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A Brief Review on the Application of Bio-Nanocomposites for Fresh Food Coating

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ABSTRACT: Food waste is a global issue affecting the environment, economy, and society. According to the Food and Agriculture Organisation of the United Nations (FAO), over 33% of global food production is wasted, resulting in 1.3 billion metric tonnes of food waste annually. This waste is a significant resource waste, a significant contributor to greenhouse gas emissions, and a clear indication of inefficiencies in the global food system. Reducing food waste, particularly during the post-harvest phase, is a significant challenge for the global food sector. The escalating demand for sustainable food packaging solutions has fostered the development of bio-nanocomposites as an eco-friendly alternative to conventional petroleum-based plastics. Bio-nanocomposites, composed of a biopolymer matrix reinforced with nanoparticles, offer a promising avenue for fresh food preservation due to their unique blend of properties. This brief review delves into the concept and the composition and preparation of bio-nanocomposites for fresh food coating applications. The properties of bio-nanocomposite coatings and the advantages of bio-nanocomposite coatings for fresh food are also discussed. Finally, the challenges and future prospects of bio-nanocomposites for fresh food coating applications are reviewed.

Keywords: Food waste, Bio-nanocomposites, Coating, Fresh Food, Packaging

1. Introduction

Food waste is a significant global concern encompassing the rejected fraction of food intended for human consumption. This issue has wide-ranging implications for the environment, economy, and society. As per the Food and Agriculture Organisation of the United Nations (FAO), over 33% of the total world food production is wasted, resulting in an alarming quantity of approximately 1.3 billion tonnes of food waste per year [1]. The substantial amount of lost food signifies a notable squandering of resources, a significant factor in the emission of greenhouse gases, and a clear indication of the inefficiencies and deficiencies inherent in the worldwide food system [2].

The reduction of food waste, especially during the post-harvest phase, presents a significant challenge for the global food sector. Fresh fruits and vegetables, being perishable commodities, are particularly vulnerable to quality degradation caused by various factors, including respiration, moisture loss, and microbiological spoilage [3]. Conventional packaging materials, such as plastic wraps and films, have demonstrated poor efficacy in prolonging the longevity of perishable agricultural products, frequently failing to adequately tackle the complex issues associated with food waste [4].

Bio-nanocomposite coatings have emerged as a possible alternative to conventional packaging materials in the pursuit of effective and sustainable solutions to address the issue of food waste. The aforementioned coatings exhibit a distinctive amalgamation of improved barrier characteristics, antibacterial efficacy, and biodegradability, owing to their composition comprising a biopolymer matrix and nanofillers. The biopolymer matrix, commonly sourced from sustainable materials like chitosan, cellulose, or zein, offers a pliable and partially permeable film that attaches to the outside of perishable agricultural products [5], efficiently mitigating water loss and gas transfer [6][7]. Nanofillers, which are tiny particles distributed throughout the biopolymer matrix, contribute to improved mechanical strength, gas barrier characteristics, and antibacterial efficacy [8]. These attributes prolong the shelf life of fresh produce and protect its overall quality [9].

This brief review paper delves into the realm of bio-nanocomposites for fresh food coating, offering an overview of the topic where it provides insight into the synthesis and properties of bio-nanocomposite coatings, the advantages of bio-nanocomposite coatings, as well as challenges and future prospects..

2. Bio-nanocomposites: Concept and composition

2.1 Concept of bio-nanocomposite

Bio-nanocomposites are materials that integrate biopolymers, naturally occurring polymers obtained from sustainable sources, with nanoparticles. The nanoparticles under consideration exhibit a range of compositions, including metallic constituents like silver or zinc oxide and non-metallic constituents like clay or cellulose nanocrystals [10]. Integrating biopolymers and nanoparticles into bio-nanocomposites yields a material that exhibits improved characteristics and functionalities. The utilization of biopolymers in bio-nanocomposites offers a sustainable and biodegradable framework for the incorporation of nanoparticles. These compounds can be obtained from various sources, such as plants [11], animals, and microbes. Biopolymers provide several advantages, including minimal toxicity, proficient film-forming capabilities, and compatibility with food systems [12].

