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Review article

Enhancing biodegradable smart food packaging: Fungal-synthesized nanoparticles for stabilizing biopolymers

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ABSTRACT

The increasing global concern over environmental plastic waste has propelled the progress of biodegradable supplies for food packaging. Biopolymer-based packaging is undergoing modifications to enhance its mechanical properties, aligning with the requirements of smart food packaging. Polymer nanocomposites, incorporating reinforcements such as fibers, platelets, and nanoparticles, demonstrate significantly improved mechanical, thermal, optical, and physicochemical characteristics. Fungi, in particular, have garnered significant interest for producing metallic nanoparticles, offering advantages such as easy scaling up, streamlined downstream handling, economic feasibility, and a large surface area. This review provides an overview of nano-additives utilized in biopackaging, followed by an exploration of the recent advancements in using microbial-resistant metal nanoparticles for food packaging. The mycofabrication process, involving fungi in the extracellular or intracellular synthesis of metal nanoparticles, is introduced. Fungal functionalized nanostructures represent a promising avenue for application across various stages of food processing, packaging, and safety. The integration of fungal-derived nanostructures into food packaging materials presents a sustainable and effective approach to combatting microbial contamination." By harnessing fungal biomass, this research contributes to the development of economical and environmentally friendly methods for enhancing food packaging functionality. The findings underscore the promising role of fungal-based nanotechnologies in advancing the field of active food packaging, addressing both safety and sustainability concerns. The study concludes with an investigation into potential fungal isolates for nanoparticle biosynthesis, highlighting their relevance and potential in advancing sustainable and efficient packaging solutions.

1. Introduction

As natural resources are depleted and global environmental waste rises due to the widespread use of petroleum-based plastic packaging, there is a need for innovative and sustainable packaging solutions. This research exploration focuses on using biopolymers in food packaging to reduce environmental impact and promote ecological sustainability [1–4]. Robertson (2006) defines active packaging as intentionally adding materials or additives to package components to improve overall performance [5]. Janjarasskul and Suppakul (2018) conducted a comprehensive analysis of active packaging systems, including oxygen and CO_2 scavengers, moisture

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and ethylene gas regulators, and flavor and odor release/adsorption systems. The analysis examined package designs that discharge antibacterial agents or antioxidants. Smart packaging combines logic and intelligence to detect environmental changes. These functions involve detecting, recording, tracking, transmitting, and using algorithms to extend shelf life. Smart packaging delivers vital information and serves as an alert system to detect potential issues [6]. Packaging material constitutes more than 30 % of the world's plastic usage [7]. Notably, the global plastic production capacity witnessed an increase from 359 million tons to 368 million tons in 2019 [8]. The food sector plays a substantial role in bioplastic packaging, as evidenced by its significant contribution [9–11]. Projections indicate that global bioplastic production is expected to surge from 2,110,000 to 2,870,000 tonnes by the year 2025 [8].

Proper packaging with gas and water vapor barrier qualities is essential for covering product shelf life and preventing deterioration caused by physicochemical or biological causes. Packaging materials based on biopolymers are a sustainable approach for extending shelf life by reducing microbiological development. These materials not only protect against moisture, water vapor, and gasses but also biodegrade responsibly to meet environmental issues. Wong et al. (1994) found that biopolymer films can improve food quality and shelf life by serving as excellent gas and solute barriers [12,13]. Biopolymer films can be enhanced with a variety of additives, including pigments, additional nutrients, antifungal agents, antioxidants, and antimicrobials [14,15]. According to recent statistics, the market for biodegradable plastics is expected to expand by 8.4 % between 2016 and 2022. By 2022, the market is expected to reach $16.8 million [16].

Due to thermal instability and brittleness [17], low barrier properties against environmental materials such as oxidants and UV radiations, and inefficiency of multi-stage fermentation processing [18], long periods of casting and evaporation processing [19], problems in the extrusion connected to the physical response of the screw-imposed stress [19] and high production costs [20], Biopolymer-based packaging materials are not commonly utilized for food packaging. Those films have been limited in industrial use due to their relatively poor mechanical and water vapor barrier properties. As a result of their hydrophilic nature [21], protein and polysaccharide films have good mechanical characteristics and act as excellent oxygen barriers at low to intermediate relative humidity. Researchers modified natural biopolymer-based coatings to enhance mechanical and water-vapor barrier characteristics [22]. Polymer nanocomposite materials, reinforced with fibers, platelets, or nanoparticles (NPs), exhibit superior mechanical, thermal, optical, and physicochemical properties [23]. Using a low polymer loading, often below 5 %, can improve strength, modulus, heat resistance, and reduce gas permeability and flammability [24].

Biological media can be used to create NPs, reducing the negative impact of physical and chemical processes [25]. NPs can be biosynthesized at mild pH levels, pressures, and temperatures without the need for poisonous or hazardous compounds. External reducing, capping, and stabilizing agents are not required. Recent research has reported the production of different NPs including metals, metal oxides, and dioxide NPs, including core/shell (CS) [26], polymer-coated [27], silver [28], copper [29], copper oxides [30], zink oxides [31], gold [32], iron oxides [33], and titanium dioxides NPs [34].

Various biological systems, including yeast, bacteria, actinomycetes, fungi, algae, and plant extracts, have been employed for the synthesis of NPs. Notably, the exploration of microbial sources, particularly bacteria and fungi, has been a subject of investigation for the production of diverse metal NPs [35]. Various organisms, encompassing both unicellular and multicellular cells, have been harnessed for the green synthesis of NPs. This eco-friendly process involves the oxidation/reduction of metallic ions facilitated by enzymes, proteins, sugars, and carbohydrates [35]. This represents a bottom-up methodology for NP synthesis. However, the mechanisms underlying microbial NP synthesis remain largely unclear, given that each type of microorganism interacts with metallic ions in distinct ways. The size, shape, and morphology of NPs are influenced by the biochemical processing and interaction activities of microorganisms, alongside environmental factors, during the synthesis process [36]. The green synthesis processes face primary challenges, including the need for optimization processes to achieve NPs with specific sizes and shapes, which can influence their biological activities. Additionally, analyzing the biological biomass filtrate is essential to discern the role of each compound in the biofabrication process [37].

As fungal metabolites can fabricate NPs, they have been extensively used for NP biosynthesis [38–40]. NP fabrication using fungi is a valuable addition to microbial options. Fungi are preferred for their ability to produce abundant proteins or enzymes and ease of handling in the lab [41]. Fungi are highly favored for metallic NP synthesis due to advantages such as easy scaling up, economic feasibility, efficient downstream handling, and the substantial surface area presented by mycelia [42]. Fungi are being explored for the biological production of metallic nanomaterials due to their metal tolerance and capacity to bioaccumulate them [43]. Since fungi produce a large amount of extracellular enzymes and proteins, it is possible to construct a vast array of enzymes [43]. Leveraging biomass for nanomaterials offers economic feasibility and sustainability, with fungi's rapid growth allowing for easy maintenance in laboratories. Fungi, through biomimetic mineralization, exhibit the capability to form metal NPs in diverse structures, including meso- and nanostructures [44]. The process of synthesizing NPs using fungi, especially in medicine, is known as myconanotechnology [45].

This study is dedicated to a comprehensive exploration of the progress in smart food packaging, encompassing three pivotal sections. Our initial focus is on biopolymer-based nanofilms for smart packaging, where we meticulously examine their importance, advantages, and limitations. Following this, we present a detailed survey on smart packaging that employs nanofilms synthesized by fungi from biopolymers. In the concluding section, we aim to thoroughly address the existing knowledge gaps of biopolymer-based nanofilms in smart food packaging.

2. Biodegradable smart food packaging

Biopolymers, derived from agricultural or biomass sources, offer biodegradable and sustainable materials for applications in packaging. These alternatives to non-renewable plastics possess enhanced physical and mechanical properties, making them competitive with conventional plastics while being degradable by microorganisms in landfills or compost [46,47]. In contrast to common petroleum-based packaging materials, biopolymers have a limited barrier, mechanical, processing, and price properties [48–50] as well as relatively high prices as packaging materials. To enhance biopolymer-based packaging materials, various modification methods have been developed. These include altering the chemical structure through block-copolymerization and post-polymerization modification, as well as incorporating organic and inorganic compounds. Strategies such as plasticization, blending with other biopolymers, and adding nanomaterials at suitable levels are employed to improve their overall properties [47,51,52].

In specific applications, the modification of biopolymer properties frequently involves the use of plasticizers. Plasticizers intermolecularly connect polymer chains, inducing conformational changes that enhance deformability [53]. Plasticization serves as a strategy to address the brittleness of bio-nanocomposite films and enhance their flexibility. Common plasticizer materials employed in food packaging polymeric matrices include sorbitol, glycerol, polyethylene glycol (PEG), tributyl citrate (TBC), and triacetin (TA) [54,55]. Plasticizers' low molecular weight causes movement to the matrix surface, posing environmental and health risks. Finding a good plasticizer with limited mobility and relatively high molecular weight is crucial [56,57]. Polymer blending is an effective strategy involving the creation of a homogenized mixture of various polymers to enhance the mechanical properties of the final film. According to Taguet (2020), achieving the desired properties relies on the miscibility and compatibility of polymers. Additionally, the incorporation of NPs is employed to reinforce polymer structures [58].

Various industries provide biodegradable packaging, utilizing diverse polymers with applications in the food industry. To meet the demand for environmentally friendly packaging, companies such as Mater-Bi®, VersaPack®, BIOPAR®, and PlanticTM are actively involved in producing biodegradable food packaging worldwide [59]. Polylactic acid (PLA), derived from sugarcane and corn starch, is utilized for biodegradable films, alongside starch. PLA production involves ring-opening polymerization with metal catalysts or condensation of lactic acid monomers. Despite its FDA classification as Generally Recognized as Safe (GRAS), PLA-based plastics have limitations in handling hot liquids due to low glass transition temperature and brittleness, emphasizing the need for cautious use in biodegradable food packaging under Good Manufacture Practices (GMP) [60]. As a result of the European Commission's approval (Commission Regulation No. 10/2011), PLA is a suitable material to use for food-contact applications [61].

