DOI: 10.21088/ijab.2454.7964.12126.8

Indian Journal of Agriculture Business
Volume 12 Number 1, January – June 2026

REVIEW ARTICLE

Insights on Emerging Bio-Nano Compounds in Sustainable Packaging: Contextualized to Edible Packaging Films

Shipra Tiwari[1], Sanjay Kumar Bharti[2], Pooja M. Chaple[3], Mohini Tripathi[4], Ambesh kumar Pandey[5], Yuvraj Singh[6], Ankita Chaudhary[7]

HOW TO CITE THIS ARTICLE:

Shipra Tiwari, Sanjay Kumar Bharti, Pooja M. Chaple et. al, Insights on Emerging Bio-Nano Compounds in Sustainable Packaging: Contextualized to Edible Packaging Films. J Agri Busi 2026; 12(1): 71–82.

ABSTRACT

With increasing emphasis on environmental sustainability, industries are shifting toward biodegradable and recyclable materials, making packaging a crucial component of both product preservation and ecological responsibility. Bio-based edible films formulated from natural polymers such as starch, cellulose, and proteins have emerged as sustainable alternatives to synthetic plastics. The incorporation of nanoparticles with high surface reactivity and mechanical strength enhances the antimicrobial, barrier, and structural properties of these films, extending food quality and shelf life. However, concerns regarding nanoparticle migration and potential toxicity necessitate comprehensive evaluation models to ensure consumer and environmental safety. Green-synthesized nanoparticles derived from biological sources, such as microorganisms, plant extracts, cellulose, collagen, and chitin, offer promising advantages due to their biocompatibility, biodegradability, and non-toxicity. This review provides insights into emerging bio-nano compounds and their transformative role in developing intelligent, eco-sustainable edible packaging systems for safer and more durable food preservation.

KEYWORDS

• Nanoparticles • Edible Films • Biodegradable Films • Active Packaging

AUTHOR'S AFFILIATION:

[1] M.V. Sc scholar, Department of Livestock Products Technology, College of Veterinary Science and Animal Husbandry, DUVASU, Mathura, India.

[2] Associate Professor, Department of Livestock Products Technology, College of Veterinary Science and Animal Husbandry, DUVASU, Mathura, India.

[3] M.V. Sc scholar, Department of Livestock Products Technology, College of Veterinary Science and Animal Husbandry, DUVASU, Mathura, India.

[4] M.V. Sc scholar, Department of Livestock Products Technology, College of Veterinary Science and Animal Husbandry, DUVASU, Mathura, India

[5] M.V. Sc scholar, Department of Livestock Products Technology, College of Veterinary Science and Animal Husbandry, DUVASU, Mathura, India.

[6] M.V. Sc scholar, Department of Livestock Products Technology, College of Veterinary Science and Animal Husbandry, DUVASU, Mathura, India.

[7] M.V. Sc scholar, Department of Livestock Products Technology, College of Veterinary Science and Animal Husbandry, DUVASU, Mathura, India.

CORRESPONDING AUTHOR:

Sanjay Kumar Bharti, Associate Professor, Department of Livestock Products Technology, College of Veterinary Science and Animal Husbandry, DUVASU, Mathura, India.

