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# Application of Nanocomposites from Biopolymers and Plant Extracts Mediated Nanoparticles as Food Bio preservatives for Fruits and Dairy Products

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## ABSTRACT

Nanotechnology approaches could involve in numerous disciplines, including food processing/ preservation. The discussion of this review is focused on identifying the utilization of nanocomposites developed from biopolymers and nanoparticles prepared by plant extract on improving food shelf life especially fruits and dairy products. These nanocomposites take advantage at the biocompatibility, antimicrobial, and antioxidative features of biopolymers, oil additives and plant-derived nanoparticles, making them more environmental friendly for use in food packaging. The addition of these oils adds a functional value to these materials by providing protection against microbial decay as well as oxidation. The review is used to analyze synthesis, action plan, and probable uses of these bio-nanocomposites focusing on shelf life, quality of foods, and the environmental conservation. Moreover, it discusses some recent issues, such as limitations in the scale-up and regulation constraints and proposes possible future studies on how to enhance these environmentally friendly food packaging technologies. This extensive commentary thus illuminates the lifesaving possibilities of plant-based nanotechnology delivery in resolving these pertinent questions of food security and producers' prospect.

***Keywords:*** Nanomaterials, food preservation, biosynthesis, natural products.

## 1. Introduction

Nanotechnology is making its way to becoming one of the greatest innovative developments that can affect numerous sectors of the economy such as food preservation. Nanocomposites especially those of bio based biopolymers and plant mediated nanomaterials are currently under intensive consideration as more effective and efficient method to enhance food quality, safety, and stability. This has brought about the idea to tackle with the increased concern of food safety and the safety of the environment as the modern consumers demand safer, healthier and environmentally friendly food products (Bajpai *et al.,* 2018). The use of bio composite materials that combine natural polymers and nanoparticles opens a new approach to using environmentally friendly material to package and preserve food products. As such, this paper aims at reviewing current developments in the application of edible bio composites in food packaging with the view of demonstrating that this type of packaging offers greater food safety, longer shelf life, and reduced environmental impact (Shafiq *et al.,* 2020).

Recent environmental challenges and the necessity of developing new kinds of food packaging have underpinned major shifts within the food industry. Biopolymers that are produced by extracting their resources from renewable natural resources can effectively replace the oil-based plastics. By incorporating these biopolers with nanoparticles especially those with antimicrobial characteristic, new generation biopolymers can be developed as they enhance not only the barrier, mechanical, and optical characteristics of the basic polymers but also the potential antifungal, antibacterial, and antiviral capabilities. This transition is well illustrated in the food packaging sector, which is now witnessing nanocomposite biopolymer-based materials that replace traditional ones. These systems, apart from

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contributing to a reduction of food wastage, also enhance sustainability within the food processing sector by cutting on the use of plastics (Lugani *et al.,* 2021). The main potential applications of biopolymers-based nanocomposites in different fields are appointed in Figure 1.

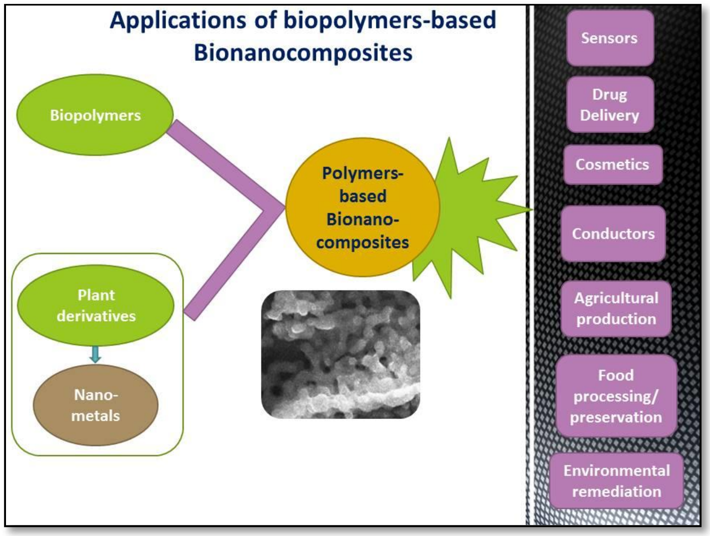


**Fig. 1:** The main potential applications of biopolymers-based nanocomposites

Among the various solutions among them, the extension of biopolymers' functionality for application in food packaging may be considered one of the most successful and efficient approaches plant-based nanocomposites, which are filled with nanoparticles obtained due to plant extract. Thus, cellulose nanocrystals, chitin nanoparticles, and plant-mediated other nanoparticles have advantages because of biocompatibility and renewability and their antimicrobial potential. This is especially important since the use of essential oils obtained from aromatic plants is effective due to their microbial, fungicidal and antioxidant activity. On the other hand, the use of essential oils in the biopolymer-based nanocomposites improves the functional properties of the packaging, in that they act as preservatives against microbes, as well as antioxidants against chemical degradation, all the while making the packaging materials even more eco-friendly (Gao *et al.,* 2024; Wang *et al.,* 2024).

The main drivers of the global increase of demand for improved and nutritious food products are the emerging fears towards food borne diseases and unsustainable means of food preservation. A lot of chemical and physical food preservation techniques that are available such as disinfectants have disadvantages like removal of natural protection layers and short usage life. Also, the use of chemical in food preservation has widely brought into perceived environmental and health impacts. This has prompted more attention being paid to the use of natural antimicrobial agents phytochemicals to improve the shelf-life and quality of food products. These natural antimicrobial agents, when used to improve bio based polymer nanocomposites, may provide an optimal solution to many of the problems typical for typical food preservation methods (Popescu & Ungureanu, 2023).

All of the previously mentioned is a novel approach that has some added advantage of integrating the use of biopolymers, plant nanoparticles, and essential oils to come up with a sustainable approach of the food packaging material and giving additional advantages to the food safety and shelf life extension. Using biodegradation capability of biopolymers, plant based nanoparticles with bioactivity, and the antimicrobial and antioxidant fond benefits of essential oils this concept focuses on the requirements of food packaging industry for environment conscious and value added packaging materials (Nura, 2018).

The aim of this review is to discuss new trends and recent findings in the synthesis of these new bio composites and their functionalities, ecological effect and most crucially, their application on food preservation. This review intends to review systematically the accomplishments, issues and prospects in relation to the nanocomposite food packaging through biopolymer and plant derived nanocomposite integrated essential oils.

**2. Biopolymers and plant extracts in food preservation**

Biopolymers are a group of naturally occurring materials and include polysaccharides extracted from cereals, starch, seeds, and soybeans, as well as polysaccharides such as proteins or polypeptides and biopolymers extracted from animal and plant tissues. The properties of biopolymers depend on their molecular weight, size, and type. Biopolymers such as proteins, polysaccharides, and some lipids (i.e., waxes) extracted from horticultural crops are generally safe for human health, which is why they are used in various pharmaceutical and food industries. The horticultural crops from plants contain a majority of active and functional phytochemicals such as phenolic acids, carotenoids, flavonoids, and monoterpenoids, which can be used as biopreservatives. Plant sap, resin, wax, pollen, and their derivatives are used as exudates from the leaves, flowers, seeds, and roots of horticultural crops. The composition and functional or beneficial attributes of agricultural crops are attributed to these properties (Bao *et al*., 2021; Adeyemi *et al.,* 2022; Khan *et al*., 2022).