In response to the adverse environmental impact of traditional non-biodegradable plastics, there is a growing market demand for biodegradable food packaging. Utilizing agroindustry wastes, plants, microorganisms, and microbes as sources, these materials aim to mitigate pollution issues by reducing reliance on oil-based products and substituting non-biodegradable plastics [62]. Biodegradable food packaging not only provides eco-friendly alternatives for extending shelf life, preserving moisture, enhancing organoleptic characteristics, and ensuring food safety but also contributes to global sustainability efforts. It stands as a pivotal technology for responsible industrial development worldwide.

2.1. Advantages of biopolymer-based nanofilms smart packaging

In recent scholarly endeavors, a multitude of studies have been undertaken to augment the physical and mechanical properties of biopolymers through the strategic integration of nanoscale particles [63,64]. Aside from improving biopolymers' mechanical properties, nanofilms (ultra-thin film or coating composed of nanoscale materials, typically in 1–100 nm thickness) are also capable of improving the polymer matrix's gas and water barrier properties, thus extending the shelf life of packaged food [65]. Aside from these qualities, antibacterial and antimicrobial properties of some nanofillers prevent the food inside the package from spoiling rapidly [49,66,67]. NP-infused packaging materials exhibit enhanced mechanical, rheological, barrier, and thermal properties, thereby elevating the overall performance of food packaging. These nanoscale reinforcements contribute quantitatively by augmenting the interface surface area, providing rigidity and reinforcement at low concentrations in composites. Beyond mechanical enhancements, these NPs confer gas adsorption and antimicrobial properties to biopolymers. Notably, nanosilicates, metals, metal oxides, phenolic compounds, and flavonoids stand out as the most extensively researched nanomaterials [49]. A variety of polymers can be enhanced by adding metal or metal oxide NPs, including their thermal stability, optical properties, glass transition temperatures, toughness, tensile strength, and antibacterial properties [68]. The use of copper, zinc, and silver NPs, along with copper oxide NPs, has been indicated to improve the physical and chemical properties of packaging materials [69]. NPs of silver, copper oxide, and zinc peroxide may develop antiviral properties when incorporated into biopolymers [70]. A biopolymer infused with those NPs inhibits microbial cells [71] and intestinal viruses [72].

Table 1 summarizes some nano-additives being used in packaging materials. The use of microbial-resistant metal NPs for food packaging has been studied in recent years. There are four types of antimicrobial agents: organic compounds, metals and metal oxides, essential oils, and herbal extracts. The mechanism of antimicrobial action of metal NPs is based on cell membrane [73] and intra-cellular [74] damage (i.e. cell wall lipids, genetic content, proteins, and enzymes) of microbial components (Fig. 1).

Food, however, is generally sensitive to oxygen. Food loses nutrients, discolors, loses vitamins, and loses shelf-life because of oxygen-produced oxidative reactions [75]. Appearance, flavor, and texture of food which determine the food quality can change due to oxidative rancidity which refers to the autoxidation of unsaturated fatty acid chains of lipids by O_2. Following a chain mechanism of free radicals, autoxidation can occur in three stages, namely, initiation, propagation, and termination (Scheme 1). A slight amount of hydroperoxides, mostly produced by enzymatic oxidation or photooxidation, synthesize radicals through metal catalysis [76].

Active packaging, employing oxygen and moisture absorbers, is vital for preserving food quality. Oxygen absorbers prevent rancidity, while active packaging reacts with or adsorbs ethylene to hinder food ripening. Moisture absorbers, like silica gel, combat excess moisture, preventing microbial growth. Chitosan/TiO_2 nanofilms, a promising active packaging solution, showed superior preservation effects in tomato storage. These nanofilms exhibited reduced quality changes and enhanced ethylene photodegradation, with potent antimicrobial activity against bacteria and fungi. This approach holds the potential for extending the storage life of

Table 1
) Application of biopolymer nanofilms with antimicrobial metal NPs agent in smart food packaging.

Biopolymers	Antimicrobial agent	Against	Quality effects	Synthesis process	Ref.
Chitosan	TiO_2	*Escherichia coli* *Salmonella Typhimuirum* *Pseudomonas aeruginosa* *Aspergillus oryzae* *Penicillium roqueforti*	1) Higher ethylene photocatalytic degradation 2) Lower CO_2 production rate 3) Higher fruit firmness 4) Lower lycopene content 5) Longer storage life	Solution casting method	[77]
Chitosan	Ag TiO_2	*Escherichia coli*	1) Higher inhibition of microorganism growth 2) Higher wettability on cantaloupe rind	Photochemical reduction method	[78]
Chitosan	ZnO	*Escherichia coli* *Staphylococcus aureus*	1) Higher shelf life of raw meat.	Solution casting method	[79]
Chitosan/PVA	Black carrot anthocyanins	*Escherichia coli* *Pseudomonas aeruginosa* *Staphylococcus aureus*	1) Lower water vapor permeability 2) Higher inhibition of microorganism growth	Solution casting method	[80]
Chitosan/calcium silicate	Ag	*Staphylococcus aureus* *Pseudomonas aeruginosa* *Candidia albicans*	1) Higher light reflectance 2) Good antibacterial and antifungal activity	Sol–gel method	[81]
Chitosan/gelatin	ZnO Black peanut seed coat anthocyanins	–	1) Strong antioxidant properties 2) High antibacterial properties 3) Enhancement of UV resistance 4) Feature pH-sensing color-change 5) High shelf life of shrimp	Solution casting method	[82]
Red apple pomace extract/ chitosan	TiO_2	*Escherichia coli* *Staphylococcus aureus*	1) Improved mechanical properties 2) Exceptional antioxidant effects 3) Outstanding antimicrobial effectiveness	Solution casting method	[83]
Chitosan	Montmorillonite/CuO	*Escherichia coli* *P.aeruginosa* *Staphylococcus aureus* *B.cereus*	1) Lower water solubility 2) Lower UV transition 3) Outstanding antimicrobial effectiveness	Solution casting method	[84]
Chitosan/polyvinyl alcohol	ZnO/purple potato or roselle anthocyanins	*Escherichia coli* *Staphylococcus aureus*	1) Darker color 2) Lower light transmittance 3) Higher antimicrobial efficacy 4) Effectively monitoring shrimp freshness	Solution casting method	[86]
Poly(sodium styrene sulfonate)	Co_3O_4	*Escherichia coli* *Staphylococcus aureus* *C. albicans* *Aspergillus niger*	1) Long-term stability 2) High sensitivity at room temperature 3) Fast response/recovery time	Layer-by-layer self-assembly	[134]
Chitosan	Ag/rich purple corn anthocyanins	*Escherichia coli* *Salmonella Typhimuirum* *Staphylococcus aureus* *L. monocytogenes*	1) Improved UV–vis light barrier 2) High water vapor barrier 3) Good antioxidant efficiency 4) Excellent antimicrobial properties	Solution casting method	[85]
Chitosan	Ag	*Escherichia coli* *Staphylococcus aureus*	1) Low moisture contents 2) Decreased water vapor permeability 3) Good antioxidant efficiency 4) Excellent antimicrobial properties	Tea polyphenols-mediated biosynthesis	[87]
Chitosan	ZnO Antioxidant of bamboo leaves (AOB)	*Escherichia coli* *Staphylococcus aureus*	1) High UV-light protection 2) Good antioxidant efficiency 3) Excellent antimicrobial properties	Solution casting method	[135]

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Table 1 (*continued*)

Biopolymers	Antimicrobial agent	Against	Quality effects	Synthesis process	Ref.
Starch/polyvinyl alcohol	Ag	*Escherichia coli* *Staphylococcus aureus*	1) High tensile strength 2) Water resistance efficiency 3) Excellent antimicrobial properties 4) Low release of NPs	Oregano essential oil-mediated biosynthesis	[89]
Cassava Starch/polyvinyl alcohol	Ag	*Listeria innocua* *Escherichia coli* *Aspergillus niger* *Penicillium expansum*	1) Good anti-bacterial and fungal activity 2) Low release of NPs	Solution casting method	[90]
Starch/polyethylene	ZnO	*Escherichia coli* *Staphylococcus aureus*	1) Good antioxidant efficiency 2) Excellent antimicrobial properties	Walnut leaf extract-mediated biosynthesis	[91]
Chitosan	Streptomycin loaded starch nanocrystals	*Escherichia coli* *Bacillus subtilis*	1) Low swelling nature 2) Sustainable release of NPs 3) Excellent antimicrobial properties	Solution casting method	[136]
Starch	Albumin/MgO	*Escherichia coli* *Staphylococcus aureus*	1) Increasing of nanofilms' thickness 2) Low moisture content 3) Low water vapor permeability 4) Excellent antimicrobial properties	Solution casting method	[92]
Starch	ZnO Chitosan	*Escherichia coli* *Staphylococcus aureus*	1) Substantial decrease of water vapor 2) Strong suppression of bacteria	Sol-gel method	[88]
Potato starch/apple peel pectin	ZrO_2 *Zataria multiflora* essential oil	*Escherichia coli* *Bacillus cereus*	1) Increased shelf life of quail meat 2) Strong suppression of bacteria	Ultrasound-mediated microencapsulation	[137]
Poly(vinyl alcohol)/graphene oxide/starch	Ag	*Escherichia coli* *Staphylococcus aureus*	1)Enhanced mechanical features 2) Improved thermal behaviors 3) Enriched antimicrobial properties	Solution casting method	[138]
Potato starch	Tea polyphenol MgO	*Escherichia coli* *Staphylococcus aureus*	1) Good hydrophilic surface 2) Increased thermal stability 3) Enriched antimicrobial properties 4) UV light-blocking 4) high hydrophobicity	Solution casting method	[98]
Sugar palm starch	Ag	*Escherichia coli* *Salmonella cholerasuis* *Staphylococcus aureus*	1)Enhanced mechanical features 2) Improved thermal behaviors 3) Enriched antimicrobial properties	Solution casting method	[93]
Starch	Ag, ZnO and CuO	*Escherichia coli* *Staphylococcus aureus*	1) High tensile strength 2) Low solubility in water 3) Enriched antimicrobial properties	Solution casting method	[94]
Chicken skin gelatin/tapioca starch	ZnO	*Escherichia coli* *Staphylococcus aureus*	1) High tensile strength 2) increased water vapor permeation 3) Enriched antimicrobial properties	Solution casting method	[96]
Starch-PVA	ZnO and phytochemicals	*S. typhimurium*	1) Enhanced UV-light barrier properties 2) Excellent water barrier 3) Enriched antimicrobial properties	Solution casting method	[97]
Starch/agar	Ag	*Escherichia coli* *L. monocytogenes*	1) Improved water vapor barrier and hydrophobicity 2) Robust antimicrobial activity	Enoki mushroom extract-mediated biosynthesis	[95]
Acrylamide/cellulose-based filter paper	Ag	*Escherichia coli*	1) Robust antimicrobial activity	Graft copolymerization	[139]