E-mail: drskbharti@gmail.com

➤ **Received:** 14-11-2025 ➤ **Accepted:** 19-12-2025

INTRODUCTION

Growing global concerns over the environmental impact of synthetic plastic packaging have led to increasing interest in natural, biodegradable alternatives for food packaging. The food industry faces the critical challenge of maintaining food safety and integrity, as the World Health Organization (WHO, 2022) reports that about 600 million people fall ill annually from contaminated food, resulting in 420,000 deaths worldwide. Children under five are particularly vulnerable, suffering significant health impacts and premature deaths. Foodborne diseases and spoilage also weaken national economies by restricting export opportunities and diverting resources to combat these issues. Packaging materials play a vital role in protecting food from contamination and spoilage during handling, transport, and storage while also improving quality and extending shelf life (Zhang *et al.,* 2021; Bharti *et al.,* 2020a). Modern packaging has evolved beyond basic protection and convenience to include smart and active systems enhanced by nanotechnology, offering features such as real-time freshness monitoring, antimicrobial action, and improved barrier properties against moisture, oxygen, and light (Bharti *et al.,* 2020b). However, most conventional packaging materials, like polyethylene, polypropylene, polyester, and polystyrene, are non-biodegradable and contribute significantly to environmental pollution (Mishra *et al.,* 2024). According to Statista (Fleck, 2024), global plastic waste has surged from 180 million tons to nearly 400 million tons in the past two decades and is expected to triple by 2060, with most of it ending up in landfills. In India, stricter regulations now require that so-called biodegradable plastics leave no microplastic residue, as microplastics have become a major pollutant in aquatic ecosystems. Moreover, studies reveal that plastic production contributes over 5% of global greenhouse gas emissions. As sustainable alternatives, natural biopolymers such as starch, cellulose, chitosan, alginate, zein, whey, soy protein, and silk fibroin are being used to produce eco-friendly, edible films that are renewable, safe, and FDA approved. In India, the edible film market particularly those based on proteins and polysaccharides is rapidly growing (Bharti *et al.,* 2021). Nanotechnology further enhances these materials by incorporating nanoparticles such as zinc oxide, titanium dioxide, silver, copper oxide, and nanocellulose to improve mechanical strength, barrier properties, and antimicrobial activity thereby extending shelf life. Despite their benefits, nanoparticles raise safety concerns due to potential toxicity and migration into food, which may cause oxidative stress, inflammation, or DNA damage. Consequently, researchers are focusing on green-synthesized nanoparticles derived from plants, fungi, and microorganisms, which offer reduced toxicity, enhanced biocompatibility, and improved environmental sustainability (Sharma *et al.,* 2016). These eco-friendly, plant-based synthesis methods are increasingly favoured for their safety, cost-effectiveness, and minimal ecological impact.

BIODEGRADABLE PACKAGING (EDIBLE FILMS)

According to American Society for Testing and Materials (ASTM), “biodegradable” is defined as “capable of undergoing decomposition into carbon dioxide, methane, water, inorganic compounds and biomass”. Natural biopolymers such as protein and polysaccharides utilized as matrixes for biodegradable packaging materials (recyclable, degradable, nontoxic, environment friendly). Polysaccharides (starch, cellulose, chitosan, and alginate) and proteins (zein, whey protein, soy protein, and silk fibroin) are clean, renewable, nontoxic, edible, biodegradable, and biocompatible materials (Mohamed et al., 2020; Bharti *et al.,* 2022a). Edible film is defined as thin, continuous or unbroken sheets made up of edible substances (Guilbert *et al.,* 1997). Natural polymers like lipids and protein are used to produce environmentally friendly edible films. Edible films and coatings that comply with good manufacturing practices (GMP) have received approval from the Food and Drug Administration (FDA) as Generally recognised as Safe (GRAS). Chitosan, for instance, is considered a safe substance and is GRAS-rated by the FDA. The edible films and coating market in India is projected to reach a projected revenue of US$ 248.1 million by 2030. A compound annual growth rate of 9.7% is expected of India edible films and coating market from 2025 to 2030. In 2024, polysaccharides represented the largest revenue-generating segment, while proteins are expected to be the most lucrative type segment, registering the fastest growth during the forecast period. India is the fastest growing regional market in Asia-Pacific region and is projected to reach USD 248.1 million by 2030. According to Horizon Databook, the Indian edible films and coatings market segment is based on protein, polysaccharides, lipids, composites covering revenue growth of each sub-segment from 2018 to 2030. However, the commercial application of edible films has been limited due to problems related to their poor mechanical and barrier properties when compared to synthetic polymers (Azeredo *et al.,* 2009). To overcome these limitations, several nanocomposites have been developed by incorporating reinforcing compounds (nanofillers) into biopolymers, thereby improving their properties and enhancing cost-performance efficiency (Sorrentino *et al.,* 2007).

Components of edible films

Components of edible films can be divided into three main groups: hydrocolloids, lipids, and composites. Hydrocolloids include proteins and polysaccharides, such as starch, alginate, cellulose derivatives, chitosan, and agar. Lipids consist of waxes, acylglycerols, and fatty acids (Min *et al.,* 2005; Bharti *et al.,* 2022b). Composites contain both hydrocolloid components and lipids. The choice of formulation for biopolymers is largely dependent on its desired function such as aesthetic appearance and good barrier properties against oxygen (Cha & Chinnan, 2004).