Biopolymers and higher plant extracts with improved antibacterial or antimicrobial activity are mainly used as food packaging materials in the food industry and can also be incorporated in food matrices to preserve quality. Extracts are obtained from horticultural crops and are used with biopolymer matrices as nanoparticle (NP) constituents for attributes of the plant's residual extract. Various nanoparticles with improved antimicrobial activity are obtained as a result. Food contact properties are influenced by complex physicochemical factors such as solubility, extractability, volatility, and thermal stability due to various biopolymer and fruit extract compositions. The biopolymer/plant extract nanoparticle film's applicability as conventional food preservation agents can be assessed by optical, mechanical, and thermal measurements. A review of the application of nanocomposites from biopolymers and the antimicrobial activity of the resulting nanoparticulate with improved active plant residual extract food preservation agent for fruits and dairy products is presented (Bao *et al*., 2021; Kumar *et al*., 2021).

**2.1. Chitosan as a biopolymer**

The sol-gel process has been used as an efficient workshop for synthesizing a variety of inorganic materials from the liquid phases. The straightforward procedure of the sol-gel method consists of the hydrolysis of metal alkoxides in an acidic or basic solvent to create the colloidal dispersion of the materials, followed by the condensation and the subsequent drying procedure with respect to the concentration of the gel and the dielectric permittivity of the wet gel. Due to the high efficiency of the sol-gel method, the biopolymer-mediated sol-gel process has been widely applied in creating advanced hybrid organic-inorganic nanocomposite materials (Khan *et al.,* 2022). In the course of the sol-gel reaction, the organic and inorganic materials are homogeneously distributed at the molecular level, providing new synergic properties that are neither displayed by the individual organic nor by the inorganic materials. For the ideal interpenetration of the organic and inorganic constituents, the hybrids can also be modified either by incorporating the organic components within the inorganic frameworks or through the covalent bonding between the halides and the matrix (Ahmad *et al.,* 2021; Cuong *et al.,* 2022).

Because of the presence of amino and hydroxyl groups (as well as ionic properties), chitosan displays several functional properties that are beneficial for usage in a range of fields. For instance, the mucoadhesive and biodegradable properties of chitosan render the effective delivery of proteins in humans as well as in the preservation of food and fruitstuffs. In the nonintravenous administration of proteins, the principal challenge is to maintain the protein bioactivity prior to and after absorption by the epithelial membrane. An additional function of proteins includes the capability to absorb the epithelial membranes, which permits the coabsorption of proteins that do not have mucoadhesive properties as chitosan does. With its mucoadhesive and biodegradable properties, the chitosan nanoparticle can preserve the bioactivity of lactoferrin within the intestinal tracts and shield them from this proteolytic and acidic degradation (Velidandi *et al.,* 2020).

**2.2. Alginate: Improving gel mechnism and moisture absorption**

Alginate, a natural anionic water soluble complex polysaccharide, derived from brown seaweeds, is particularly suited to gelation, moisture conservation and control release system which are very important aspects pertaining to food industry and packaging systems(Goh *et al.,* 2012). Alginate hydrogels utilize moisture absorbing nature for packaging fresh produce and meat because moisture content plays an important role in determining the texture of these products by preventing shrinkage and spoilage. For example, calcium alginate coatings have been known to minimize moisture loss and extend the greenish color in fresh fruits and vegetables, and keep their refrigerated freshness longer(Olivas & Barbosa-Cánovas, 2005).

As an addition, alginate can be used with chitosan where alginate improves moisture control while chitosan has antibacterial activity against numerous foodborne pathogens. It is widely found that the synergistic effect is more effective for producing a host of biodegradable and biocompatible films for food packaging with alginate chitosan complexes. These films can substitute synthetic preservatives by creating a barrier on the surface of the food items to minimize perishability and maximize food quality. Furthermore, the biocompatibility and biodegradability characteristics of alginate based films are suitable for the current market pull and the recent direction of extending sustainable packaging materials, making alginate as a potential green food packaging material(Chaudhari *et al.,* 2023).

### 2.3. Gelatin

Gelatin biopolymer with enormous application in the fields of food packaging, preservation and as a versatile packaging material is a natural biopolymer derived from collagen. It is biodegradable and derived from natural sources and its use in food packaging is preferred to other synthetic materials. However, the use of standalone gelatin films could be challenging as they can be easily torn apart and are hygroscopic. When incorporating gelatin with other substances such as chitosan, which possesses antibacterial characteristics and tensile strength, investigators have developed multi-film materials that are moveable mechanically and biodegradable as well(Rezaee *et al.,* 2020).

Molecular simulation was used to study the effect of stable chiral oligomers on polymer properties, specifically on increasing molecular flexibility and mechanical strength. The addition of chitosan to gelatin can enhance the mechanical properties of gelatin-based films by up to 45% of increased flexibility and tensile strength in most cases when subjected to stress. This flexibility is imperative in case of food packaging purposes, where packaging material should be able to match the shape of the food product and should not tear at any point. The findings have revealed that the gelatin-chitosan blend offers an intermediate pore size that offered improved tensile strength and the elongation properties of the film to support mechanical handling in packaging line (Wang *et al.,* 2021a).

Moreover, gelatin is biodegradable to allow the product to disintegrate fully, and hence has a minimal environmental effect. This biodegradability is crucial in foods since most of the packaging materials used are disposables, and therefore they are usually chucked after use. In addition to being an eco-friendly packaging system, a matrix of gelatin and chitosan has the added advantage of a food preservative that consists of chitosan which can suppress the growth of food-borne pathogens and enhance the shelf life of perishable commodities(Sánchez-González *et al.,* 2011).

### 2.4. Polyvinyl alcohol (PVA)

Polyvinyl Alcohol (PVA) is gradually attaining more importance in the polymer family for food packaging and preservation applications, owing to its biocompatibility and film forming and water soluble nature. Since it is synthetically derived but biodegradable, PVA is particularly effective for environments where the degradation rate can be managed, which is desirable for both active food packaging and food preservative systems. PVA is barely elastic and transparent combined with natural antimicrobial chitosan polysaccharide, making it ideal as a carrier and an excellent shield for bioactive compounds that renew and prolong the shelf life of foods (Patil *et al.,* 2021; Zhang *et al.,* 2024).

In active packaging, PVA-chitosan blends are advantageous because they yield strong, yet flexible and regularly adherent to the food structures, yet are mechanically appropriately capable. It is attractive the biocompatibility of blend, because this blend can slowly and steady release bioactive additives such as antioxidants or antimicrobials, which allows to constantly improve the food's quality for longer periods. Research findings reveal that the chitosan-PVA matrix develops high transparency and tensile strength, which is relevant for foods packaging that requires both appealing and sturdy packaging (Ali & Ahmed, 2021).

The biocidal properties of blends containing PVA and chitosan are well researched and greatly enhance food protection. Chitosan by itself has antimicrobial activity against different microorganisms, and when incorporated with PVA, the resulting composite has been reported to have an ability to suppress bacterial and fungal growth efficiently. This antimicrobial functionality can be quite beneficial in packaging of fresh produce, meats among other perishable products where microbial influence is paramount. By further adding other bioactive agents including essential oils or plant extracts, the company has been in a position to increase on the preservative capability thus acting as an active packaging material that does not only contain but also protect the food product(Jiang *et al.,* 2024).

**2.5. Polyethylene oxide (PEO)**

The general formula of polyethylene oxide is a polymer with many uses in film forming, biodegradable and biocompatible in food packaging and preservation. PEO possesses good water solubility and flexibility, which allows for blending of this polymer with natural polymers such as chitosan to improve on the features of biodegradable films. The incorporation of PEO in to chitosan enhances the films mechanical properties, thus the films exhibits better flexibility, homogeneity, and storage stability. This combination is particularly useful in food packaging uses because stability and evenness of the film is a big issue to do with preservation quality of the foods to be packed (Zivanovic *et al.,* 2007).