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Table 1 (*continued*)

Biopolymers	Antimicrobial agent	Against	Quality effects	Synthesis process	Ref.
Carboxymethyl cellulose	Ag ZnO CuO	*Escherichia coli* *Staphylococcus aureus*	1)Enhanced mechanical features 2) Improved thermal behaviors 3) Enriched antimicrobial properties 4) Decreased water vapor permeability	Solution casting method	[99]
Bacterial cellulose	Ag	*Staphylococcus aureus* *Pseudomonas aeruginosa* *Escherichia coli* *Candida albicans* *Trichosporon* sp.	1) Enriched antimicrobial properties	Gluconacetobacter xylinus (ATCC53582)-mediated biosynthesis and *ex situ* synthesis	[140]
Carboxymethyl cellulose/cellulose coated paper	Ag	*Escherichia coli* *Staphylococcus aureus*	1)Enhanced mechanical features 2) Improved barrier behaviors 3) Enriched antimicrobial properties	Solution casting method	[141]
Semi-transparent regenerated cellulose	ZnO	*Escherichia coli* *Staphylococcus aureus* *Bacillus cereus* *L. monocytogenes* *S. typhimurium* *V. parahaemolyticus*	1) Improved UV and oxygen barrier behaviors 2) Enriched antimicrobial properties	Solution casting method	[100]
Monolayer and multilayer bacterial cellulose	ZnO	*Escherichia coli* *Staphylococcus aureus*	1)Enhanced mechanical features 2) Decreased water vapor permeability 3) Enriched antimicrobial properties	Gluconacetobacter xylinus (ATCC53582)-mediated biosynthesis and ultrasonic power	[101]
Cellulose nanofiber	Ag	*Escherichia coli* *Staphylococcus aureus*	1) Enriched antimicrobial properties	Ultraviolet (UV) irradiation method	[142]
Carboxymethyl Cellulose/Gelatin	TiO_2–Ag	*Escherichia coli* *Staphylococcus aureus*	1) Effective antioxidant properties 2) Good antimicrobial activity 3) Increased film elasticity	Solution casting method	[102]
Cotton linters-based cellulose/ tamarind nut power	Cu	*Escherichia coli* *Staphylococcus aureus* *Pseudomonas aeruginosa* *Bacillus licheniformis*	1)Enhanced thermal stability 2) Good antimicrobial activity	*In situ* generation by hydrothermal method	[143]
Cellulose/banana peel powder	Ag	*Escherichia coli* *Staphylococcus aureus* *Pseudomonas aeruginosa* *Bacillus licheniformis*	1)Enhanced thermal stability 2) High tensile properties 3) Good antimicrobial activity	Solution casting method	[103]
Cellulose/sodium alginate (SA)	CuO	*Escherichia coli* *Salmonella* sp. *Candida albicans*	1) Challenging antioxidant activity 2) Good antimicrobial activity	Solution casting method	[144]
Bacterial cellulose	ZnO Propolis	*Escherichia coli* *Bacillus subtilis* *Candida albicans*	1) No impact on Gram-negative and eukaryotic cells 2) Enhanced thermal stability 3) Effective antioxidant properties	Gluconacetobacter xylinum (ATCC53582)-mediated biosynthesis and ultrasonic power	[145]
Hydroxypropyl methylcellulose	Ag	*Escherichia coli* *Staphylococcus aureus*	1) Superior mechanical and barrier properties 2) High water vapor barrier properties 3) Good antimicrobial activity	Solution casting method	[104]
Sodium alginate/polyaniline	TiO_2	*Escherichia coli* *Staphylococcus aureus* *Candida albicans* *A. niger*	1) Maximum electrical properties 2) Enhanced thermal stability 3) Effective antibacterial properties	Sol–gel process and solution casting method	[105]
Sodium alginate	ZnO Citronella (lemongrass) essential oil (CEO)	*Escherichia coli* *Salmonella Typhi* *Bacillus cereus* *Staphylococcus aureus*	1) Good UV light barrier activity 2) Enhanced thermal stability 3) Effective antibacterial	Solution casting method	[106]

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Table 1 (*continued*)

Biopolymers	Antimicrobial agent	Against	Quality effects	Synthesis process	Ref.
			properties 4) High water vapor barrier properties		
Sodium alginate	Au-TiO_2	*Escherichia coli* *Staphylococcus aureus*	1) Good UV light barrier activity 2) Effective antibacterial properties	Solution casting method	[107]
Calcium cross-linked alginate	Sulfur NPs	*Escherichia coli* *L. monocytogenes*	1) Good UV light barrier activity 2) Enhanced thermal stability 3) Effective antibacterial properties 4) High water vapor barrier properties	Solution casting method	[146]
Sodium/chitosan/carboxymethyl chitosan	ZnO	*Escherichia coli* *Staphylococcus aureus*	1) Effective antibacterial properties 2) High water vapor barrier properties	Solution casting method	[108]
$CaSO_4$-crosslinked alginate	ZnO	*Escherichia coli* *Staphylococcus aureus*	1) High strength and low elasticity 2) Effective antibacterial properties 3) High water vapor barrier properties	Solution casting method	[147]
Poly(vinyl alcohol)/sodium alginate	Borate-stabilized Ag	*Escherichia coli*	1) Effective antibacterial properties	Solution casting method	[148]
Sodium alginate	TiO_2	*Salmonella typhimurium* *Candida albicans*	1) High photocatalytic activity 2) Effective antibacterial properties	Solution casting method	[111]
Starch/sodium alginate	Cu deposited graphitic carbon nitride (g-C3N4)	*Escherichia coli* *Staphylococcus aureus*	1) Enhanced tensile strength and barrier properties 2) Effective antibacterial properties	Solution casting method	[112]
Pectin-laponite/oxygen plasma surface-modified polypropylene films	Ag	*Escherichia coli* *Staphylococcus aureus*	1) Decreased oxygen transmission rate 2) High water vapor barrier properties 3) Effective antibacterial properties	Roller coating method	[109]
Pectin	Ag	*Escherichia coli* *Listeria monocytogenes*	1) Good optical and thermal properties 2) Effective antibacterial properties	Caesalpinia mimosoides Lamk (CMLE) extract-mediated biosynthesis	[113]
Pectin	Ag	*Escherichia coli* *Salmonella Typhimurium*	1) High water vapor barrier properties 2) Effective antibacterial properties	*In situ* synthesis using γ-irradiation	[114]
Chitosan-gelatin/pectin-gelatin	ZnO lemongrass essential oil (LEO)	*Escherichia coli* *Staphylococcus aureus* *B. subtilis*	1)Enhanced mechanical features 2) Decreased water vapor permeability 3) Enriched antimicrobial properties 5) Prolonged shelf life	Solution casting method	[110]
Pectin	TiO_2	*Escherichia coli*	1) Low thermal conductivity 2) Improved mechanical and thermal properties 3) Good antimicrobial properties	Sol-gel process	[115]
Chitosan/zein	Curcumin-loaded pectin-based NPs	*Escherichia coli* *Staphylococcus aureus*	1) High thermal stability 2) Good UV light barrier activity 3) Good antimicrobial properties	Solution casting method	[116]
Pectin/chitosan-	Fe_3O_4	*Escherichia coli* *Staphylococcus epidermidis*	1) Ferrimagnetic behavior 2) High antimicrobial properties	Solution casting method	[117]

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Table 1 (*continued*)