1. Carbohydrate/Polysaccharide-Based Films

Polysaccharides are among the most widely used materials for edible films due to their film-forming abilities derived from starch, alginate, dextrin's, pectin, chitosan, carrageenan's and their blends (Han *et al.,* 2005). These are non-toxic, widely available, selectively permeability to CO_2 and O_2 and are hydrophilic in nature (Nisperos-Carriedo, 1994). Consequently, these films are poor barrier to water vapor and allow movement of water vapor across the film, thus, preventing water condensation that can be a potential source of microbial spoilage (Cha & Chinnan, 2004).

i. Starch

The amylose content of starch is responsible for its film forming capacity (Claudia *et al.,* 2005). Starches with higher amylose content produces films with higher flexibility, oxygen impermeability, oil resistance; heat-seal ability, and water solubility. Films of high-amylose corn starch or potato starch was more stable during aging (Krogars *et al.,* 2003).

ii. Carrageenan

Carrageenan is a collective term used to express 'polysaccharides' that are extracted from certain species of red seaweed of the Rhodophyceae family. Carrageenan's are anionic linear sulphated polysaccharides composed of d-glucopyranose residues bonded by regularly alternating a-(1/3) and b-(1/4) bonds. κ-carrageenan is the most commercially used carrageenan out of the three main types of carrageenan's, the others being ι-carrageenan and λ-carrageenan. κ-carrageenan contains one negatively charged sulphate group and has 3,6-anhydrod-galactopyranose residues in the chain that impart κ-carrageenan the ability to form gels (Thanh *et al.,* 2002) Polysaccharide-based coatings including carrageenan have good gas barrier properties (Pavlath & Orts, 2009).

iii. Chitosan

Chitosan is the second most abundant natural and non-toxic polymer in nature after cellulose and is mainly made from crustacean shells. In industrial processing, chitin is extracted by acid treatment to dissolve the calcium carbonate followed by an alkaline solution to dissolve proteins. In addition, a decolorization step is often added to remove pigments and obtain colourless pure chitin. Chitosan films are advantageous as it forms films without the addition of additives, exhibits good oxygen and carbon dioxide permeability along with excellent mechanical and barrier properties (Elsabee & Abdou, 2013).

iv. Alginates

Calcium is the most common and effective divalent cation in gelling alginates, though magnesium, manganese, aluminium, ferrous, or ferric ions are also used (Kester & Fennema, 1986). The strength of alginate films can be further enhanced by incorporating modified starches, oligosaccharides, or simple sugars (Gennadios *et al.,* 1997).

2. Protein-based Films

Film-forming proteins are derived from animals (casein, whey protein concentrates and isolate, collagen, gelatine, and egg albumin) or plant sources (corn, soybean, wheat, cottonseed, peanut, and rice).

Protein-based films adhere well to the meat hydrophilic surfaces and provide a barrier for oxygen and carbon dioxide but do not resist water diffusion (Cutter, 2006) Films prepared from proteins and carbohydrates are excellent barriers to oxygen, because of their tightly packed matrix and ordered hydrogen-bonded network structure (Yang & Paulson, 2000).

3. Lipid-based films

Lipid-based films are composed of animal or vegetable oils, fats, waxes, essential oils, emulsifiers, and surface-active agents (Debeaufort & Voilley, 2009). Films composed of lipids have good water vapor barrier properties but exhibit reduced mechanical strength and increased oxygen permeability. When such ingredients are combined, they could physically and/or chemically interact and may result in films with improved properties (Diab *et al.,* 2001) To conquer the poor mechanical strength of these films, they can be used in combination with hydrophilic materials using the formation of an emulsion or through lamination with a hydrocolloid film lipid layer (Bourlieu *et al.,* 2008)

