL)) [27,28]. Both types of biopolymers find applications in various fields, including biosensors [29], food packaging [30], water treatment [31], adsorbents [32], and industries such as food, biomedical, pharmaceuticals, cosmetics, bone tissue engineering, medicine, and cancer therapy