Biopolymers	Antimicrobial agent	Against	Quality effects	Synthesis process	Ref.
Pectin	Curcumin and sulfur NPs	*Escherichia coli* *Listeria monocytogenes*	1) pH change and ammonia vapor responsive 2) Good antioxidant properties 3) Good antimicrobial properties 4) Improved UV–vis light barrier features	Solution casting method	[118]
Pectin/Polyvinylpyrrolidone	TiO_2 Bael shell extract	*Escherichia coli* *Listeria monocytogenes*	1) Good tensile strength 2) Good UV light barrier activity 3) Good antimicrobial properties	Solution casting method	[119]
Black mulberry pectin/chlorophyll encapsulated carboxymethylcellulose	SiO_2	*Escherichia coli* *Staphylococcus aureus*	1) Good antioxidant properties 2) Good antimicrobial properties 2) Decreased water vapor permeability	Encapsulation	[120]
Pectin/chitosan	Ag	*Escherichia coli*	1) Increased thermal stability and crystallinity 2) Increased mechanical behaviors 3) Good antimicrobial properties	Solution casting method	[121]
Isolated mung bean protein/apple pectin	True cardamom extract microencapsulation CeO_2 Graphite carbon quantum dots	*Escherichia coli* *Staphylococcus aureus*	1) Good photocatalytic properties 2) Increased tensile strength and elongation length 3) High antimicrobial properties	Encapsulation	[122]
Pectin/alginate	ZnO	*Aspergillus niger* *Colletotrichum gloeosporioides* *Escherichia coli* *Saccharomyces cerevisiae*	1) Decreased water vapor permeability 2) Increased tensile strength and elongation length 3) High antimicrobial properties	Solution casting method	[123]
Poly(vinyl) alcohol/graphene oxide/Glutaraldehyde	Au	*Escherichia coli*	1) Increased tensile strength 2) Extended the shelf life 3) Good mechanical and antimicrobial properties	Separate cross-link method	[124]
3-aminopropyltrimethoxysilane/chitosan	Au	*Salmonella*	1) Good antimicrobial properties	Core-shell method	[125]
Furcellaran/graphene oxide/multi-walled carbon nanotubes	Ag	*Pseudomonas aeruginosa* *Enterococcus faecalis* *Staphylococcus aureus*	1) Excellent structural, physical, and thermal properties 2) Good antimicrobial and antifungal activity	Solution casting method	[126]
Soy Protein Isolate/Persian Gum	Ag	*Escherichia coli* *Staphylococcus aureus*	1) Enhanced tensile strength 2) Decrease elongation at break 3) Good antimicrobial activity	Solution casting method	[127]
Ethylene–vinyl alcohol copolymer	Ag	*Listeria monocytogenes* *Salmonella* spp.	1) Good antimicrobial activity	Solution casting method	[128]
Soybean Protein	Ag	*Escherichia coli* *S. enteric*	1) Enhanced tensile strength 2) Good oxygen barrier behavior 3) Good mechanical and antimicrobial properties 4) Good thermal stability	Solution casting method	[129]
Dextrin/polyvinyl alcohol	TiO_2	*Enterococcus faecalis*	1) Enhanced tensile strength 2) Decreased water solubility 3) Good mechanical and antimicrobial properties	Solution casting method	[130]
Dextran/cellulose nanofibrils	Ag	*Escherichia coli*	1) Reduced tensile strength 2) High flexibility 3) Minimized oxygen permeation and wettability	Solution casting method	[131]

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Table 1 (*continued*)

Biopolymers	Antimicrobial agent	Against	Quality effects	Synthesis process	Ref.
			3) Controlled antimicrobial properties		
Carboxymethyl chitosan	MgO	*Listeria monocytogenes* *Shewanella baltica*	1) Improved Thermal Stability 2) Better UV Shielding Performance: 3) The nanocomposite films exhibit resistance to water, making them ideal for packaging water-rich foods and preventing moisture-related issues. 4) Enhanced Crystallinity 5) Increased Elasticity and Ductility 6) Excellent Antimicrobial Activity	Solution casting method	[149]
Nanocellulose and arabinoxylan acetate	Ag	*Shigella flexneri* *Pseudomonas aeruginosa* *Aspergillus brasiliensis*	1) Improved Functional Properties. 2) The incorporation of AgNPs contributes to the good mechanical stability of the composite films. 3) The nanocomposite films demonstrate improved thermal stability, ensuring their performance under varying temperatures. 4) The nanocomposite films are eco-friendly and biodegradable, offering a sustainable solution for active food packaging.	Solution casting method	[150]
PVA-montmorillonite K10 clay	Ag	*S. Typhimurium* *Staphylococcus aureus.*	1) Superior Mechanical Properties: Compared to control films, the nanocomposite blend exhibited enhanced mechanical strength. 2) Water Resistivity: The film showed improved resistance to water. 3) Light Barrier Ability: Enhanced light barrier properties were observed in the nanocomposite blend films.	Solution casting method	[132]
Zein/sodium alginate	TiO_2	*Escherichia coli* *Staphylococcus aureus*	1) Surface Hydrophobicity: High surface hydrophobicity was observed. 2) Antioxidant Activity: The nanofiber sample showed DPPH scavenging activity of 64.42 ± 3.56 %. 3) Biocompatibility: In-vitro cell cytotoxicity assays confirmed the biocompatibility of the fabricated nanofibers.	Electrospinning	[133]

seasonal fruits [77]. In recent research, novel Ag/TiO_2/chitosan nanocomposites were developed through photochemical reduction [78]. Chitosan/ZnO was employed for the first time in portable packaging, extending the shelf life of raw meat [79]. Anthocyanin-infused chitosan/PVA nanofilms with bentonite nanoclays exhibited enhanced physical, thermal, and antimicrobial characteristics [80]. Investigating Ag NPs in chitosan/calcium silicate nanofilms revealed improved optical and antibacterial properties for food packaging [81]. Chitosan/gelatin/ZnO nanofilms, incorporating anthocyanins from black peanut seed coats, showed strong antioxidant, and antibacterial properties, and excellent freshness monitoring [82]. Nanofilms of chitosan/TiO_2 and red apple pomace were developed to preserve salmon fillets [83]. The addition of montmorillonite−CuO NPs into chitosan films improved tensile strength, elongation at break, and reduced water vapor and oxygen permeability [84]. Combining anthocyanins from purple potato or roselle with metal and metal oxide NPs demonstrated effective antimicrobial and antioxidant properties in chitosan films [85,

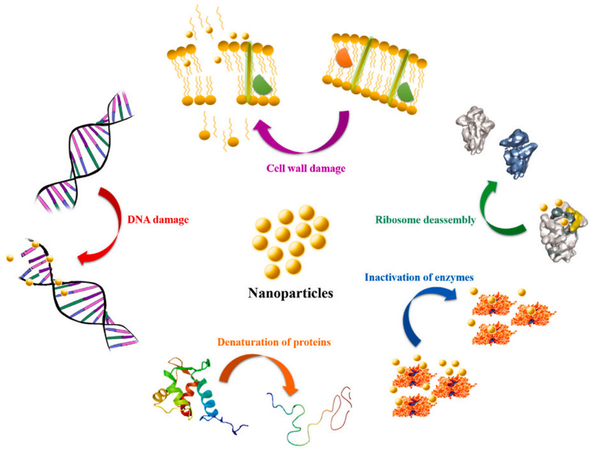
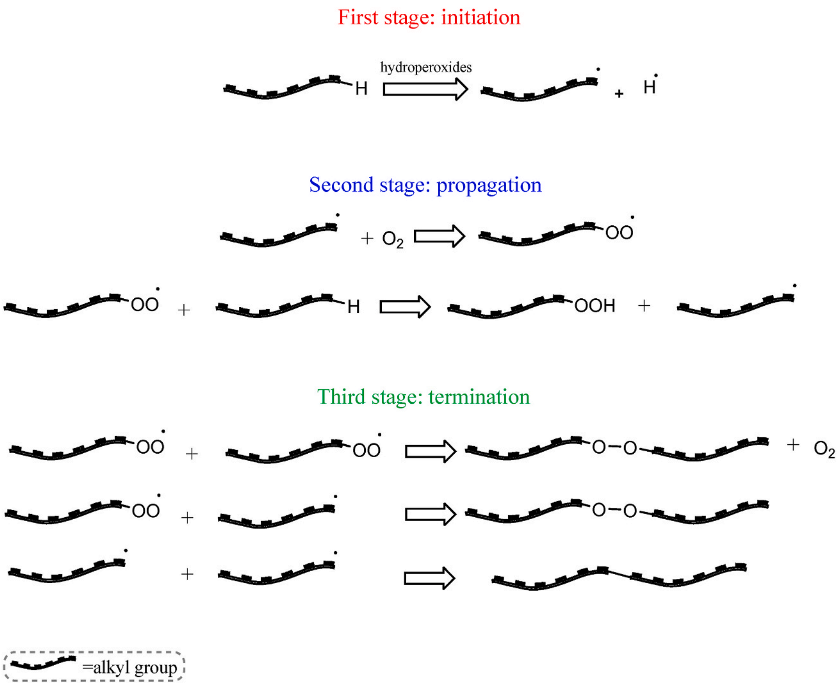


Fig. 1. Schematic illustration of damages introduced by NPs into microorganisms.



Scheme 1. Mechanism of oxidative deterioration of food material.

86]. Tea polyphenols were used as a stabilizing medium for the synthesis of metal NPs in chitosan/Ag NPs nanofilms [87].

Hu et al. (2019) inivestigated the antimicrobial NPs' incorporation, specifically 57.3 wt% ZnO, into a starch matrix for nanofilm synthesis using the sol-gel method. The findings revealed that integrating 3 % NPs into the starch matrix during the fabrication of antimicrobial films significantly enhanced their antibacterial efficacy against Gram-positive bacteria, outperforming films made exclusively from the starch matrix [88]. Incorporating green synthesized silver NPs with oregano essential oil, polyvinyl alcohol/starch films showed improved water resistance and synergistic antibacterial activity [89]. Using starch-PVA nanofilms with Ag NPs, antimicrobial packaging films have been developed and studied in terms of their physical and antimicrobial properties, as well as silver release kinetics in polar and nonpolar food media. The results restricted the use of nanofilms in fat-rich dietary supplements [90]. Using walnut leaf extract, a study demonstrated that incorporating ZnO NPs into polyethylene–starch films resulted in strong antioxidant and antibacterial effects against common foodborne pathogens, including *Staphylococcus aureus* and *Escherichia coli* [91]. MgO NPs were also utilized to improve the physicochemical characteristics of starch-albumin biopolymers [92]. In addition, combination of starch with Ag [93–95], ZnO [94,96,97], MgO [98] and CuO [94] NPs in the presence of other polymers such as gelatin [96], PVA [97], agar [95] and additives tea polyphenol [98] and phytochemicals [97] were utilized as nanofilms with high mechanical, thermal and antimicrobial features in food packaging.