Nanoparticle

Nanotechnology is currently regarded as one of the most significant advancements in traditional scientific disciplines and a central focus of research, development, and innovation activities. It encompasses the manipulation, fabrication, and characterization of materials at the nanoscale, typically ranging from 1 to 100 nm in size. Reducing materials to the nanoscale results in substantial deviations in their physical and chemical properties compared to their micro-or macro-scale counterparts (Kuswandi *et al.,* 2016). Several types of nanostructures have been developed, among which polymeric nanoparticles, metallic nanoparticles, liposomes, and nano emulsions are the most notable (de Moura *et al.,* 2009). Incorporating nanoparticles or nanomaterials into edible films is being widely explored, as these materials can enhance antimicrobial and antioxidant activity while improving thermal stability, mechanical strength, and gas-barrier properties (Yan *et al.,* 2019). Nanomaterials can also help in controlling the physical-chemical stability of actives, such as OEs, maintaining the biodegradable and nontoxic characteristics of oils, also contributing to the durability and functionality of the film (AI Tayyar *et al.,* 2020). Inclusion of lipid-based nanoparticles, like nano emulsions, can improve the dispersion of hydrophobic bioactive compounds, such as essential oils or antioxidants, within the films. This facilitates better release control and increased bioactivity, offering additional benefits for food preservation (Sanchez Gonzalez *et al.,* 2011) Similarly, zinc oxide nanoparticles (ZnO) and titanium dioxide nanoparticles (TiO_2) are also used due to their antimicrobial and UV-blocking properties, which can protect food from spoilage and degradation caused by light exposure. Zinc oxide nanoparticle is the second most abundant metal oxide after iron and it is inexpensive, safe, and as well as it can be prepared easily. Copper oxide nanoparticles (CuO NPs) are highly regarded in the industrial sector for their unique physicochemical properties, which can be attributed to their large active surface area and the quantum size effect (Siddiqi & Husen, 2020) These characteristics render CuO NPs indispensable for drug delivery, antioxidation, and antimicrobial processes, among others (Maliki *et al.,* 2022) CuO NPs have a wide range of applications, the associated negative consequences present considerable obstacles. As a result, green nanotechnology arises as a critical domain, with the objective of alleviating these consequences by implementing sustainable manufacturing techniques (Dikshit *et al.,* 2022) Nanocellulose, derived from plant fibres, is another promising nanomaterial that enhances the tensile strength and water resistance of edible films, making them more durable and effective in maintaining food quality.

Table 1: Application of nanoparticle in food industry

Area	Application Type	References
Foods	Nanoemulsions (essential oils), Nanoencapsulation	Rathod *et al.,* 2024
Food Packaging	Nanocomposites, Smart/ Intelligent Packaging, Antimicrobial Packaging	Jayprakash & Nandini, 2024
Product Monitoring	Nanosensors for detecting product condition	Ningombam, 2024

Nanoparticles in edible films

Nanotechnology plays a vital role in enhancing the functionality of edible films and coatings. It can assist in detecting the presence or growth of bacteria within food packaging and can also help maintain product quality by modulating sensory and barrier properties (Singh Sekhon, 2014). The incorporation of nanocomposites has been shown to improve the functional performance of edible and biodegradable films (Lagaron *et al.,* 2005; Ray & Bousmina, 2005).

When nanoparticles are embedded into edible films, they can extend the shelf life of foods by regulating gas exchange and removing undesirable gases that may accelerate spoilage (Silvestre *et al.,* 2011). Nanotechnology influences multiple aspects of food processing and preservation by enhancing stability and durability through nanoscale engineering, molecular synthesis, and improved heat and mass transfer. It involves: (i) the development of nanoparticles, nano emulsions, nanocomposites, and nanostructures for integration into food products or packaging; (ii) the incorporation of nanomaterials during product formulation, packaging, or storage; and (iii) the use of nano sensors or nano tracers to enhance food safety and traceability (Nile *et al.,* 2020).

Nanoparticles can be synthesized from a wide range of materials, each offering specific functional advantages to the food industry. These materials are broadly classified as organic and inorganic. Organic nanoparticles are typically derived from polysaccharides, proteins, and lipids favoured for their biocompatibility, biodegradability, and safety (Gupta *et al.,* 2024; Bumbudsanpharoke & Choi, 2015). In contrast, inorganic nanoparticles such as silver, zinc oxide, titanium dioxide, copper oxide, carbon, and graphene provide superior stability, durability, and barrier performance (Herrera Rivera *et al.,* 2024).