As active packaging, PEO-chitosan blends because of the barrier for films that have better resistance to oxygen, and water vapor permeability which are requirements for preservation of food and its shelf life. PEO-chitosan films have an oxygen barrier effect that minimizes the oxidation processes that tend to spoil the ingested food's flavor. Also, as with any PEO film, the fairly slow release rate makes it effective for slow release of active agents such as antimicrobials or antioxidants coated within the film. This controlled release function helpful for food preservation since it facilitates a gradual and constant release of preservatives, thus increasing the efficiency of the packaging during the entire storage period (Thambiliyagodage *et al.,* 2023).

Another advantage is biodegradability of PEO, which possession of the ability to degrade by natural processes without leaving any toxin behind, this shows conformity to the current laws for environmentally friendly packages and consumer demand for a green product. The incorporation of PEO with chitosan adds value not only to the antimicrobial nature of chitosan and the fact that the developed film possess high mechanical properties that make it possible for use with different types of perishable food products (Cheng *et al.,* 2024; Liu *et al.,* 2022).

**2.6. Starch**

Carbohydrate polymers such as starch have attracted considerable attention in the creation of packaging due to their availability and renewability. This versatility in film formation enhances the ability of starch based films to act as barriers against environmental factors that can complicate the quality of food. Starch on its own often do not exhibit the necessary mechanical strength and water resistance to perform in high performance packaging. Starch based films also showed that the incorporation of chitosan, a natural polysaccharide sourcing from crustacean shells, provides improved tensile strength, good barrier properties for gases and moisture, and favorable antimicrobial properties (Wang *et al.,* 2024).

The chitosan to starch blend is remarkable since while starch has the benefits of cheap and environment friendly, chitosan has antimicrobial properties that enhance shelf life through polling microbial activity. This combination the develop a highly functional, biodegradable film, apposite for packing of perishable food such as fruits, vegetables and baked good. The amalgamation enables excluding the intrusion of moisture or oxygen in to the food items which are the major factors aggravating the rate of food spoilage and also help in retaining the quality of the foods kept for later consumption(Alvarado *et al.,* 2021).

Further, the packaging made from starch and containing chitosan has potential as a natural preservative and as a replacement for plastics and chemicals that are being sought by consumers and regulators for food preservation products. Starch-chitosan films have also been found to inhibit microbial growth on the food surface; this is very important given that fresh fruits and vegetables are reactive to microorganisms and Microbial spoilage is a cause of food borne illnesses and food waste (Priyadarshi & Rhim, 2020).

**2.7. Polyhydroxybutyrate (PHB)**

Polyhydroxybutyrate (PHB) is a microbial biopolymer manufactured through fermentation of renewable resources in bacterium and widely appreciated due to specialties such as biodegradable and thermoplastic. PHB is a stable material naturally and is biodegradable; it degrades in most favourable conditions to form water and carbon dioxide. While research into PHB has focused on its desirable characteristics since it is a highly crystalline polymer, it is also highly brittle, this has seen researchers try to incorporate other polymers like chitosan to modify its mechanical properties and flexibility(Patel *et al.,* 2022).

Combining of PHB with Chitosan produced a composite that shows enhanced mechanical strength and structure. The formulated chitosan-PHB matrix is more suitable for the packaging of perishable commodities as chitosan has antibacterial features that slow down the rate of spoilage through microbial activities. Overall, the blending strengthens the tensile strength and the flexibility of PHB to Nod be brittle and more appropriate for food packaging demanding endurance and biodegradability(Nair & Laurencin, 2007).

Organic decomposition of PHB gives it high value since it degrades under eco-friendly conditions. In contrast to other hydrocarbon-based thermoplastics, PHB can decompose in both aerobic and anaerobic environments, so that compostable food packaging contains it. The blend with chitosan improves this property by affording a rational rate of degradation in relation to the packing longevity of perishable products. It has been demonstrated that films based on the PHB/chitosan composite have a higher degradation rate within the conditions of composting and can be fully composted within a few months. This characteristic makes PHB-based films fit well for packaging applications within circular economy since they do not end up in landfill or pollute the environment(Avérous, 2024).

### 2.8. Collagen

Collagen is a natural protein derived from animal tissues with primary concentration in skin, bones and tendons. It has been long known for its structural applications in biological systems and has only recently received interest in the food industry especially for its applications in food preservation. Application of collagen based films and coatings have several advantages of encapsulating foods because they create a physical barrier to prevent moisture loss, control the permeability of oxygen, and protection against microbes. It will also be beneficial to know how these films could increase the longevity of fresh foods such as fruits and vegetables and seafood and likewise bio-degradable compared to synthetic plastic(Cao *et al.,* 2020). These features can be further perfected by incorporating antimicrobial compounds in the form of essential oils, or functionalized silver nanoparticles, in the construction of collagen films. Collagen and their derivatives including gelatin, there is evidence that possess antioxidant activities which are important in the prevention of oxidation of foods. This is most relevant where fats and oils are involved as oxidative rancidity is always a leading cause of spoilage(C. Ding *et al.,* 2024; Sridhar *et al.,* 2020).

The use of collagen based materials has been documented to hinder decomposition of free radicals hence preserving colour, taste and nutritional value of foods in storage. The antimicrobial activity of collagen has been investigated in relation to the ability of the material to suppress the colonization of pathogenic bacteria and fungi on food contact surfaces(Andreou *et al.,* 2021).

Collagen in combination with other bioactive compounds delays the perishability of food, so it has also been considered as a raw material for biodegradable food packaging material reducing the hazardous effect of hazardous petroleum based plastics. Seafood is best known to be preserved with the help of collagen, which is an important attribute to be mentioned. For example, collagen derived films are being employed to make a cover of seafood and improve the stays freshness in fish(Duhan *et al.,* 2021).

### 2.9. Plant Extracts as Nanoparticle Mediators

Secondary metabolites in plants include terpenoids, alkaloids, tannins, flavonoids, and phenolic compounds, which are the major factors that reduce the metal ions to metallic nanoparticles in the synthesis and antifungal activities of the nanoparticles. The biopolymeric compounds from plants include pentacyclic triterpenes, cycloartanes, cycloartenes, friedelanes, araboranes, and lanostane triterpenes, glycosides, steroids, and flavonoids. The biosynthesis of gold nanoparticles has revealed that hydrophobic interaction between the pentacyclic terpenes that act as stabilizing molecules, and the polar end of the primary alcohols that cover the nanoparticles, is responsible for the activity (Adeyemi *et al.,* 2022; Cuong *et al.,* 2022; Khan *et al.,* 2022). Furthermore, the remaining side chains of the terpenes are hydrophobic, which have demonstrated their interaction with the lipophilic regions of the mycelium cell wall, allowing their interaction from inside and outside of the membrane, leading to significant antifungal activity. The mycelium-defensive inhibitory effect is due to the electron shield on the particles, reducing the viscosity of the membrane, changing its permeability and fluidity, ultimately leading to ruptured and deformed cell membrane and concomitant spillage of the cytosol from the cell into the suspension medium. The silver/gold nanoparticles obtained by using different flavanol polyphenols showed very high cellular uptake, and their mechanism of action on Trichophyton mentagrophytes, via damages to DNA and cells, was observed (Khan *et al.,* 2022; Al-darwesh *et al.,* 2024).