Ebrahimi et al. (2019) incorporated Ag, ZnO, and CuO metallic NPs into carboxymethyl cellulose biofilms, resulting in improved UV–VIS absorption, reduced water vapor permeability, increased mechanical resistance, and inhibition of Staphylococcus aureus and Escherichia coli, suggesting enhanced preservation capabilities for food [99]. Semi-transparent antimicrobial films for potential food packaging, composed of regenerated cellulose and 7 wt% ZnO NPs, exhibited enhanced UV and oxygen barrier properties, improved thermal stability, crystallinity, and effective inhibition of the growth of gram-positive and gram-negative bacteria at 3 wt% ZnO concentration [100]. Besides, a monolayer and multilayer nanofilm of bacterial cellulose - 5 wt % ZnO has been obtained using ultrasound irradiation to improve the mechanical and antimicrobial properties and minimize water vapor permeability and moisture absorption [101]. Pirsa et al. (2020) found that the carboxymethyl cellulose/gelatin nanofilm loaded with TiO2–Ag possesses significant antimicrobial and antioxidant properties, attributed to the silver, titanium dioxide, and gelatin properties individually, making it a promising active/antioxidant packaging system [102]. The banana peel powder and AgNPs were also utilized as reinforcing fillers in cellulose-based nanofilms, leading to improved thermal stability and effective antimicrobial properties, suggesting potential applications in active packaging [103,104].

Nanocomposite films of sodium alginate polymer and polyaniline nanoceramics, synthesized through solution casting with TiO_2 NPs, exhibited exceptional antimicrobial activity against various bacteria, suggesting their potential application in active packaging [105]. Alginate-based antibacterial packaging, enhanced with ZnO NPs and citronella essential oil, effectively controlled pathogens, especially Bacillus cereus, and demonstrated improved UV light barrier properties and reduced water vapor permeability, making alginate/ZnO/CEO nanofilms promising for cheese preservation [106]. Successful development of a degradable and antibacterial sodium alginate film with Au-TiO_2 nanocomposites for food packaging, incorporating hydrothermally synthesized Au-TiO_2 nanohybrids, enhances the film's light absorption, water stability, and antibacterial efficacy, achieving approximately 60 % and 50 % inhibition against Staphylococcus aureus and Escherichia coli under light conditions. The film generates reactive oxygen species (ROS) due to enhanced surface plasmonic resonance of Au NPs, contributing to its antibacterial properties [107]. Combination of biopolymers such as chitosan/sodium alginate/carboxymethyl chitosan-ZnO [108], pectin-laponite/polypropylene/Ag [109], chitosan/gelatin/pectin-gelatin/ZnO-lemongrass essential oil (LEO) [110], pectin/chlorophyll/carboxymethylcellulose-SiO_2, pectin/chitosan-Ag, pectin/alginate-ZnO, poly(vinyl) alcohol/graphene oxide/glutaraldehyde-Au, 3-aminopropyltrimethoxysilane/-chitosan-Au, furcellaran/graphene oxide/multi-walled carbon nanotubes-Ag, soy protein/Persian Gum-Ag, dextrin/polyvinyl alcohol-TiO_2 and dextran/cellulose nanofibrils-Ag can enhance the poor properties of single biopolymer while using stabilized NPs can remove the limitations of using metal NPs in food packaging due to their toxicity and migration to the food matrix [109–131]. The biodegradable PVA-montmorillonite K10 clay nanocomposite mix films with ginger extract-mediated silver NPs have shown significant antibacterial activity against *S. Typhimurium* and *S. aureus*, superior mechanical properties, water resistance, and light barrier ability, making them promising for extending the shelf life of food products in eco-friendly packaging [132]. New nanofibers based on zein/sodium alginate (Z/SA) incorporating titanium dioxide NPs (TiO_2NPs) and betanin (B) were prepared via electrospinning for food packaging applications. The resulting Z/SA/TiO_2NPs/B nanofibers displayed a bead-free morphology with strong mechanical properties, high surface hydrophobicity, significant antibacterial activity against food-borne pathogens, and notable antioxidant properties, demonstrating their potential to enhance the shelf life and quality of food products [133].

2.2. Concerns in smart packaging: insights into biopolymer-based nanofilms

Migration refers to the widespread transfer from packages to food. This phenomenon is influenced by several factors, including temperature of contact (higher temperatures increase migration rates), food item composition and physical properties (e.g., fat content), packaging formulation and type (e.g., packaging ingredients), and packaging interaction with food [151].

There is limited information on the migration of nanomaterials from food packaging material to food since NPs are still a relatively new application [152]. Various factors contribute to NP migration from packaging to food [153]. Kim et al. (2020) delved into the physical attributes of nanomaterials, encompassing crystal structures, morphology, size, and dispersion through solvent casting. Additionally, the study examined environmental factors like temperature, pH, food nature, viscosity, polymer matrix structure, and contact time, shedding light on their impact on NP migration [154]. Cushen et al. (2014) studied silver and copper NP migration and concluded that NP concentration was more significant than contact time, particle size, and temperature for NP migration [155]. Since each type of NP exhibits unique properties, each type must be evaluated individually to understand and control NP migration [154]. Additionally, food packaging regulators should develop standards for NPs [156]. Food packaging containing silver NPs is currently rejected by the European Food Safety Authority (EFSA) in the European Union [157]. Furthermore, only zinc oxide has been approved by the Food and Drug Administration (FDA) of the USA (21CFR182.8991) [158].

On the other hand, most food packaging materials that reach domestic purposes are usually disposed of in the environment and accumulate in various environments, such as air, soil, and water. NPs exposed to air are more likely to undergo photochemical changes after being exposed to sunlight and UV light. There are multiple transformations involved in these nanomaterials, such as size dissipation and volatile compound condensation [159]. Due to their high surface area, NPs adhere to soil particles when exposed to soil pores. Depending on their concentration, silver NPs aggregate and form Ag^{+} ions in the soil. In the presence of adsorbed NPs on soil, the growth and germination of plants will be affected [160]. In addition, TiO_2 and ZnO NPs affected the biodiversity of soil microorganisms. There is an enormous amount of accumulation, degradation, diffusion, and interaction of NPs in the aquatic environment for flora and fauna [161].

These limitations emphasize the use of biological systems, such as microorganisms [162], and plant extracts [163]. The use of biological systems for NPs acts as a capping, reducing, and stabilizing agent [164]. NPs can be synthesized biologically by combining plant extracts with phytochemicals, which are non-toxic, economical, and environmentally benign [165–167]. As a result, nanomaterials are often more stable. In addition to providing an organic natural coating, biogenic NPs also prevent NP aggregation. Chemical synthesis, however, requires stabilizing agents to prevent aggregation. Menon et al. (2019) suggested that biogenic synthesis reduces the toxicity of NPs by utilizing bacteria and plants, which are readily available raw materials [168]. Nevertheless, microorganisms are used to synthesize biogenic NPs with disadvantages. Some of these factors are pathogenicity, long synthesis times, and complex post-harvest processes [169].

3. Biosynthesis of nanoparticles

3.1. Metal tolerance capabilities among fungal species

Recent studies have shed light on the diverse metal tolerance capabilities among fungal species, revealing intriguing variations across different environmental contexts. For instance, Aspergillus sp. and Penicillium sp. have emerged as particularly resilient against a range of metals including arsenic (As), lead (Pb), chromium (Cr), copper (Cu), and zinc (Zn), with tolerance thresholds varying significantly among species and strains. Researchers have observed that fungi isolated from metal-contaminated environments often exhibit enhanced tolerance compared to those from non-contaminated sites, underscoring the adaptive strategies fungi employ in response to environmental stressors. This variability in metal tolerance not only reflects biological adaptations but also underscores the influence of soil physiochemical properties and carbon content on fungal growth and resilience in metal-rich environments. Such insights are crucial for understanding fungal ecology and their potential applications in bioremediation and environmental sustainability efforts [170].

In studies focusing on fungal tolerance to heavy metals, various fungal species have been tested for their ability to withstand different concentrations of metals. For Cr, *Aspergillus* sp. and *Micrococcus* sp. tolerate up to 1000 mg L^{-1} and 800 mg L^{-1}, respectively [171]. *Penicillium chrysogenum* and *Trichoderma viride* show tolerance to 600 mg L^{-1} of Cr [172]. *Aspergillus flavus* can tolerate concentrations of 400 mg L^{-1} [172], while other species like *Trichoderma brevicompactum* QYCD-6 and *Fusarium solani* exhibit tolerance to 300 mg L^{-1} and 100 mg L^{-1} of Cr, respectively [173]. For Pb, *Alternaria alternate* and *Trichoderma brevicompactum* QYCD-6 tolerate up to 1200 mg L^{-1} and 1600 mg L^{-1}, respectively [174]. *Aspergillus niger* and *Aspergillus flavus* can withstand concentrations of 1000 mg L^{-1} and 600 mg L^{-1} of Pb, respectively [175]. For Cu, *Aspergillus niger* (SF-5) exhibits high tolerance at 1716 mg L^{-1}, while other species like *Rhizopus micosporus* and *Fomitopsis meliae* tolerate up to 1000 mg L^{-1} [176,177]. *Alternaria alternate*, *Pithym* sp. (SF-1), and *Geotrichum candidum* tolerate Cu concentrations of 1000 mg L^{-1}, 700 mg L^{-1}, and 400 mg L^{-1}, respectively [176,178]. For Cd, *Aspergillus* sp. and *Curvularia* sp. (GF-6) can tolerate up to 9218 mg L^{-1} and 5732 mg L^{-1}, respectively, while *Talaromyces helices* and *Trichoderma brevicompactum* QYCD-6 tolerate concentrations of 600 mg L^{-1} and 250 mg L^{-1}, respectively [176,179]. Zn tolerance is observed in *Aspergillus flavus* (1000 mg L^{-1}), *Trichoderma brevicompactum* QYCD-6 (450 mg L^{-1}), and *Aspergillus niger* (250 mg L^{-1}) [173,175]. For As, *Rhizopus micosporus* and *Aspergillus niger* can tolerate concentrations of 500 mg L^{-1} and 100 mg L^{-1}, respectively [177]. Ni tolerance is observed in Aspergillus flavus (1000 mg L^{-1}) and Aspergillus niger (100 mg L^{-1}) [175].