Silver nanoparticles (AgNPs), in particular, have been extensively studied for their antimicrobial activity and are increasingly applied in active food packaging. Metal oxide nanoparticles, such as AgNPs, enhance the mechanical and barrier properties of biodegradable films. Their high surface-to-volume ratio promotes stronger interactions with microbial cells, thereby improving antimicrobial efficacy (Bahrami *et al.,* 2019; Bumbudsanpharoke *et al.,* 2015; Zimoch-Korzycka *et al.,* 2015).

Recent research on nanoparticle-enriched edible coatings has revealed that such additions not only strengthen antimicrobial, antifungal, and antiviral properties but also improve the cost-effectiveness and functional performance of edible films (Sorrentino *et al.,* 2007). Overall, nanomaterial-based edible coatings provide enhanced food preservation and quality maintenance compared to conventional packaging materials (Bumbudsanpharoke & Choi, 2015).

Disadvantages and Toxicological Aspects of Nanoparticles

Nanoparticles (NPs) offer several advantages for the food industry, particularly in improving food preservation and safety. However, their potential toxicity and the risk of migration from packaging materials into food products are major concerns. During the development of any novel food packaging system, it is essential to evaluate the migration characteristics of its components to determine whether harmful or undesired substances can leach into the food (Tsagkaris *et al.,* 2018). According to the European Commission (2011), a migration test is defined as "the determination of the release of substances from the material or article either into food or into a food simulant" (Souza & Fernando, 2016).

The large surface area-to-volume ratio of nanoparticles significantly alters their physicochemical behaviour compared to bulk materials, which may also account for their potential toxicity upon migration into food and subsequent exposure in the body (Qadri *et al.,* 2020). As nanotechnology applications expand, concerns regarding their safety and health implications have intensified. The toxicity of nanoparticles depends on several factors, including particle type, concentration, exposure duration, and individual sensitivity (Dimitrijevic *et al.,* 2015).

Currently, sufficient data on the long-term toxicity and hazardous effects of nanoparticles remains limited. Organic nanoparticles such as proteins, lipids, starch, and chitosan are generally considered non-toxic because they can be digested within the gastrointestinal tract and are not bio-persistent (Divya & Jisha, 2018). However, due to their high surface area and altered bioavailability, even organic nanoparticles can induce toxicity under certain conditions, emphasizing the need for comprehensive in vitro and in vivo studies to ensure safety.

Research on nanoparticle migration has mainly focused on silver nanoparticles (AgNPs), which provide antimicrobial and mechanical advantages in packaging materials but may also pose health risks. AgNPs have been associated with neurotoxic, genotoxic, and organ-specific effects, including accumulation in the liver, kidneys, testes, and brain; however, actual migration levels detected in food remain very low. Additionally, positively charged hydrophilic nanoparticles can persist in the bloodstream and may pose risks to certain organs, though further research is needed in this area (Naseer *et al.,* 2018).

The migration behaviour of nanoclays depends on temperature, food contact conditions, and nano–polymer interactions. Certain nanoclays can induce cytotoxic effects after prolonged exposure (Bandyopadhyay & Ray, 2019). The unique properties of nanoparticles particularly their increased surface area and reduced size enhance their chemical reactivity and cellular uptake, allowing them to penetrate tissues and organs more easily, which contributes to their potential toxicity (Abbasi *et al.,* 2025; Enescu *et al.,* 2020).

Numerous studies have reported several mechanisms of nanoparticle-induced toxicity, including the generation of reactive oxygen species (ROS), mitochondrial dysfunction, oxidative stress, and inflammatory responses leading to apoptosis and DNA damage (Xuan *et al.*, 2023). For example, silver nanoparticles, while effective antimicrobials, have demonstrated cytotoxic effects on mammalian cells, emphasizing the need for detailed toxicological evaluation (Jaswal *et al.,* 2021). The toxicity of nanoparticles is influenced by size, shape, surface charge, and agglomeration state, all of which determine their interactions with biological systems (Abbasi *et al.*, 2025).

In addition to human health concerns, the environmental implications of nanoparticles are significant. Studies have shown that NPs can be absorbed by terrestrial plants, potentially leading to phytotoxic effects and bioaccumulation in the food chain (Gao *et al.*, 2023). The presence of nanoparticles in edible plants can interfere with physiological and cellular processes, raising concerns about food safety and ecosystem health.