**Table 1:** Biopolymers and their applications in food packaging.

| Biopolymer | Key Properties & Mechanisms | Applications in Food Packaging | Advantages | References |
|---|---|---|---|---|
| **Chitosan** | Sol-gel process, mucoadhesive, biodegradable; enhances protein bioactivity and protects against proteolytic degradation | Protein delivery, food and fruit preservation | Antimicrobial, biodegradable, improves food shelf life | (Khan *et al.,* 2021) |
| **Alginate** | Gel-forming, moisture absorption, releases control; effective in moisture management | Fresh produce, meat packaging, combined with chitosan for enhanced antibacterial properties | Moisture retention, biodegradable, effective in minimizing spoilage and preserving color | (Suryavanshi *et al.,* 2023) |
| **Gelatin** | Biodegradable, flexible; enhances mechanical properties with chitosan | Seafood, meat, and general food packaging | Improved tensile strength, antimicrobial, biodegradable | (Wang *et al.,* 2021b) |
| **Polyvinyl Alcohol** | Biocompatible, water-soluble, combines well with chitosan | Active packaging, food preservation, carriers for bioactive compounds | Strong, flexible, transparent, gradually releases bioactive additives | (Pang *et al.,* 2024) |
| **Polyethylene Oxide** | Film-forming, moisture and oxygen barrier, controlled release | Packaging for fresh produce, meat, controlled release applications | Biodegradable, resistant to oxidation, effective for slow release of preservatives | (Hou *et al.,* 2024) |
| **Starch** | Easily available, renewable; good gas and moisture barrier properties when combined with chitosan | Packaging for fruits, vegetables, and baked goods | Biodegradable, cost-effective, antimicrobial, retains food quality | (Hou *et al.,* 2024) |
| **Polyhydroxy butyrate (PHB)** | Biodegradable, thermoplastic; blends with chitosan for enhanced properties | Packaging for perishables; compostable applications | Environmentally friendly, high degradation rate in composting conditions | (Adnan *et al.,* 2022) |
| **Collagen** | Barrier to moisture, oxygen, and microbes; antioxidant activity when combined with essential oils | Fresh produce, seafood, and other perishable items | Biodegradable, antimicrobial, prevents oxidation, maintains freshness | (Ding *et al.,* 2024) |

The utilization of plant extracts as reducing and stabilizing agents in the synthesis of nanoparticles can contribute to greener nanotechnological advancements. Plant-mediated synthesis of nanoparticles is preferred because it is less harmful and a clean process compared to several other methods. The plant extracts also function as stabilizing agents by protecting the nanoparticles from coagulation and aggregation. Plants are cost-effective and natural entities, rich in antioxidants, and their water extract does not require further processing. Secondary metabolites in plants such as alkaloids, saponins, flavonoids, tannins, steroids, quinones, terpenoids, lignans, coumarins, and cardiac glycosides interact

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with the metal ions present in the reaction mixture to form metal-oxygen complexes for their biochemical activity (Ahmad *et al.,* 2021; Khan *et al.,* 2022; Dash *et al.,* 2022).

## 3. Nanocomposites for Food Biopreservation

Finally, the definition of ecological food wrapping refers to the goods capable of meeting biodegradation specifications. Pure polymers with natural additives and/or antimicrobial composites have a role to mimic these biodegradable requirements. If it is possible to use the composites also in the production of micro or light agricultural cultivation assets, an innovative chain of biodegradable materials for internal and external packaging field application, particularly in tomato, is suggested (Bao *et al.,* 2021; Khan *et al.,* 2022; Al-darwesh *et al.,* 2024).

The need and application of different biopolymer-based nanocomposites is important in food biopreservation. In order to process a better ecological disintegration of the natural environment, the possible applications of manufactured biodegradable polymeric composites for packaging certain natural products in the food industry, compatible with modern food manufacturing techniques, to better preserve and become usable for a long time, are constantly noted. Biodegradable composites, particularly those whose dissolving can be degraded with ample emission of carbon dioxide and water, are particularly critical for many unprocessed fruits and fruit items. Biodegradation of plant products can only be effectively used in a special humidity level environment. Biodegradable composites like this are easily used in industrial and home composting plants and, in principle, do not create any problems with disposal after their service life in plant products as a result of the biopolymers owned and partially because of less litter on the ecosystem. Small molecular weight biologically active components immobilized in the structure of the composite fed and/or disintegrated as a result of the biodegradation of the biodegradable plastic matrix contribute to the development of a new concept of active packing (Muthukumar *et al.,* 2020; Velidandi *et al.,* 2020).

### 3.1. Selenium Nanoparticles

The applied fruit and milk are needed to provide nutrition. Because SeNPs were mediated by water leaf extracts and SeNPs painted fruits have higher glutathione peroxidase activities, the storage periods of fruits and the retention of nutrition were prolonged after being painted (Nayak *et al.,* 2021; Alghuthaymi *et al.,* 2021; ElSaied *et al.,* 2021; Ikram *et al.,* 2021). The theory of desorption of natestannic acid or chitosan in the tested fruits is helpful to prevent the fruits from rot. Although the treated SVT+CP rna SNs had high antifungal activity, after 30 days the effectiveness had an attenuation, resulting from the rapid degradation without coatings and the release of biological molecules in the banana or kiwi with SNs coatings. Therefore, the extracts could prolong the antifungal effect of SeNPs. Regardless of whether SeNPs had contact with fungi or not, it was observed that the microbiological count of banana and kiwi with SeNPs and extracts coated fruits was low even after 27 days. Due to water leaf plant extract, the fruits with SeNPs took advantage of antioxidant enzymes and possessed nutrition, which could extend the storage lives of fruits and milk without any hazardous chemicals, rendering the food more palatable (Muthukumar *et al.,* 2020; Ahmad *et al.,* 2021).

Figure 2 illustrates the direct and facile method for SeNPs biosynthesis using plant extract, followed by their characterization.

Selenium nanoparticles (SeNPs) are parallel to the activity of Se ions, concentrated on inhibiting the food intake of predation pests and reducing the emission of greenhouse gas in animal bodies (Garza-García *et al.,* 2022; Shehab *et al.,* 2022). Furthermore, Se could reserve the freshness of fruits. They are easily obtained because Se elemental could redimension the formation of Se NPs. In our laboratory, water leaf extract was used to yield SeNPs. Then, banana and kiwi fruits were painted with SeNPs, and enzyme membrane was used for dairy product pretreatment, followed by storage of fruits and treated dairy products. After the storage period, the enzymatic activities and color variation abatements exhibit that banana and kiwi could keep their freshness (Shehab *et al.,* 2022; Abd-Elraoof *et al.,* 2023; Meshref *et al.,* 2024). Acidity and microbial population abatements were observed in dairy products. This result can be explained by the high preservation of antioxidant activities of treated fruits and milk, which are 5-20 times higher than the initial ones of fresh fruit and milk. Meanwhile, the antifungal activities of stored fruits and dairy products were improved due to the extracts (Patil and Chandrasekaran, 2020; Mohammadzadeh *et al.,* 2022; Aziz and Setapar, 2022).