The evolution of metal resistance in microorganisms spans over 3.5 billion years, driven by their enduring exposure to toxic metals. The interaction between metals and fungi hinges on factors such as metal type, concentration, organism, and environmental conditions. Fungi have developed sophisticated strategies, both intracellularly and extracellularly, to combat metal toxicity. Extracellular mechanisms involve metal chelation and binding at the cellular periphery to prevent internalization, while intracellular strategies include conjugation with fungal biomolecules like proteins and organic ligands. These defense mechanisms are broadly categorized into biosorption [180–182], bioaccumulation [183,184], compartmentalization [185,186], metal chelation [187,188], and efflux transport for metal exclusion [189,190], depicting the diverse strategies employed by fungi to resist toxic heavy metals.

3.2. Mechanism of nanoparticle biosynthesis

Due to the high costs associated with physical and chemical processes, the biosynthesis of NPs became necessary. According to Ahmed et al. (2016) [191] and Hussain et al. (2016) [192], the main advantages of the green method are the use of non-toxic materials, the use of environmentally friendly solvents, and the use of renewable, biodegradable materials. The nature of inorganic materials has been enriched by various processes for synthesis that have led to the development of a relatively new and relatively unexplored area of research [191,193] focusing on the biosynthesis of nanomaterials. Plant phytochemicals or microbial enzymes play a crucial role in metal reduction in green chemistry, particularly in the synthesis of NPs. In the context of green chemistry, key considerations include selecting an eco-friendly solvent, employing a non-toxic reducing agent, and choosing a harmless material for NP stabilization. While organic solvents have been commonly used, the hydrophobic nature of capping agents is a contributing factor. Notably, various bacteria can produce metal structures, either intra or extracellular [194] as a resistance mechanism, or to conserve energy for growth (Hennebel et al., 2011). Researchers have investigated various biological agents to produce metallic NPs like copper, zinc, titanium, gold, and silver NPs [195]. Biosynthesis of NPs, involving reduction and oxidation, has become essential due to the cost of physical and chemical processes. Green synthesis, using phytochemicals and microbial enzymes, proves to be a cost-effective and environmentally friendly alternative, avoiding the absorption of toxic chemicals on medical devices often seen in chemical synthesis. This method, which relies on the antioxidant or reducing properties of metal compounds, is advantageous for large-scale production as it doesn't require high pressure, energy, temperature, or toxic chemicals [196].

Researchers are concentrating on microbial sources for the synthesis of metal and metal oxide NPs, which is a cutting-edge area of scientific research. For the synthesis of NPs, bacteria, fungi, algae, and actinomycetes are used [197]. NPs can be synthesized intracellularly or extracellularly by microorganisms. Markus et al. (2016) demonstrate that novel probiotic *Lactobacillus kimchicus* DCY51T isolated from Korean kimchi can synthesize Au NPs via an intracellular membrane-bound mechanism [198]. Microbiological growth medium can be used to synthesize NPs extracellularly. Muller et al. (2016) investigated the effect of various culture media and their components on the extracellular AgNP synthesis of *K. pneumoniae* UVHC5, E. coli ATCC 8739, and *Pseudomonas jessinii* UVKS19 [199].

It is well known that fungi are excellent microorganisms for synthesizing metal and metal oxide NPs. NPs are synthesized mainly extracellularly by fungi, and the synthesized NPs have good polydispersity, size, and stability. There is considerable potential in myconanotechnology, partly because of the wide range and diversity of fungi. A mycofabrication process involves using fungi to synthesize metal NPs extracellularly or intracellularly [200]. Extracellular biosynthesis of NPs starts with cell wall-trapping of metal cations and enzyme- or metabolite-reducing them to NPs. In the intracellular method, the metal cations are transferred into the cell matrix, reduced, and stabilized using enzymes and capping agents (Fig. 2).

Recently, fungal systems have emerged as "bionanofactories" that synthesize NPs of silver, gold, platinum, cadmium, etc. [201]. According to Vago et al. (2016), 21 types of microscopic fungi were randomly selected and used to synthesize gold NPs in a one-step and green method. From cell-free extracts of fungi, highly stable particles of various shapes and sizes can be obtained depending on the microorganisms and experimental conditions (such as fermentation conditions), as revealed by spectroscopic and electron microscopic measurements [202]. Devi and Joshi (2015) synthesized silver NPs from three endophytic fungi isolated from *Potentilla fulgens* L, an ethnomedicinal plant. It is rare for yeasts, algae, and actinomycetes to be used for the production of metal and metal oxide NPs compared to bacteria and fungi [203]. According to El-Rafie et al. (2013), water-soluble polysaccharides extracted from four marine macroalgae, including Pterocladia capillacae, Jania rubins, Ulva faciata, and Colpmenia sinusa, were used as reducing and stabilizing agents for silver ions and AgNPs synthesized [204]. In 2016, Zhang et al. reported the first report on the green synthesis of metal NPs using *Magnusiomyces ingens* (yeast) [205]. *Gordonia amarae* was also utilized to synthesize the biogenic gold NPs by Bennur et al. (2016) and used for rapid copper ion sensing [206]. Pothiraj et al. (2022) investigated Mycosynthesis of NPs from Basidiomycetes Mushroom Fungi, highlighting fungi's global adaptability, stress tolerance, and novel metal reduction capabilities. Fungal-mediated psychosynthesis is touted for its high biomedical applicability, cost-effectiveness, and easy separation. The process involves the production of secondary metabolites and macromolecules, serving as reductants/stabilizers for nanocrystal production. Fungal NPs find extensive use in biomedicine, boasting oxidation resistance, diverse surfaces, and lasting stability [207].

In Fig. 3, potential fungal isolates for NP biosynthesis are illustrated. Numerous fungi species are useful in the biosynthesis of metal NPs with the desired size, and morphology: *Pestalotiopsis* sp., *Phoma* sp., *Humicola* sp., *Fusarium oxysporum, Aspergillus niger*, *Trichoderma* sp., *Hormoconis resinae*, *Phaenerochaete chrysosporium* and, *Penicillium* sp.

Fungi are proposed for efficient and low-toxicity reduction and stabilization of AgNPs. While the synthesis mechanism is not fully understood, adjusting parameters like silver salt concentration, biomass, temperature, pH, and cultivation time can optimize the process. These fungal-synthesized structures show potential for pathogen control [208] similar to bacteria-produced AgNPs. Future research in the food industry's use of metal NPs as antimicrobial agents is guided by these findings. AgNPs, particularly notable for direct application to microorganisms' cell walls and membranes, induce reactive oxygen species production and alter signal transduction, damaging cellular structures [209,210]. Using fungi to synthesize AgNPs involves culturing them on agar and then transferring them to a liquid medium. NPs are then synthesized from biomass by transferring it to water. Adding silver nitrate to the filter after filtration eliminates biomass from the filter [211,212]. The first report on the synthesis of AuNPs by fungi came from *Verticillium* sp. [213], although other fungi are also involved, such as *Paraconiothyrium variable, Aspergillus* sp., *Penicillium* sp., *Candida albicans*, *Alternaria alternate*, *Hormoconis resinae*, *Volvariella volvacea*, *Colletotrichum* sp., and *Trichothecium* sp. to successful biosynthesis of AuNP. Food industry-relevant AuNPs are also produced by the living and dead cells of *Aspergillus oryzae* [214]. *Colletotrichum* sp., a parasitic fungus that grows on geraniums, produces AuNPs with rodlike and prismlike morphologies when exposed to chlorate ions [215]. Au-Ag bimetallic alloys can be produced with *F. oxysporum.* A recent study found that exposure to *F. oxysporum* can increase metal ion accumulation by many mechanisms, including extracellular binding by polymers and metabolites, specific polypeptide binding, and metabolism-dependent accumulation [216].

It has also been shown that exposure of *F. oxysporum* biomass to $AgNO_3$ and $HAuCL_4$ solutions yielded highly stable Au–Ag alloy NPs with different molar ratios [215] as well as extracellular production of CdS NPs in $CdSO_4$ solution. This method produces particles

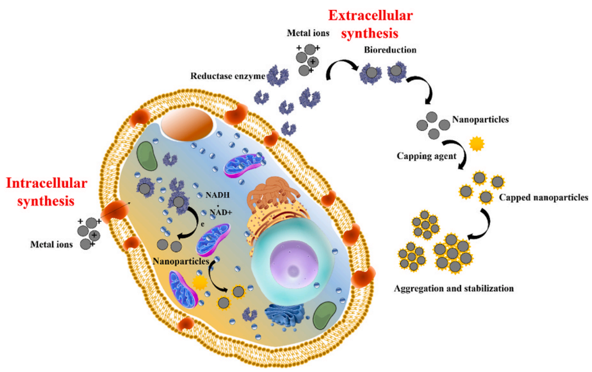


Fig. 2. Schematic illustration of the extracellular and intracellular mechanisms for biosynthesis of NPs by the fungal system.