The emerging field of nanotoxicology seeks to evaluate nanoparticle safety and elucidate their health and environmental impacts. Traditional toxicity assays often face limitations due to nanoparticle interference with standard cytotoxicity measurements. Therefore, advanced approaches such as metabolomics and omics-based analyses are being explored to better understand nanoparticle-cell interactions (Awashra & Mlynarz, 2023).

In conclusion, while nanotechnology offers promising advancements in food preservation and packaging, the toxicological profiles of nanoparticles remain complex and incompletely understood. Future studies should focus on developing standardized evaluation models, long-term risk assessments, and environmentally safe nanomaterial designs to ensure consumer and ecological safety (Xuan *et al.,* 2023). Following table is the examples of nanoparticles, their toxicity mechanism and biological outcomes.

Table 2: Mechanism of toxicity of nanoparticles & their biological outcomes

Nanoparticle Type	Mechanism of Toxicity	Observed Biological Outcomes	References
Silver nanoparticles (AgNPs)	Generation of reactive oxygen species (ROS), mitochondrial dysfunction, DNA damage.	Oxidative stress, apoptosis, genotoxicity in mammalian cells, impaired bacterial metabolism.	Ahamed *et al.,* 2010
Gold nanoparticles (AuNPs)	Protein corona formation altering cell signalling; endocytosis-mediated uptake.	Altered gene expression, inflammation, hepatotoxicity at high doses.	Khlebtsov & Dykman, 2011
Zinc oxide nanoparticles (ZnO NPs)	ROS generation, dissolution to Zn^{2+} ions, lysosomal damage.	Cytotoxicity, lipid peroxidation, apoptosis, inflammatory response.	Sharma *et al.,* 2012
Titanium dioxide nanoparticles (TiO_2 NPs)	Photocatalytic ROS generation under UV light, oxidative DNA damage.	Inflammation, pulmonary injury, DNA strand breaks.	Shi *et al.,* 2013
Silica nanoparticles (SiO_2 NPs)	Membrane disruption, oxidative stress, lysosomal rupture.	Apoptosis, cytokine release, impaired cell viability.	Napierska *et al.,* 2010
Iron oxide nanoparticles (Fe_3O_4 NPs)	Fenton reaction generating hydroxyl radicals; iron overload.	Oxidative stress, lipid peroxidation, neurotoxicity.	Singh *et al.,* 2010
Copper oxide nanoparticles (CuO NPs)	Ion dissolution (Cu^{2+}), ROS generation, mitochondrial impairment.	Cell death, oxidative DNA damage, inflammation.	Karlsson *er al.,* 2008
Carbon nanotubes (CNTs)	Physical interference with cell membranes, oxidative stress, chronic inflammation.	Granuloma formation, fibrosis, DNA damage, carcinogenicity.	Donaldson *et al.,* 2010
Graphene oxide nanoparticles (GO NPs)	Oxidative stress, physical membrane damage, charge interaction with proteins.	Cell viability reduction, DNA fragmentation, immune activation.	Gurunathan *et al.,* 2012

Bio nanoparticles

Bio nanoparticles are nanoscale materials synthesized from natural sources such as microorganisms, plants, and marine organisms. These biologically derived nanoparticles are increasingly recognized for their eco-friendly, biocompatible, and cost-effective nature. Unlike conventionally synthesized nanoparticles that often involve toxic chemicals or energy-intensive procedures, bio-based nanoparticles rely on biological processes or renewable materials, making them ideal for applications in food packaging, biomedicine, and environmental technologies.

Nano-chitosan, a derivative of chitosan obtained through physical, chemical, or enzymatic methods, has demonstrated significant improvements in antimicrobial activity, controlled release, stability, and mechanical strength. Owing to these properties, nano chitosan has found diverse applications in drug delivery, cosmeceuticals, and biodegradable food packaging (Manna *et al.,* 2022). When incorporated into biodegradable polymer matrices such as polylactic acid (PLA), chitosan nanoparticles enhance gas and moisture barrier properties due to strong hydrogen bonding and electrostatic interactions between the polymer and nanoparticle phases. These interactions also contribute to improved antimicrobial activity by disrupting bacterial cell walls and restricting nutrient transport, ultimately leading to cell death (Divya & Jisha, 2018).