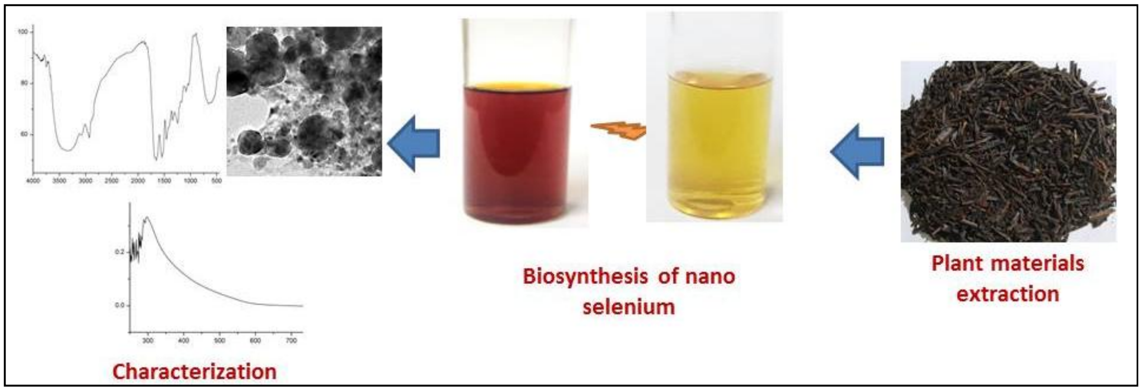


**Fig. 2:** The direct and facile method for SeNPs biosynthesis using plant extract, followed by their characterization

### 3.2. Zinc oxide nanoparticles (ZnO-NPs)

Zinc oxide nanoparticles (ZnO-NPs) have been studied extensively for food packaging applications because of their dual functionalities as an antimicrobial agent, and a physical and chemical sensor that effectively improves other properties of the packaging materials. ZnO-NPs are effective against diverse foodborne pathogens including the mode of ROS production that affects the structural organization of microbial cells. ZnO-NPs combined with polymer materials enhance mechanical properties, moisture resistance, thermal stability, and optical transparency of foods and packaging materials, and also increase the barrier properties of the packaging. As mentioned above, ZnO-NPs efficiency depends on the particle size, concentration, as well as dispersion within the polymer matrix, to achieve an optimal performance without detriment to the overall material structure. More than that, using ZnO-NP based packaging materials for the intelligent packaging that could indicate the change in food quality and increase the shelf life(Gao *et al.,* 2024).

Issues surrounding the transfer of ZnO-NPs into food have been raised and some research has shown that ZnO-NPs which are used in packaging material do not pose high migration rates into foods and hence safe for use in foods applications. However, much more research will be needed to determine the long-term safety and to evaluate production parameters concerning the food safety requirements. Moreover, goods packaged in ZnO-NP-based packaging material can save food from spoiling and therefore, they represent an effective solution to such issues in such products. Because they can become integrated into smart packaging systems to measure food quality and freshness, ZnO-NPs hold the key to the next generation of food packaging( Wang *et al.,* 2023).

### 3.3. Preparation and Characterization of Nanocomposites

In the present scenario, bioplastics are being used as a replacement for fossil polymers due to their nonrenewable nature, which leads to various environmental problems upon disposal. The properties of the biopolymers have been enhanced using the nanofillers. These proposed biopolymers have desired favorable properties such as UV barrier for the preservation of light-sensitive food; low oxygen and water vapor transmission rates, good mechanical and thermal properties, and antimicrobial activity for extending the shelf life. The different types of nanocomposites are reported using different types of biopolymers in the presence of plant extracts mediated nanoparticles. Also, different phytochemicals are added to the polymer-based nanomaterials to create bio-nanocomposites. Then, the food preservative characteristics of such nanocomposites are elaborated. The proposed nanocomposites and bio-nanocomposites not only solve the problems due to the usage of conventional petroleum-based polymers one step further by adding the benefits of the green-synthesized nanoparticles and nutraceuticals, the quality and safety of the packaged food products are further preserved (Tiwari and Sharma, 2023; Naghib & Garshasbi, 2023).

The different types of nanocomposites, related bio-nanocomposites, and their preparation techniques such as solution casting, melt intercalation, melt extrusion, compression molding, film extrusion, in-situ polymerization, and electrospinning intercalation, polylactide cellulose, and other natural polymers nanocomposites have been reviewed by multiple authors. In this chapter, recently, the potential application of biopolymers and plant extracts mediated nanoparticles are visited, and the nanoparticles are produced by a green synthesis method. The confirmations for the synthesis of the biosynthesized nanoparticles such as FTIR, XRD, and SEM are studied. The incorporation of phytochemicals in the food packaging materials and their characterization and antibacterial activity investigations are studied. The above discussion includes a general idea of the preparation and characterization of such nanocomposites. Then, the applications of the eco-friendly biocomposites as the bio-preservatives using different nanocomposites and bio-nanocomposites of the fruits and dairy products are explained (Ahmad *et al.,* 2024; Velidandi *et al.,* 2020).

**Table 2:** Plant extracts and nanoparticles: properties, mechanisms, and applications in food packaging nanocomposites

| Material/Compound | Properties & Mechanisms | Applications in Food Packaging | Advantages | References |
|---|---|---|---|---|
| **Plant Extracts (Secondary Metabolites)** | Terpenoids, alkaloids, tannins, flavonoids; reduce metal ions and provide antifungal properties | Synthesis of metallic nanoparticles, antifungal coatings | Eco-friendly, cost-effective, high antioxidant content | (Khan *et al.,* 2022) |
| **Gold Nanoparticles (AuNPs)** | Stabilized by terpenes; hydrophobic interaction with cell membranes for antifungal activity | Antifungal food packaging, preservative for perishable items | High antifungal efficacy, enhances shelf life of perishables | (Ikram, 2015) |
| **Silver Nanoparticles (AgNPs)** | High cellular uptake; damages DNA and cell structure of pathogens | Preservative packaging for fresh produce and dairy products | Improves food safety, inhibits microbial spoilage | (Ahmed *et al.,* 2016) |
| **Selenium Nanoparticles (SeNPs)** | Enhances antioxidant activity; prolongs shelf life, prevents rot in fruits and milk | Packaging for fruits and dairy, prolongs storage life | Prolongs shelf life, enhances nutritional quality | (Pyrzynska & Sentkowska, 2021) |
| **Zinc Oxide Nanoparticles (ZnO-NPs)** | Antimicrobial activity, ROS production; acts as physical and chemical sensor in packaging | Intelligent and antimicrobial packaging, shelf-life extension | Improves mechanical strength, moisture barrier, and food freshness detection | (Al-darwesh *et al.,* 2024) |
| **Biodegradable Nanocomposites** | Biodegradable, enhanced with nanofillers; UV barrier, moisture resistance, and antimicrobial properties | Bio-preservative packaging for fruits, dairy, and light-sensitive food items | Minimizes food spoilage, environmentally sustainable, extends shelf life | (Bari *et al.,* 2016) |

## 4. Mechanisms of Action

The limiting value for these microorganisms (LAB and incubation temperature) in order to attain the benefits of mixed cultures and ripening time extends shelf life successfully. Natural biopolymers contribute to the inhibition of microorganisms present, as these biopolymers provide anti-inflammatory and suppress acid-mediated increases. The natural biopolymers with incorporated plant extracts show a better antimicrobial activity against the evaluated test microorganisms. The use of embedded plant extracts in natural biopolymers avoids the formation of toxic compounds that are present in chemical alternatives, as well as reducing the degradation of biopolymers and retaining freshness and increasing fruit hardness. Natural plant extracts include varied antimicrobial and antioxidant compounds and enzymes, and thus have attracted attention in the food industry for food preservation. Antimicrobials such as enzymes, antimicrobial peptides, organic acids, and lysozyme inhibit the growth of foodborne pathogens in food (Mohammadzadeh *et al.,* 2022).