In contrast, nanoparticles possess distinct characteristics that contribute to the bio-nanocomposites. These materials can enhance mechanical strength, barrier characteristics, and thermal stability. Moreover, specific nanoparticles exhibit antibacterial characteristics, suppressing bacterial growth and prolonging the durability of coated commodities [13]. Integrating biopolymers and nanoparticles within bio-nanocomposites has a diverse array of potential applications, including the coating of perishable food items. Applying bio-nanocomposite coatings to fresh food can potentially prolong its shelf life by establishing a protective barrier that effectively mitigates the detrimental effects of moisture, air, and microbial contamination. This practice can potentially enhance the longevity of the food product while ensuring its quality and safety.

Bio-nanocomposites offer a novel strategy for creating environmentally friendly and versatile materials that can be applied in a wide range of fields, such as the coating of perishable food items [14]. These materials provide enhanced qualities and functions compared to conventional substances, concurrently catering to the escalating need for environmentally sustainable alternatives within the food business [15][16].

2.2 Composition and characteristics of bio-nanocomposite materials

Materials referred to as bio-nanocomposites are made up of a mixture of biopolymers and nanoparticles. Biopolymers are natural polymers that are produced by breaking down renewable resources like starch, cellulose, proteins, or chitosan into their component monomers [17]. These biopolymers provide the matrix or foundational material for the bio-nanocomposite. On the other hand, nanoparticles are particles whose size falls from one nanometer to one hundred nanometers. They might be non-metallic, like clay or silica, or metallic, like silver or zinc oxide. Clay and silica are two examples of metallic materials. In order to improve the characteristics of the bio-nanocomposite, these nanoparticles are uniformly distributed throughout the biopolymer matrix [18].

The biopolymer matrix and the nanoparticles contribute to the characteristics of the bio-nanocomposite materials [19]. These qualities are what determine the characteristics of the materials. The following are some important characteristics:

1. Mechanical properties: The addition of nanoparticles can give the bio-nanocomposite improved mechanical strength, stiffness, and toughness, making it more resistant to physical damage. For example, in the area of bone regeneration, it is possible to create bio-nanocomposites that imitate the natural structure of bones. These composites have increased strength and stiffness, which are essential for supporting the growth of tissues. On the other hand, when it comes to food packaging, bio-nanocomposite films may give more importance to being flexible and strong in order to endure transit and handling without sacrificing their ability to block substances from passing through. The appeal of bio-nanocomposites resides in their capacity to surpass the constraints of individual materials. Nanoparticles serve as internal reinforcements, enhancing the strength and rigidity of the biopolymer matrix beyond the inherent capabilities of the polymer. This presents a vast array of opportunities for developing lightweight, yet durable materials that can endure rigorous mechanical pressures.

2. Properties as a Barrier Bio-nanocomposites have enhanced properties as a barrier against moisture, oxygen, and other gases. This helps to increase the shelf life of fresh food by preventing it from going bad and keeping the product quality from deteriorating [20]. Bio-nanocomposite films and coatings can effectively extend the shelf life of perishable commodities such as fruits and vegetables by reducing moisture loss, oxidation, and the penetration of volatile chemicals. This practise diminishes food waste and economises consumers' expenses.

3. Antimicrobial activity: Certain nanoparticles, such as silver or zinc oxide, have the ability to inhibit the growth of microorganisms. They can limit the growth of bacteria and other microorganisms when they are included in the bio-nanocomposite, which in turn reduces the risk of foodborne infections.

4. The capacity to tolerate high temperatures while being processed or stored bio-nanocomposites have the potential to display better thermal stability, which enables them to do so.

5. Biodegradability: Many different kinds of bio-nanocomposites are biodegradable, which means that natural processes can break them down over time. Because of this, using natural materials rather than synthetic ones is better for the environment [21]. The increasingly prevalent existence of microplastics in our surroundings is a mounting apprehension. Conversely, bio-nanocomposites undergo degradation, resulting in benign byproducts such as water, carbon dioxide, and biomass. This measure aids in reducing the pollution of our oceans, soils, and food chain, hence lessening the harmful impact of microplastics on both ecosystems and human well-being.