Nanocellulose, another widely studied biopolymer-based nanoparticle, is produced from plant cellulose via mechanical or chemical treatments. It exists mainly in two forms: nanocrystalline cellulose (NCC) and nano fibrillated cellulose (NFC), typically possessing diameters below 100 nm. Nanocellulose exhibits high tensile strength, biodegradability, and exceptional hydrogen-bonding capability, allowing the formation of dense, impermeable films with superior mechanical and barrier properties (Ferrer *et al.,* 2017; Naseer *et al.,* 2018). These attributes have made nanocellulose a valuable additive in paper, packaging, and composite industries.

Nanostarch (or starch nanocrystals) is synthesized by the controlled hydrolysis or mechanical disruption of starch granules. The resulting particles typically have at least one dimension below 300 nm and exhibit a high surface-area-to-volume ratio (Moran *et al.,* 2021; Yu *et al.,* 2021). When used as nanofillers in biodegradable composites, nanostarch enhances tensile strength, flexibility, water impermeability, and thermal stability, while maintaining the overall biodegradability of the material (Dularia *et al.,* 2019; Campelo *et al.,* 2020).

Protein-based nanoparticles are also gaining importance in food and packaging applications due to their biocompatibility and ability to improve mechanical integrity and moisture resistance. Peanut protein nanoparticles have been shown to increase the strength, temperature resistance, and water-barrier properties of protein–starch composites (Zubair & Ullah, 2020). Similarly, the incorporation of zein nanoparticles into whey protein isolate films enhances both mechanical robustness and moisture barrier performance.

Recently, growing attention has been directed toward biogenic or green-synthesized nanoparticles, which are produced through biological routes involving plants, fungi, bacteria, or marine organisms. These methods utilize naturally occurring biomolecules such as terpenoids, flavonoids, aldehydes, and carboxylic acids that function as reducing and stabilizing agents during nanoparticle formation (Dikshit *et al.,* 2021). Compared with conventional chemical or physical synthesis, green synthesis offers distinct advantages, including non-toxicity, environmental sustainability, lower cost, and improved biocompatibility (Ashique *et al.,* 2022). Metal nanoparticles prepared through green methods, such as those using plant extracts, exhibit enhanced stability and functional properties without generating hazardous by-products (Tade *et al.,* 2020). Plant-based synthesis is particularly advantageous because phytochemicals not only mediate nanoparticle formation but also enhance the biological activity of the final product, resulting in particles with improved antioxidant and antimicrobial performance.

Furthermore, biogenic synthesis techniques have been reported to produce nanoparticles with desirable size uniformity, polydispersity, and stability, making them suitable for incorporation into biodegradable polymer matrices (De *et al.,* 2008; Ingale *et al.,* 2013). These nanoparticles serve as potential reinforcements for bio-based packaging materials, improving barrier, mechanical, and functional properties while maintaining environmental compatibility.

In summary, bio-nanoparticles derived from renewable and biological sources represent a promising class of sustainable nanomaterials for use in food, packaging, and biomedical applications. Their tuneable physicochemical properties, coupled with their environmental and health safety, make them attractive alternatives to conventional nanoparticles. Continued research is essential to standardize synthesis protocols, ensure stability, and establish safety guidelines for large-scale industrial use.

CONCLUSION

In recent years, nanoparticles have emerged as a crucial focus area in food research, offering immense potential for the development of advanced edible films and coatings with enhanced preservation capabilities. The incorporation of nanoparticles can significantly improve the mechanical strength, barrier properties, and functional performance of edible films. However, for safe and sustainable applications, these nanomaterials should ideally be non-toxic, biocompatible, and derived from natural or renewable sources. Functionalized nano systems enable the controlled and sustained release of bioactive compounds, even those with low solubility, thereby improving food quality and shelf life. Continued advancements in green synthesis and extraction technologies will allow researchers and the food industry to effectively harness the potential of nanotechnology for developing safe, efficient, and environmentally friendly edible films designed for modern food preservation needs.

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