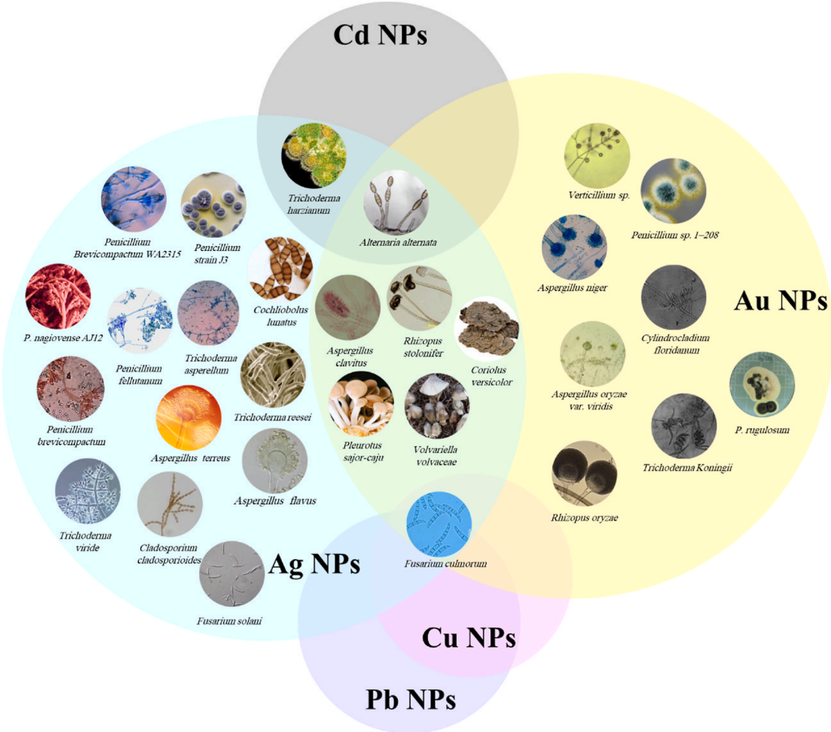


Fig. 3. A potential source of NPs derived from fungal isolates.

with uniform dispersion and dimensions between 5 and 20 nm [217]. Several fungi have been used to produce cadmium quantum dots, including *Coriolus versicolor*, *Schizosaccharomyces pombe*, *Candida glabrat,* and *F. oxysporum* [218]. Nanocrystalline zirconia zirconium hexafluoride anions were also hydrolyzed extracellularly in the reaction of k_2ZrF_6 with *F. oxysporum* [219].

Research into antifungal NPs has been revolutionized by myconanotechnology. A study has examined the antifungal activity of AgNPs versus rose powdery mildew induced by *Sphaerotheca pannos* var. *rosae* by spraying nanosilver solution over a large contaminated surface area. For a week, no recurrence of the rose powder was observed after more than 95 % of the powder had been removed [220]. According to a related study, AgNPs showed significant growth retardation of the anthracnose pathogen Colletotrichum gloesporioides in several fruits [221]. It has been demonstrated that AgNPs synthesized using *Epicoccum nigrum* have antifungal activity against a wide range of pathogenic fungi. As a result of using *Guignardia mangiferae*, AgNPs were efficiently synthesized and found to be effective against phytopathogenic fungi [222]. *Fusarium solani*, a plant pathogen isolated from wheat, produced AgNPs that showed antifungal activity against wheat, barley, and corn kernel diseases [223]. Strawberry plants infected with *Botrytis cinerea* or *Sclerotinia sclerotiorum* are treated with Ag NPs synthesized using *Aspergillus versicolor*. Fungi-produced NPs have coatings that are directly obtained from the fungi, making them more stable [224]. The biological activity of the NP cap depends on the fungus used, and while fungi offer advantages for metal NP biosynthesis, selecting the right fungus, ensuring sterile conditions, and understanding growth time is crucial. Challenges include scaling up production due to uncertainties in cap layer formation and contained molecules. Despite the need for more research, studies indicate fungi can generate metal NPs with diverse applications, particularly in pest control [222].

3.3. Application of fungal nanoparticles

Fungal-synthesized NPs have received a lot of attention because of their wide range of uses. *Saccharomyces prombe*, for example, has been used to synthesize cadmium sulfide NPs, which have potential applications in electric diodes (Kowshik et al., 2002). *Usnea longissima* has been researched for its bioactive NPs containing usnic acid, which have shown potential antifungal activity and could be useful in treating fungal infections [225]. *Fusarium oxysporum* has shown effective in creating silver NPs, which are particularly valuable in improving the antimicrobial characteristics of textile fabrics and reducing pathogen growth on fabric surfaces [226].

Moreover, fungal NPs are being explored for targeted drug-delivery systems within the body. Their small size and biocompatibility make them ideal candidates for delivering drugs to specific tissues and organs, enhancing therapeutic efficacy while minimizing side effects. Studies have demonstrated the feasibility of using fungal-synthesized NPs for drug delivery in conditions like inflammatory bowel disease and tuberculosis, leveraging their stability, high carrier capacity, and versatility in administration routes including oral and inhalation [227].

Furthermore, fungal nanocrystals are emerging as carrier-free colloidal systems for drugs, addressing solubility challenges and improving therapeutic outcomes. Their application extends to biomedical imaging, where NPs derived from fungal sources are being explored for diagnostic purposes, offering enhanced imaging capabilities with potential therapeutic implications [228].

In biosensing and molecular labeling, fungal NPs contribute to advanced techniques such as immunoassays and biomolecular detection due to their unique properties and functional versatility [229,230]. Ongoing research into the interactions of fungal NPs with biomolecules and microorganisms promises further insights into their applications in diagnostics and therapeutics. Overall, fungal-synthesized NPs represent a promising frontier in medical research, offering innovative solutions for combating infections, improving drug delivery, and advancing diagnostic technologies.

4. Future trends in food packaging

4.1. Application of smart packaging materials for food preservation

Several studies used solution casting to create smart and active packaging materials, which were tested with real food goods at ambient or refrigerated temperatures. A bovine skin gelatin sheet containing ZnO NPs and clove essential oil has shown antibacterial efficacy against *Listeria monocytogenes* and *Salmonella Typhimurium* in refrigerated shrimp preservation [231]. Packaging for chicken breast meat using carboxymethyl cellulose, okra mucilage, and ZnO NPs showed antibacterial and antioxidant capabilities, minimizing microbial growth, oxidation, and gas production [232]. The use of a corn-zein-laminated LDPE film with essential oils including thymol, carvacrol, and eugenol prevented lipid oxidation and color changes in vacuum-packed beef patties [233]. Pork meat packaged with distiller dry grains, soluble protein, and tea extracts showed increased antioxidant activity [234]. Lamb meat preserved in whey protein isolate and cellulose nanofiber films with TiO_2 NPs and rosemary essential oil showed lower bacterial counts and longer shelf life, with greater suppression of Gram-positive bacteria [235].

Another study found that frozen blue sharks packaged with low-density polyethylene (LDPE) and barley husk extracts were sensitive to antioxidant concentration and storage period in terms of hydrolytic activity and lipid oxidation [236]. Palm oil packed in cassava starch films with mango and acerola pulp provided significant antioxidant protection [237]. Strawberries kept in clay/PE polymer films containing carvacrol and thymol essential oils showed antifungal efficacy against *Botrytis* [238]. Tomatoes wrapped with chitosan and TiO_2 NPs ripened later due to the films' gas-scavenging capabilities [238]. Pears preserved with films containing papaya puree, ascorbic acid, and moringa leaf extract exhibited longer shelf life and better sensory characteristics [239]. Bananas wrapped with chitosan and Sonneratia caseolaris leaf extract films showed longer shelf life due to their antibacterial capabilities [240]. Incorporating natamycin in Gorgonzola cheese films boosted the inhibition of *P. roqueforti*, indicating antifungal action [241]. Fish wrapped with chitin nanofiber and methylcellulose films containing red barberry anthocyanins showed antibacterial, antioxidant, and colorimetric capabilities, indicating quality modifications [242].

Hibiscus rosa-sinensis anthocyanin added to chicken, chitosan, and corn starch films showed good optical and morphological qualities while being sensitive to pH variations [243]. Sausages packed in agar/tapioca starch films containing red cabbage anthocyanin altered color due to quality variations during storage [244]. The chicken was preserved in cassava starch films with blueberry residual anthocyanin and pork/fish in chitosan films with Bauhinia blakeana Dunn [245]. Flower anthocyanin exhibited colorimetric reactions to pH variations, indicating quality alterations [246]. Lamb flesh with chitosan nanofibers, methylcellulose, and saffron petal anthocyanins have shown antibacterial, antioxidant, and colorimetric characteristics. Red meat preserved in methylcellulose and chitosan nanofiber films containing barberry anthocyanin had similar multifunctional characteristics [247]. Bananas packaged with PVA/glucomannan and Sappan wood extracts changed color during storage [248], while milk preserved in starch/polyvinyl alcohol films containing purple sweet potato anthocyanin demonstrated antibacterial action and colorimetric responsiveness to quality changes [249].

4.2. Smart packaging nano biofilms using fungal functionalized nanostructures

Fungal functionalized nanostructures can be used in food at various stages, including processing, packaging, and safety. There are few reports of using fungal biomass for the synthesis of NPs in food packaging. Silver NPs (AgNPs) were synthesized from the wild mushroom *Ganoderma sessiliforme* in this study using a cost-effective and eco-friendly method. Researchers found that the synthesized AgNPs are effective at controlling the growth of foodborne pathogens and could be used in food packaging [250]. El-Naggar et al. (2022) created superhydrophobic antimicrobial films (cellulose acetate/polycaprolactone) using mycosynthesized CuNPs and stearic acid. The CuNPs, averaging <50 nm with a zeta potential of -30 mV, were incorporated into the film, rendering rough surfaces. The films demonstrated excellent mechanical properties, air permeability, and antimicrobial activity. Cytotoxicity tests confirmed safety for the normal Wi38 cell line. The biodegradable film loaded with fungal-mediated biosynthesized CuNPs exhibited favorable hydrophobic properties, showcasing its suitability for food packaging (particle size <50 nm, zeta potential < -30 mV) [251]. Utilizing a facile hydrothermal method, gelatin/carrageenan films with mushroom-derived carbon dots (EnmCDs) demonstrated high antioxidant activity, negligible cytotoxicity, improved mechanical properties, and enhanced physical and functional attributes, making them suitable for active food packaging applications to extend shelf life [252]. In a second study, AgNPs were produced via a green method using mushroom water extracts and incorporated into starch/agar films. The AgNPs, with a size of 10 nm and spherical shape, exhibited potent antibacterial activity. The uniform dispersion of AgNPs in starch/agar films improved their water vapor barrier and hydrophobicity. Thermal stability and mechanical strength remained unaffected. The AgNPs-enhanced starch/agar film demonstrated strong antibacterial properties against *E. coli* and *L. monocytogenes*. Starch/agar films have improved physical (mechanical strength, water vapor barrier) and functional (antibacterial activity) properties, making them suitable for active food packaging applications

[95].