It is essential to remember that the structure and properties of bio-nanocomposite materials might change depending on the applied processing methods and the particular combination of biopolymers and nanoparticles incorporated into the material [21]. Therefore, it is essential to carefully select these components and optimise them to get the appropriate qualities for certain applications such as coating for fresh food

3. Preparation of bio-nanocomposites for fresh food coating applications

Preparing bio-nanocomposites to cover fresh food entails a series of sequential procedures. Presented below is a comprehensive outline of the procedure:

1. Biopolymer selection: choose biopolymers that exhibit compatibility with the intended application. Typical instances encompass proteins (e.g., gelatin or casein), polysaccharides (e.g., chitosan or cellulose), or their derivatives [22]. These biopolymers must possess favourable film-forming characteristics and exhibit compatibility with nanoparticles.

2. Nanoparticle selection: choose nanoparticles that possess the capacity to augment the desired characteristics of the coating, including but not limited to mechanical strength, barrier qualities, or antibacterial activity [23]. Illustrative instances encompass silver nanoparticles, zinc oxide nanoparticles, or clay nanoparticles. Various factors, including the nanoparticles' size, shape, and surface qualities, can influence the bio-nanocomposite's performance.

3. Nanoparticle dispersion: The nanoparticles should be dispersed in an appropriate solvent or dispersing agent to achieve a homogeneous distribution inside the biopolymer matrix. To attain adequate dispersion, methods such as ultrasonication or high-shear mixing can be employed [24].

4. The process of blending biopolymers with nanoparticles involves the combination of dispersed nanoparticles with a solution or suspension of biopolymers. This can be achieved by many methodologies, including stirring, homogenization, or extrusion. The objective is to attain a uniform amalgamation of biopolymer and nanoparticles.

5. Film formation involves the application of a bio-nanocomposite material onto the surface of fresh food utilizing techniques such as dip coating, spray coating, or casting. The control of coating thickness can be achieved through the manipulation of the concentration of the bio-nanocomposite solution [25].

6. Drying or curing: The coated fresh food should be subjected to a drying or curing process contingent upon the particular biopolymer employed. This particular procedure facilitates the development of a robust film characterized by enhanced mechanical properties [26].

It is imperative to acknowledge that the particular process of preparation may exhibit variability contingent upon the selection of biopolymer and nanoparticles alongside the intended characteristics of the coating [27]. The optimization of formulation and processing parameters plays a critical role in attaining the desired performance of the bio-nanocomposite coating for applications in preserving fresh food.

4. Properties of bio-nanocomposite coatings

The previous study investigated the impact of incorporating metal nanoparticles into biopolymers on food's shelf life and quality, specifically focusing on bio-nanocomposite films and edible coatings. Using bio-nanocomposite films and edible coatings on fruits and vegetables has demonstrated potential in reducing colour changes, respiration rate, weight loss, and extending shelf life. Additionally, these applications have shown promise in delaying ripening and offering environmental benefits. The review has examined physical-chemical properties, specifically focusing on moisture barrier and antimicrobial properties and also examination of the mechanical properties and biodegradability. A composite material's characteristics are contingent upon its constituent materials, which may encompass natural biopolymers, synthetic biodegradable polymers, inorganic or organic nanomaterials, and nano-scale minerals [28]. At present, a multitude of nano-materials are being employed in the realm of food packaging as highly effective additives.

Nevertheless, due to the inherent disparities in their chemical composition and distinctive attributes, each nanomaterial exhibits a unique set of characteristics within the matrix. Consequently, this divergence engenders a diverse range of functional applications for packaging purposes. The following explains the properties of bio-nanocomposites nanocoating for fresh food.