Biological compounds can inhibit decay fungi and bacteria at a low concentration, compared to synthetic compounds, and their biosynthetic process is more cost-effective and non-toxic. This gives an advantage in applying biological materials in order to prevent fruit spoilage. Both biodegradable biopolymers and plant extracts enhance the shelf life of the dairy product. The recommended doses of plant extracts and biopolymers allow for the enhanced quality of a dairy product as well as its longevity, primarily because they demonstrate strong aseptic properties. Dynamic changes in the correct functioning of dairy products can be reflected by the count (LAB and TB in general) of various types of microorganisms (Lactobacillus, *Streptococcus thermophiles*, and Lactococci as lactic acid bacteria (LAB)). In the case of non-standard dairy products, fungi and yeasts are reported, which hinder processing (Aziz and Setapar, 2022).

The biopreservative potential of both biopolymers and plant extracts is well studied and finds significant application in the preservation of fruits and dairy products. The preservation of fruits always depends on additives that can extend the shelf life of the fruit from the time of harvest until its consumption. Biopreservatives avoid changes in sensory and nutritional properties and also improve the safety of the product by reducing food contaminants. The bioactive compounds present in biopolymers and plant cell wall matrix (CW) act as preservation agents and inhibit fruit decay. A variety of bioactive compounds have been tested to avoid fruit spoilage. The auto-oxidation of lipids plays an important role in color changes and the off-flavor of fruits. The activation of various enzymes in fruit contributes to its softening, and also increases the production of toxic compounds such as ethylene, and denature cellular proteins (Taherimehr *et al.,* 2021; Basumatary *et al.,* 2022).

### 4.1. Antimicrobial Properties

The use of metal nanoparticles is employed in the research area of application as biocidal agents such as fruit and dairy product preservatives by slow diffusion and exposure of overcoat nanocomposites. Due to their biocompatibility and biodegradability, lipids and phospholipids are usually included in the matrices in food packaging involving fungicides and malodor adsorbent. Several of the initial research project reports on biopolymer nanocomposites that include metal nanoparticles relate to synthesis and mechanical and thermal property development. It is just recently that the deliberate synthesis approaches, antimicrobial activity, and leaching behavior of NPs in biopolymer were extensively examined. Since the legislative barriers to the use of nanocomposites have not been authorized, the important body of the content of the chapter is to review the last 15 years' discourses on polymer and food engineering scientific pressure and to illustrate and prioritize the continuing downside (Gharpure *et al.,* 2020; Zhang *et al.,* 2022).

In food preservation, food packaging, and coating in particular, active control of the environment in direct contact with food has received particular attention. The active control is mostly done by introducing antimicrobial agents such as organic acids, ethylene oxide, essential oils into the polymer matrix. In these, organic acids and essential oils are derived from some plant, and microbial inhibition of these compounds is affected. However, the small molecule moves from the packaging to food, and the taste of the food can be changed by its accumulation in the food. The use of metal nanoparticles is promising here as they are highly stable and much less or no transfer of nanoparticles from the packaging to food. Most of the manufactured nanocomposites for food packaging are of synthetic nanoparticles. However, nowadays, interest is growing in the construction of biopolymer and plant extract-mediated nanoparticles to enhance food protection. The use of biopolymer and plant extract-made nanoparticles in food packaging would satisfy more of the public's environmental recognition than synthetic nanoparticles. Bio-based nanocomposites, where nanofillers are more environmentally friendly and with novel properties (Radusin *et al.,* 2016; Hoseinnejad *et al.,* 2018).

The antimicrobial properties of nanoparticles are due to their small size. The greater the surface area of the particle, the faster the release of biocidal ions. The nanoparticles are thought to combine with the cell membrane of the microorganism. The nanoparticles aid the rupture of the cell wall, causing the leakage of cell content. The dissociated metal ions from nanoparticles further help in bacterial apoptosis by adhering to the sulfhydryl groups present in proteins. The synthesis of bionanocomposites having acceptably high antimicrobial effect, ease of fabrication and performance, with reduced environmental impact and biodegradability, has acquired considerable attention (Kumar *et al.,* 2021; Dey *et al.,* 2022; Adeyemi and Fawole, 2023).

### 4.2. Antioxidant Properties

It has been proven beyond doubt that natural antioxidants can be effectively incorporated into polyphenol-polysaccharide nanoparticle matrices. They have shown potentiality in quenching lipid peroxidation and preserving the bioavailability of these bioactive remainders in the biological system. Along this line, the massive research domain of biopolymers has been prolifically employed to synthesize various nanocomposites by incorporating nonmetallic phytocompounds. Their commendable antioxidant and antimicrobial effects are noteworthy. With the capacity to form highly interactive domains within lipid bilayers, these biopolymer nanocrystal structures are capable of altering the emulsion structure and function of phospholipid vesicles, according to their size, concentration, and chemo-physical properties (Ge *et al.,* 2022; Vieira *et al.,* 2022; Cheng *et al.,* 2024).

Antioxidant constituents are of pivotal importance as they can prevent the propagation of oxidative reactions that lead to the development of rancidity and thereby prolong the shelf life of food. Natural-based antioxidants represent an inherent branch of this significant strip of bioactives. A plethora of polyphenolic and flavonoidal derivatives are present in plant extracts that can contribute to various biomedical properties such as antipathogenicity, antidiabetics, and potent antioxidant response. Such bioactive agents are best associated with the biocompatible polysaccharide groups of biopolymers including chitosan, alginate, cellulose, protein, starch, and their various derivatives. Owing to their free radical scavenging and metal chelating abilities, polyphenolic/polysaccharide nanoparticle formulations are capable of suppressing lipid peroxidation and thereby delaying the oxidation of the lipid fraction of foodstuffs (Rangaraj *et al.,* 2021; Wang *et al.,* 2022).

**5. Applications in Fruits Preservation**

Naturally derived biopolymer coatings and films incorporated with natural extracts will enrich the functional compounds' usage, which is a cost-effective and environment-friendly method through a circular thinking process of utilization of waste and valorization of agro-industrial by-products. It is known that the biopolymer coating and films have good water-vapor barrier and film-forming properties. The usage of biodegradable films becomes a good option. Essential oils and its major compounds are volatile compounds such as oregano, mint, basil, and thyme, which are strong antioxidants and have antimicrobial activities (Xing *et al.,* 2019; Jung *et al.,* 2020). The active compounds can be encapsulated through a polymer matrix, such as biopolymers including chitosan, pectin, and alginate coating and films to form a sustained and controlled release throughout 90 days of storage. A simple and environmentally sound method in combining the chitosan biopolymer with a particular concentration of eugenol present a high potential method employing herbs to develop an effective antimicrobial film in food preservation (Jung *et al.,* 2020; Jafarzadeh *et al.,* 2021; Basumatary *et al.,* 2022).

Food wastage is a major concern globally. This waste is generated at various stages of the food chain such as cultivation, processing, packaging, and retail. Considering this, research on developing new materials that could prolong the shelf life of food has attracted enormous attention. Packaging and storage are key to maintaining the preservation of food, as they are the surfaces where most of the waste is generated. There is a call for the development of cost-effective and eco-friendly packaging with long-term preservation. Polymeric materials along with nanomaterials have been explored for this purpose (Xing *et al.,* 2019; Jung *et al.,* 2020; Riseh *et al.,* 2023).