Ensuring the longevity of preserved food relies on a delicate interplay of factors, encompassing water vapor and gas barriers, tensile strength, and appropriate density. The continuous advancement of smart active packaging materials involves a deliberate integration of various components, including crosslinkers, plasticizers, and antimicrobial agents, to enhance food safety and elevate functional properties. While significant strides have been made in the systematic development of bio-intelligent active packaging materials, several intricate areas necessitate in-depth exploration:

Utilization of Cost-Effective NPs: The exploration of low-cost, energy-efficient NPs synthesized from plant or microbial sources involves optimizing synthesis processes. This includes refining extraction methods, exploring novel plant sources, and improving microbial synthesis conditions to enhance efficiency and reduce costs.

Investigating the unique potential of fungal-stabilized NPs requires a thorough understanding of fungal physiology. This involves studying various fungal strains, their growth conditions, and the influence of different parameters on the stability and properties of the resulting NPs.

Kinetics of Active Substance Diffusion: Conducting a comprehensive study on the kinetics of active substance diffusion involves sophisticated analytical techniques. Utilizing advanced imaging methods, such as atomic force microscopy and electron microscopy, can provide insights into the dynamic processes at the nanoscale. Developing predictive models for slow-release mechanisms requires collaboration between material scientists and mathematicians. Employing computational modeling, such as finite element analysis, can simulate diffusion kinetics under various conditions, aiding in the creation of accurate predictive models.

Advancements in Mycobiotechnology: Furthering advancements in mycobiotechnology for the preparation of packaging materials entails optimizing fungal fermentation processes. This includes tailoring growth media, exploring new fungal strains with desirable properties, and fine-tuning fermentation conditions to achieve consistent and high-quality materials.

Addressing performance gaps in packaging materials involves a multidisciplinary approach. Collaborating with material engineers, biochemists, and process engineers can help identify weaknesses in current preparation methods and develop innovative solutions for improved performance.

Understanding NP Synthesis Mechanisms: Uncovering the precise mechanisms involved in NP synthesis within fungal systems demands advanced spectroscopic and imaging techniques. Techniques like X-ray diffraction and nuclear magnetic resonance can provide insights into the crystallography and chemical composition of synthesized NPs.

Investigating the influence of various factors on metal ion reduction necessitates systematic experimentation. Designing factorial experiments and employing statistical methods can help discern the impact of factors such as temperature, pH, and concentration on the synthesis process.

Impact on Waste Reduction and Environmental Safety: The assessment of the potential of plant or microbial-sourced NPs for waste reduction involves life cycle assessments. Analyzing the environmental impact from raw material extraction to end-of-life disposal aids in understanding the overall sustainability of the packaging material.

Evaluating the sustainability benefits of incorporating fungal-stabilized NPs requires a comprehensive analysis. This involves considering factors such as energy consumption, waste generation, and ecological footprint to determine the net environmental gain.

Optimizing Mechanical and Chemical Properties: Emphasizing the importance of meticulous preparation to optimize the mechanical and chemical properties of packaging nanobiomaterials requires a detailed characterization process. Employing techniques like rheology, tensile testing, and spectroscopy can provide a comprehensive understanding of material behavior.

Studying the correlation between preparation methods and the resulting performance of packaging materials involves systematic experimentation. Identifying key process parameters and their influence on material properties enables targeted improvements in material design and performance.

Enhancing Antibacterial Properties: Investigating strategies to enhance the antibacterial properties of smart active packaging materials involves exploring synergistic effects. Combining NPs with natural antimicrobial compounds or incorporating multifunctional nanomaterials can enhance antimicrobial efficacy.

Exploring the potential of NPs in synergistic antibacterial effects requires a nuanced understanding of microbial interactions. Studying the mechanisms through which NPs disrupt bacterial cell membranes or interfere with cellular processes can guide the design of effective antibacterial strategies.

Developing Scalable Production Processes: Evaluating the scalability of production processes for fungal-stabilized NPs involves process engineering. Implementing continuous flow systems, optimizing reactor design, and streamlining downstream processing contribute to scalable and cost-effective production.

Identifying challenges and proposing solutions for large-scale synthesis in smart food packaging applications requires collaboration between engineers and biotechnologists. Addressing issues such as reactor scale-up, purification methods, and cost optimization ensures the practical viability of large-scale production.

Integrating Computational Modeling: Integrating computational modeling to predict diffusion kinetics and optimize slow-release mechanisms entails developing sophisticated simulations. Utilizing computational fluid dynamics models and machine learning algorithms can provide accurate predictions of substance diffusion in complex NP systems.

Applying simulations to understand the impact of NP characteristics on overall packaging performance involves a comprehensive approach. Considering factors such as NP size, shape, and surface chemistry in simulations aids in tailoring materials for specific applications and performance requirements.

Exploring Multidisciplinary Applications: Exploring the diverse applications of fungal-derived NPs across fields such as medicine, pharmaceuticals, agriculture, and electronics requires collaboration between scientists from various disciplines. Interdisciplinary research teams can leverage expertise to uncover novel applications and address challenges in diverse fields.

Identifying interdisciplinary opportunities for harnessing the full potential of fungal systems in NP synthesis involves engaging with professionals from different scientific domains. Understanding the unique properties of fungal-derived NPs and their compatibility.

5. Conclusion

Various biopolymer nanofilms, incorporating antimicrobial metal NPs, find application in smart food packaging. Examples include chitosan and its composites (e.g., chitosan/PVA, chitosan/calcium silicate), starch combinations (e.g., starch/polyvinyl alcohol, graphene oxide/starch/polyvinyl alcohol), cellulose and bacterial cellulose composites (e.g., acrylamide/cellulose-based filter paper, carboxymethyl cellulose), sodium alginate and its combinations (e.g., sodium alginate/polyaniline), pectin composites (e.g., pectin-laponite/oxygen plasma surface-modified polypropylene films), poly(sodium styrene sulfonate), dextrin/polyvinyl alcohol, dextran/cellulose nanofibrils, and soy protein isolate/persian gum. Despite the potential benefits of nanotechnology in sustainable food packaging, the full assessment and management of the ecotoxicity of these nanomaterials are crucial for responsible development.

The solution casting method has been effectively employed to create smart and active packaging materials that significantly enhance the preservation and quality of various food products at ambient and refrigerated temperatures. These materials, integrating antimicrobial and antioxidant agents, have shown promising results across multiple studies. For instance, films incorporating ZnO NPs, clove essential oil, carboxymethyl cellulose, okra mucilage, and various essential oils have demonstrated potent antibacterial and antioxidant capabilities, reducing microbial growth, oxidation, and gas production in foods such as shrimp, chicken breast, and beef patties. Other innovative packaging solutions include the use of whey protein isolate, cellulose nanofibers, TiO_2 NPs, and rosemary essential oil, which have been effective in extending the shelf life and maintaining the quality of pork and lamb meat by lowering bacterial counts. Additionally, films containing natural extracts and anthocyanins, such as those from barley husk, mango, acerola, red barberry, and saffron petals, have provided excellent antioxidant protection and colorimetric capabilities, indicating quality changes in products like strawberries, tomatoes, pears, bananas, fish, and milk. These advancements highlight the significant potential of smart and active packaging materials in improving food safety and extending shelf life, emphasizing the need for further research and development in this field.

Fungi have emerged as excellent microorganisms for synthesizing stable metal and metal oxide NPs extracellularly. However, the production efficiency of these microbial systems needs improvement. Myconanotechnology, utilizing fungal functionalized nanostructures, plays a significant role in various aspects of food processing, packaging, and safety. Fungal functionalized nanostructures hold significant promise in enhancing various aspects of food processing, packaging, and safety. Studies have demonstrated the efficacy of using fungal biomass to synthesize NPs (e.g. AgNPs and CuNPs), for food packaging applications. These NPs have shown potent antibacterial and antimicrobial properties, effectively controlling foodborne pathogens. The use of AgNPs synthesized from *Ganoderma sessiliforme* and integrated into food packaging has been particularly effective in enhancing food safety. Additionally, mycosynthesized CuNPs have been incorporated into superhydrophobic antimicrobial films, showcasing excellent mechanical properties and cytocompatibility, thus making them suitable for food packaging. Gelatin/carrageenan films embedded with mushroom-derived carbon dots have also demonstrated high antioxidant activity and improved physical attributes, extending the shelf life of food products. Furthermore, starch/agar films enhanced with AgNPs have exhibited significant antibacterial properties and improved water vapor barrier and hydrophobicity, suggesting their potential for active food packaging. These advancements underscore the potential of myconanotechnology in creating eco-friendly, effective, and safe food packaging solutions, highlighting the need for further research and development in this innovative field.

While there are reports on fungal biomass-mediated biosynthesis of NPs for food packaging, more studies are needed to enhance mycobiotechnology for packaging material preparation. The utilization of fungal-synthesized NPs offers a cost-effective, eco-friendly, and energy-saving approach, contributing to waste reduction and ensuring safe products for both humans and the environment. Despite the unique applications of fungal-stabilized NPs, further research is required, particularly in the context of smart food packaging, to explore their full potential.

Data availability statement

The data associated with this study have not been deposited into a publicly available repository. No data was used for the research described in the article.

CRediT authorship contribution statement

Mina Rezghi Rami: Writing – original draft, Supervision, Investigation, Conceptualization. **Shayan Forouzandehdel:** Writing – review & editing, Resources, Methodology. **Farhad Aalizadeh:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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