4.1 Antimicrobial properties

Poor packaging is a primary factor contributing to the contamination of fruits and vegetables. With the increasing demand for fresh vegetables and fruits, there is a pressing necessity to prolong the shelf life of these products in order to maintain their quality and reduce losses. An active storage method with antimicrobial features can be utilized to reduce the deterioration of fruits and vegetables and regulate the growth of microbial organisms. Nanoparticles exhibiting high aspect ratios are of particular interest due to their elevated specific surface area, antimicrobial characteristics, and ability to enhance the structural integrity of the matrix. Besides chitosan and aloe vera gel, other coating/film materials lack inherent antifungal and antibacterial properties [29]. However, biocidal properties can be added to their formulas with antimicrobial agents. The coating/film formulation can contain organic acids, plant extracts, and essential oils as antimicrobials.

Before large-scale applications, it is important to evaluate the impact of these materials on other coating/film properties, such as mechanical, barrier, and sensory properties. According to Emamifar and Bavaisi [30], the lowest growth rate of bacteria was seen in strawberries coated with 1.5% sodium alginate and 1.25 g/L nano-zinc oxide. The antimicrobial properties of the coating are enhanced by the incorporation of nano-zinc oxide into the formulation of the coating. As a result, the period of time that fresh fruits can be preserved throughout is increased to up to 20 days. On the other hand, Li et al. [31] conducted research to determine how the quality of freshly sliced apples was affected by nano packaging films that contained zinc oxide nanoparticles and PLA matrix over the course of 14 days while being stored at 4 degrees Celsius. According to the findings, there was a significant reduction in the rate of microbial growth, which led the researchers to hypothesize that nanocomposite films could be utilized to lengthen the shelf life of fresh-cut produce.

4.2 Mechanical properties

Mechanical properties refer to the physical attributes of a substance that determine how it reacts when subjected to an external force. The following characteristics are encompassed by these properties. First, tensile strength refers to the highest amount of stress that a material can endure before it fractures under tension. A greater tensile strength signifies a coating that is more robust and resilient.

Second, elastic modulus which refers to the quantification of a material's rigidity or ability to withstand elastic deformation. A greater elastic modulus signifies a more rigid and less pliable covering. Third, elongation at break refers to the maximum percentage of deformation a material can undergo before it reaches its breaking point. A greater elongation at the point of fracture implies a covering that is more pliable and capable of being stretched. Lastly, yield strength which refers to the level of stress at which a material undergoes permanent deformation and does not go back to its initial shape once the external force is eliminated. A greater yield strength signifies a coating that is more resilient and capable of enduring larger loads without experiencing irreversible deformation. Fresh fruits and vegetables are susceptible to physical harm. The aforementioned properties exhibit a correlation with the tensile strength and elongation at the break of the coating/film, as stated by Nor and Ding [32].

4.3 Gas permeability

The process of fruit or vegetable ripening is characterized by a significant increase in respiration, which involves the consumption of oxygen (O2), the production of carbon dioxide (CO2), and the release of ethylene. This increase in respiration is attributed to the climacteric nature of the ripening process [29]. According to the research of Kundu, Adhikary, and Maji [33] has established a clear correlation between the respiration rate of fruits or vegetables and their respective shelf life. According to Hoque, Chowhan, and Kamruzzaman [34], the preservation of fruits and vegetables can be achieved by decreasing the levels of oxygen and increasing the concentration of carbon dioxide in the surrounding environment. In order to prevent anaerobic fermentation, it is imperative to maintain the O2 level above the critical concentrations, typically ranging from 1% to 3%. Anaerobic fermentation takes place under conditions of significantly reduced oxygen concentrations, resulting in unfavourable alterations to the aroma, colour, and texture of fruits. Therefore, an optimal edible film or coating material should possess the characteristic of being semi-permeable to respiratory gases while simultaneously inhibiting respiration without inducing undesirable fermentation.

5. Advantage of bio-nanocomposite coatings for fresh food

Bio-nanocomposite coatings are innovative materials that offer many advantages for the storage and preservation of fresh foods. Table 1 shows a summary of the advantages, type of bio-nanocomposite coatings and outcome from the previous research.