**5.1. Case Studies**

**5.1. Case Studies**

In the last years, it was described that it is possible to encapsulate the experimental nanomaterials, such as TiO2 nanoparticles, into the complex polymer matrices to prepare highly functional nanocomposites with unique properties and performances. That, on the basis of cost-effective production and environmentally compatible nature of constituents, remain unparalleled by any other class of pelletized (compounded) materials in applications such as food packaging and biopreservative functional additives. The development of these types of initiates from the fact that the metallic and metal oxide nanoparticles have potential biocidal activity due to the damage to the cellular functions and cell death arising from the strong interactions between these nanoparticles and the cells by released ions on the nanoparticle surface or/and nanomaterial-induced cell membrane damage. The large surface-to-mass ratio of these nanoparticles and the release of metallic or metal oxide nanoparticles as particulate matter to the surrounding media make these materials harmful to living organisms because these nanoparticles are applied in antifungal coatings and materials, and conversely, widely used in food nanotechnology.

**6. Applications in Dairy Products Preservation**

Indeed, these nanoenabled flexible cheese packaging systems can incorporate different commercially available bactericidal plant extracts and critically improve their performances. By adapting these nanoenabled flexible active cheese packaging systems with various combinations of biopolymers and plant extracts-coated nanoparticles, the shelf-life of the cheese is critically increased. Due to turning the packaged wrapped cheese inside the wrap would expose them to sanitary issues, both macroscopic and microscopic investigations are performed and interpreted (Li *et al.,* 2021; Perera *et al.,* 2022; Wang *et al.,* 2024).

Such a flexible, safe, and pollutant-free cheese packaging system has high implications in the milk and dairy industries. Consisting of conveniently swelled cheese samples for VOCs analysis, controversial issues about storage temperature are also discussed as well as resolved. It is indeed beneficial for increasing the shelf-life of the cheese for future applications in both small and large-scale dairies (Angelopoulou *et al.,* 2022; Paidari *et al.,* 2023; Brandelli *et al.,* 2023).

In order to design and prepare new food packaging materials to control cheese spoilage microbes, nano-enabled active cheese packaging systems incorporating nanocomposites from biopolymers/gelatrix and different plant extracts mediated nanoparticles are prepared. Dip-coating technique is used for efficient and homogeneous incorporation of AgNi blended gelatrix/biopolymers coating onto the cotton cloth. In order to check the antimicrobial activities of these 'nanoenabled flexible active' packaging systems and in the triplicate tests, Cheddar cheese pieces are wrapped using a (nano-enabled) cotton cloth and their shelf-life studies are performed. Moreover, in the control experiments, the shape of the wrapped Cheddar cheese pieces using a bare pack is maintained. This will be a crucial case study for food industries to develop/choose a nanoenabled cheese packaging system to enhance the cheese shelf-life (Perera *et al.,* 2022; Angelopoulou *et al.,* 2022; Brandelli *et al.,* 2023; Brandelli, 2024; Wang *et al.,* 2024).

### 6.1. Case Studies

The study reported the encapsulation of lemon and fenugreek oil, which have strong antimicrobial activity, into a mixture of sodium alginate and chitosan to verify the potential utilization of such mixtures to extend food shelf life. The fruit of sweet cherries (*Prunus avium* L.) is a highly perishable fruit, prone to fast decay during postharvest handling. The objective of this work was to evaluate the impact of coating sweet cherry fruits and maintaining film barrier properties during fruit storage on the quality of the product. The fruit of sweet cherries was coated with chitosan nanoparticles suspensions at different concentrations and molecular weights. The results of the study showed that the application of chitosan and sodium alginate nanoparticles produced antioxidant fruits. Their bioactive films are both promising in reducing oxidative reactions during storage and improving oxidative stress caused by exposure to hypothermic conditions. Thus, the development of new biocomposite coated fruits can be exploited as innovative technology in the food industry.

For the development and application of encapsulation biopolymer nanoformulations, pomegranate fruit peel extract was synthesized and then the synthesized nanoparticles were dispersed into biopolymer materials such as gellan gum, sodium alginate, and composite materials were prepared. The prepared materials were tested for antibacterial activity on food items like apples, grapes, and paneer. The gellan gum and pomegranate peel synthesized nanoparticles composite biopolymer material performed well in maintaining the shelf life of all the food items. This approach might provide an advanced concept of food preservation in fruits and dairy food materials. The maintenance of shelf life for a longer time requires validation of the performance of the material and more application tests with different food products.

## 7. Challenges and Future Directions

A green-farming concept should be considered as a future prospect for food preservation in a synergistic way, which consequently also benefits smallholding farmers/processors of different fruits and dairy products. The innovation of encapsulated nanoparticles, such as phytogenic green formulated packaging agents in edible coatings, could bring new possibilities for future applications. The use of phenolic polymer materials derived not only from regional biocomposites which support the regional economy, but also from regions already struck by negative climate impacts. Furthermore, inexpensive processing methods are needed for scaled-up production and application in small-scale industries. Encapsulation procedures applied to constituents possessing moderate natural antimicrobial activity with opportune immobilization/adsorption/complexing agents under mild green/sustainable chemistry conditions could efficiently preserve the epidemiological quality of different food products without compromising their sensorial properties (Kumar *et al.,* 2020; Taherimehr *et al.,* 2021; Sobhan *et al.,* 2021).

This process minimizes the formation of free radicals during storage. The driving force behind the use of these nanoparticles in food is the hidden potential for enhancement of the shelf life of different types of food products. Attention should be given to the application of biocompatible nanocomposites as food packaging imitation through Federal Institute for Risk Assessment (BfR) guidelines by evaluating the migration of new components from natural resources-based nanocomposites to the food, in order to ensure the safety of products during storage. The addition of phytogenic agents should not negatively influence the characteristics of the packaged food. Importantly, the utilization of biocompatible agents such as silver or zeolites should not be known to unfavorably influence the nutritional qualities of the preserved food. These aspects, in addition to the effect of antimicrobial components on the environmental bacterial community prevailing inside food, should be evaluated in detail in future investigations (Sarfraz *et al.,* 2020; Souza *et al.,* 2020; Sobhan *et al.,* 2021; Ansari, 2023).

### 7.1. Regulatory Considerations

In recent decades, concern in society about the use, release, exposure, consumption, and behavior of novel materials such as nanomaterials has increased. This facet generates considerable challenges for the agri-food sector and is key on the regulatory roadmap of various countries and international bodies. These concerns have been raised despite the expectation that these types of novel materials will bring benefits that exceed the costs or will be able to provide benefits where currently used materials are not able to meet the cost-benefit expectations. To mitigate these concerns, proposals have been made by international bodies, which in most cases so far are aimed mainly at a regulatory framework to control the behavior of materials suspected of being potentially hazardous to human health or on the environment, but much less so to foster the use of novel materials that pose no hazard (Kumar *et al.,* 2020; Sarfraz *et al.,* 2020; Taherimehr *et al.,* 2021; Sobhan *et al.,* 2021).

Government food and drug regulatory agencies have approved the application of nanocomposites from biopolymers in food packaging, albeit with an emphasis on compliance with existing regulations. In this context, the present chapter, as well as the results obtained from different studies, can only provide an estimate of the potential risks of these nanocomposites. However, the final proof of their safety must be studied using biocompatibility tests and in vivo tests before these nanocomposites can be industrially manufactured and step into the commercial world. Since direct or incidental oral intake of nanocomposites from biopolymers may occur, all considerations of food-contact nanomaterial risk assessment will be valid. The use of nanocomposites from biopolymers must comply with all prevailing relevant legislation to ensure that only safe food is available to consumers and that only safe materials are in contact with food (Franz *et al.,* 2020; Alfei *et al.,* 2020; Singh and Kumar, 2023; de Sousa *et al.,* 2023).