Table 1. Summary of the advantages of bio-nanocomposite coatings for fresh food.

Advantages	Type of bio-nanocomposite coatings	Outcome	References
Extending shelf life	Nano-SiO_2	The preparation of edible coating by ultrasonic processing and incorporation into a soil protein isolate (SPI) matrix results in decreased respiration rate, firmness maintenance, and shelf life extension. Fruits: Apples	[35]
	Methylcellulose (MC) (Dip coating) Palm Oil (PO) (anti-browning agents, antioxidants, and antimicrobials)	Decrease peroxidase (PO), polyphenol oxidase (PPO), pectin methylesterase (PME) activity and discolouration; Increase anti-browning effect and retention of ascorbic acid; Delay the loss of total phenolic content; Extend the shelf life by three days. Fruit: Sapota fruits (a large berry)	[36]
Maintaining quality and freshness	Chitosan and carboxymethyl cellulose with stearic acid and phenylalanine elicitor. Types of polysaccharides: Carboxymethyl cellulose Chitosan	Carboxymethyl cellulose and chitosan coating significantly improved fruit's resistance to chilling and fungal pathogens, enhanced storability and better taste quality. Fruit: Avacado	[37]
	Pectin and maltodextrin in a ratio of 60:40 with	Coating delayed in the reduction of fruit firmness with higher values of greenness and	[38]

	100 ppm sodium chloride was used for coating.	yellowness during 14 days of storage at room temperature. Fruit: Starfruit (Averrhoa carambola)	
	Carboxymethyl cellulose (CMC) (Coating) Lactobacillus plantarum (antimicrobials, probiotic)	Reduce the growth rate of molds and yeasts on the surface of strawberries; Improve functionality (as a probiotic) Fruits: Strawberries	[39]
	Hydroxyethyl cellulose and sodium alginate (Dip coating) Asparagus waste extract (antioxidants, antimicrobials)	Maintain the Total Flavonoid Content (TFC) and Total Phenolic Content (TPC), delay colour change and weight loss. Fruits :Strawberries	[40]
Improved Barrier Properties:	Sodium alginate (Dip coating) Essential Oil extracted from sweet orange (antimicrobials)	Decrease weight loss up to 3-fold lower than uncoated samples; Decrease bacterial growth; Increase the firmness by up to 33%. Fruits: Tomatoes	[41]
	Sodium alginate (Dip coating) Citral nano-emulsions (anti-browning agents, antioxidants, antimicrobials)	Better colour retention, low respiration rate, reduce microbial growth Fruits: Pineapples	[42]
	Sodium alginate (Dip coating) $CaCl_2$ (antioxidants, antimicrobials)	Significantly reduce the respiration rate and weight loss; Improve total phenolic content and antioxidant activity. Fruits: Rose apple	[43]
	Sodium alginate, konjae glucomannan and starch (Dip coating) lotus leaf extract (antioxidants, antimicrobials)	Reduce decay rate and weight loss; Maintain ascorbic acid (AA), total soluble solids (TSS) and titratable acidity (TA). Fruits: Goji berries (Lycium barbarum L.)	[44]

Reduced Microbial Growth	Edible coating based on carboxymethylated cellulose nanofiber with 2% (w/w) of multi-valent cations ($CaCl_2$)	Respiration and CO_2 release were reduced significantly. Delayed in the ripening process and maintained firmness during the storage period due to the restricted respiration and the prevention of microbial contamination.	[45]
	Sodium alginate in hot water with thyme and oregano essential oils and 1% (v/v) Tween 80 as a surfactant	Delay in consumption of organic acids, reduced weight loss and respiration rate and improved microbiological safety for 12 days of storage period.	[46]
	Chayotextle starch mixed with microcapsules of resistant starch in the presence of ascorbic acid.	The respiration rate decreased significantly, leading to a decrease in fruit ripening and reduced the change in coated fruit surface colour compared to uncoated samples. Fruit:Guava	[47]
	Hydroxypropyl methyl Cellulose (Spraying)	Reduce weight loss and browning, maintaining higher firmness, brightness, greenness and total soluble solids (TSS);	[48]
	Aloe vera gel and lemon essential oil (antioxidants, antimicrobials)	Reduce the microbial load. Fruit : Hayward kiwis	
	Chitosan (Dip coating)	Decrease microbial growth and decay rate; Increase shelf life.	[49]
	8% and 12% blueberry (Vaccinium spp.) fruit and leaf extracts (BLE) (antioxidants, antimicrobials)	Fruit : Blueberries (Vaccinium spp.)	
	Chitosan (Coating) Vanillin and trans-cinnamaldehyde and mandarin extract (antioxidants, antimicrobials)	Reduce microbial load; Increase storage life; Maintain sensorial attributes. Fruit : Fresh-cut melon	[50]