### 7.2. Sustainability Aspects

The resultant nanocomposites demonstrate promising potential in food packaging and they have been processed, shaped, and endowed with optimal mechanical properties to allow potential application in melt processing protocols. The freshness of fruit and vegetables could be effectively extended by the biodegradable hydroxypropylcellulose/silver-particle@chitosan-grafted hydroxypropylcellulose films. Active poly (butylene adipate-co-terephthalate) (PBAT) films incorporated with Esselement, a new additive from Oregano extract, were designed for the first time to improve microbial and lipid oxidation control in dairy products. Significant improvements in the mentioned properties were obtained in PBAT/Esselement films related to the presence of oregano phenolics on the surface and migration of these compounds to the headspace atmosphere inside the package. These studies show the potential use of agro-industrial byproducts as an alternative source for both natural antimicrobial particles and additives with antioxidant and preserving functionality activities (Ahmad *et al.,* 2023; Wypij *et al.,* 2023).

In recent years, environmental concerns have arisen to manufacture eco-friendly polymeric bio-blends from biopolymers and metallic nanoparticles. In order to control food spoilage and extend shelf life, corn fiber cellulose (CFC) nanoparticles are used to prepare cellulose nanocrystal@nano-silver (CNC@Ag) bio-nanocomposites, where CFCs are extracted from corn byproduct. The bio-nanocomposites show better biocompatibility and low cytotoxicity when compared to synthetic counterparts. Sustainable bio-based polymeric nanocomposites consisting of non-degradable and renewable hydrophobic cellulose derivatives (CDs) dispersed in hydrophilic poly (lactic acid) (PLA)-based matrix are developed. By utilizing different fatty acids and succinic anhydride, CDs with varied hydrophobicity are prepared and successfully dispersed in PLA (Ahmad *et al.,* 2023; Wypij *et al.,* 2023; Sarker *et al.,* 2023).

## 8. Conclusion and Recommendations

Plant-based fortifier and preservative nanoparticles and nanomaterials are envisaged or proven to be fully biodegradable and non-toxic and demonstrate prolonged stability with biodegradable products in nanocomposite applications. Acceptability of the product packaging by target consumer markets yields epitomized economic value with the growth enabled by embracing matched rigorous investigation and economic analysis for research validation success. Biographically, the success storyline of the emerging nanotechnology-enabled food-packaging utilization journey requires the presentation and discussion of insightful concerns or experiences in realizing novel ideas, selection and identification of the region and scope niches in the nanopackaging design and architecture, building safety and secure designs, embracing sustainable and economically feasible focus, evaluation and static materials analysis tests, and large-scale dynamic trial assessments. Iterative pre-launch multifaceted strategic roadmap visioning and road-driving workflows, collaborative networking, and continuous re-design approaches incorporating characterizing advances enhance wider interdisciplinary teamwork and accelerated solution delivery timelines. With the advent of 3D and 4D manufacturing technology, potential ventures in and the hope for full graphics, holographic food-package look and feel is envisaged through investment infusing, multi-sector collective interactions by governments, academia, and food and packaging industries. Conclusively, proven compact nanoparticle food-packaging composites with fully developed econometric signposts beckon.

Nano-enabled advanced packaging is indispensable in preventing quality degradation and spoilage of food. Physical, chemical, and biological decay of foodstuffs are advantageously decelerated by embracing food preservation and protective biocompatible, biodegradable, and non-toxic enabled materials such as biopolymer-nanofillers. A promising functionality enhancement technique among others is the biopolymer encapsulation vis-à-vis green synthesized metallic, metal-oxide, and organic-coated or metal-decorated metal oxide nanoparticles, so-called bioactive nanofillers that deliver improved product shelf-life and economy. Research output and validation of the claimed properties of the suggested nanocomposites account for a significant share in current scientific services. However, the journey from academia to real food-package prototypes is marked by essential quality and standardized analysis assessments and collective synergistic interdisciplinary industrial-linked experimental fabrications complemented by computer simulations such as the finite element method, discrete-element method, and machine learning-based tools to deliver successful results for commercialization. The journey locomotion advantages, challenges, and guidelines presented and discussed in this review begin in and beckon academic and industrial stakeholders to embark on a mission to realize economically necessary commercial applications. Measurements, trials, and errors among other tests and simulations are mandatory.

### 8.1. Summary of Findings

Ecofriendly fabrication strategy is thus a major criterion in modern nano industry, and biodegradable biopolymer reinforcement via bio-nanomaterials or nanostructures as active food packaging has been given considerable importance in recent times by impacting the behavior or the properties of the materials. We have tried to compile thus a brief summary and current status of the omnipotent induced effective biopolymeric materials reinforced by plant-based bio-nanoparticles. Therefore, practical and theoretical models of biopolymeric materials that are functionally reinforced by bio-nanomaterials are discussed and the most popular strategies of the concept of the biopolymer bio-nanocomposites for smart food packaging are examined in detail. Different bio-nanomaterials mediated biopolymeric composite systems for possible applications have also been described in detail. Last but not least, an outlook of the direction of the extension, future, and challenges of the biopolymeric mediated nanomaterials used as an active food packaging for enriched and safe consumption of the foods have been discussed.

The introduction of nanocomposites using biopolymers is highly demanded due to its biodegradability, biocompatibility, non-toxicity, renewability, risklessness, cost efficiency, easy availability, better adsorption, high robustness, and intrinsic antimicrobial activity. The significance of these properties has been magnified through the promotion of multifunctional bio-nano raw materials using conventional and cutting-edge composite fabrication methods. The new face of the developed nanocomposites from biopolymeric nanomaterials for active food packaging is very promising and the most modern character contributes to accomplishing the necessary regulation vast sways of the food industry. It is hoped that the investigation for ensuring their large scale upgradation and finalization will take the researchers in the streams of food packaging and the food industry to the next metamorphosed and finalized sets of the goal of achievement.

### 8.2. Future Research Directions

In this way, novel strategies for improving product performance could focus on the generation and/or release of anti-biofilm compounds only when/if required. The multiscale, structured, functional anti-biofilm biopreservative materials could be used as components in various processes (for example, handling harvests or packaging presents) to minimize biofilm formation. Finally, regular comprehensive surveys are required to clarify the attitudes and behaviors of different societal groups towards nano-biopreservatives in order to characterize potential acceptability challenges and to suggest more suitable communication strategies. In this period, the research on the preparation and characterization of the "next generation" of biocompatibility, biosafety, and biodegradability by means of nanotechnological approaches and active, bioactive, and intelligent food packaging of fruit and dairy-based systems company with economic, industrial, and commercial explorations.

Nanoscience and nanotechnology have the potential to revolutionize agriculture and food systems. A particular focus of scientific and technological advances in the food-related field has been the development of safe, effective, and environmentally-friendly approaches for efficiently decontaminating and preserving foodstuffs and for improving food quality and safety, while also addressing the inherent challenges of using conventional techniques. Therefore, research aiming to overcome the existing problems associated with limited effectiveness, selectivity, and environmental sustainability will continue to intensify, particularly through the development of synergistic, innovative, science-based processes that harness current knowledge and technologies. For example, the design and synthesis of novel pharmaceutically-active and biocompatible materials, including metal chelators, natural antioxidants, or quorum-quenching agents, and the integration of these materials within micron-/micro-/nanostructured composite systems, powders, or relevant coatings.

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