6. Challenges and future prospects

6.1 Challenges

While applying bio-nanocomposites for fresh food coating holds immense promise, certain challenges must be addressed to propel this field forward. One prominent challenge lies in the scalability of production processes [2]. As the demand for sustainable packaging solutions rises, achieving large-scale synthesis of bio-nanocomposites with consistent quality becomes crucial. Researchers need to explore cost-effective and efficient methods to ensure the practicality of integrating bio-nanocomposite coatings into mainstream food packaging practices.

Another challenge is related to the potential health and safety concerns associated with using nanoparticles in food packaging [51]. Ensuring the biocompatibility and non-toxicity of bio-nanocomposite coatings is imperative to gain regulatory approval and consumer acceptance. Comprehensive studies on the long-term effects and migration of nanoparticles from the coating to the food matrix are essential for addressing these concerns.

Establishing clear and comprehensive safety guidelines for the use of nanoparticles in food applications also needs to be addressed [52]. The potential for nanoparticle migration into food and their possible toxicological effects necessitate rigorous research and standardized testing protocols. The scientific community must work together to develop robust methodologies for evaluating the safety of bio-nanocomposite coatings and establish clear safety thresholds for different nanoparticle compositions and concentrations.

Another challenge lies in improving the cost-effectiveness of bio-nanocomposite coatings [53]. The current production methods are relatively expensive compared to traditional synthetic packaging materials, making them less attractive to commercial food producers. The focus should be on developing scalable and cost-effective production processes that reduce the manufacturing cost of bio-nanocomposite coatings, making them a more viable option for large-scale food packaging applications.

Standardization and regulatory frameworks also play a crucial role in ensuring the consistent and safe use of bio-nanocomposite coatings [54]. The lack of standardized protocols for developing and evaluating these coatings hinders their widespread adoption. Establishing clear regulatory guidelines and standardized testing procedures is essential to ensure that bio-nanocomposite coatings meet safety standards and perform consistently across different applications.

6.2 Future Prospect

Looking towards the future, the prospects for applying bio-nanocomposites in fresh food coating are bright [55]. Continued research efforts can refine the composition and synthesis methods, optimizing the properties of these coatings for diverse food types. Innovations in nanotechnology and material science may lead to breakthroughs in overcoming scalability issues and improving the cost-effectiveness of production.

Moreover, exploring multifunctional bio-nanocomposite coatings that protect fresh food and offer additional functionalities, such as intelligent sensors for freshness monitoring, could revolutionize the industry. Collaborations between researchers, industry stakeholders, and regulatory bodies will play a pivotal role in shaping the future landscape of bio-nanocomposites in food packaging.

7. Conclusions

In conclusion, bio-nanocomposite coatings offer a promising approach to revolutionizing fresh food packaging, providing an effective solution to extend shelf life, reduce food waste, and improve food quality. By addressing the challenges and harnessing promising future prospects, these innovative coatings can significantly ensure food safety, promote sustainability, and contribute to a more environmentally responsible food packaging industry. As scientific research continues to advance and consumer understanding deepens, bio-nanocomposite coatings are poised to become the cornerstone of sustainable fresh food packaging solutions in the years to come. With continued advancements in this field, bio-nanocomposites are promising to revolutionise fresh food packaging and reduce food waste.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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