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Recent Advances in Natural Antimicrobial Food Packaging: Review

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ABSTRACT

This review presents a recent advance in natural antimicrobial food packaging. this packaging has emerged as a promising solution to improve food safety and extend shelf life decreases the carbon foot print while meeting consumer demand for sustainable packaging materials. The main tendency in package evolution is the switch from wasteful, polluting plastic to edible, biodegradable, film packaging that is antimicrobial active. This review comprehensively reviews recent research advances trends of polysaccharide-based materials in edible packaging addition of various components from natural agents (bacteriocins, essential oils, and natural extracts) to synthetic agents, organic.

1. Introduction

The Food and Agriculture Organization of the United Nations, FAO, statistical data indicate that about one-third of the produced food is lost or wasted each year because to shelf life expiring, alteration, or spoilage due to microbial activity. consumers are more and more asking for minimally processed, preservative free food products with longer shelf-life (Fernandez-Lopez et al., 2005). At present, most food packaging materials are based on petrochemical polymers because of historic factors, low-cost, and good barrier performances. These polymers are no biodegradable and worldwide they have already raised a lot of environmental concerns regarding short- and long-term pollution. Under various natural and anthropogenic forces, plastic fragments (from waste plastic containers, sheets, and films) break down into small particle sizes, further generating microplastics with a diameter smaller than 5 mm. These two factors are putting an increasing pressure on food industry to develop new types of antimicrobial packaging materials, mainly based on natural, renewable sources, or biopolymers that are environmentally safe. The development of antimicrobial packages is a promising path for actively controlling the bacterial and fungal proliferation that leads to food spoilage. According to Lebreton et al, over 79,000 tons of plastic waste float on the Great Pacific Garbage Patch, and the content of marine microplastics has increased rapidly from 0.4 kg/km2 in the 1970s to 1.23 kg/km2 in 2015. Then Barrett et al. estimated that there could be as much as 14.4 million tonnes of microplastics in the top 9 cm of sediment throughout the global ocean, which was 34–57 times more than that at the ocean surface. Moreover, microplastics have been ubiquitously detected in oceans (from the continental shelf to deep-sea waters, from the eastern North Pacific Ocean to the Indian Ocean, and from coral reef to whales, freshwater systems, air borne, plants, animals, and even humans. Unfortunately, the plastic (including micro plastics) pollution is posing a serious threat to the global environment and human health. Therefore, it is of great significance for packaging to develop a series of renewable environment-friendly materials to replace the traditional petrochemical-based materials, among which the edible material is one of the most promising materials. The antimicrobial packaging strategies can be classified in two types. First type is represented by the packaging materials with direct contact between the antimicrobial surface and the preserved food, in which the active agents can migrate into the food. Such packaging is used for food that is wrapped in foils or under vacuum. A second strategy is having the antimicrobial agent inside the package, but not in direct contact with the food. The natural antimicrobial compounds are obtained from vegetal sources like cloves, cinnamon, thyme, ginger, oregano, rosemary, garlic, etc. All these have a good potential for the meat industry. In a similar way, other natural antimicrobial agents can be isolated from substances produced by bacterial or fungal activity such as pediocin, nisin, and various bacteriocins.

The problem of food loss due to spoilage by microorganisms can be addressed by using antimicrobial packaging, be it traditional fossil- based polymers (PVC, PET, PE, PP, etc.) or biodegradable ones (cellulose, starch, chitosan, etc.). The ecological impact generated by the plastics cannot be solved unless we replace the traditional packaging materials with biopolymers from renewable sources.

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2. Natural Antimicrobial Agents

2.1 Bacteriocins

Bacteriocins are natural antimicrobial peptides with positively charged compounds and hydrophobic moieties produced by Archaea, Gram- positive and Gram-negative bacteria. These positively charged compounds can interact electrostatically with the negative charges of the phosphate groups on the microbial cell membranes, resulting in the generation of pores in the membrane and subsequent cell death. Bacteriocins have been used for food preservation because of their GRAS status recognition by the FDA and their lack of activity and toxicity to consumers. Furthermore, after ingestion, they are inactivated by digestive tract proteases and do not influence the consumer's gut microbiota. Regarding their antimicrobial effectiveness, these compounds are active over a wide range of temperature and pH and have a relatively broad spectrum of antimicrobial activity against foodborne pathogens and spoilage bacteria especially against Gram- positive bacteria such as Listeria, Bacillus and Clostridium species as well as lactic acid bacteria.

Over the last decades, bacteriocins have been used for food preservation because of their GRAS status recognition by the FDA and their lack of activity and toxicity to consumers.

2.2 Natural Extract

The increased awareness of consumers regarding synthetic-based antimicrobials and the knowledge of their serious adverse effects on human health has discourage food scientists and consumers to use them and search for novel natural alternatives. In this regard, plants, herbs and spices are being considered as the most important and rich natural source of antimicrobial substances like saponins, tannins, alkaloids, alkenyl phenols, glycoalkaloids, flavonoids, sesquiterpenes, lactones, terpenoids and phorbol esters. Additionally, the new circular economy strategy for plastic reduction and the search for biodegradable, bio-based packaging materials also encourages the incorporation of natural substances in packaging materials for a "greener", plastic-free and more sustainable food industry. Regarding the antimicrobial mechanism of action of natural extracts and phytochemicals it is thought that these natural antimicrobials have a multi- target action on microbial cells being able to disrupt membrane function and structure, interrupt DNA/RNA synthesis/function, interfere with intermediary metabolism, induce coagulation of cytoplasmic constituents and interfere with cell-to-cell communication.

Most plant-derived extracts are generally recognized as safe (GRAS) and Qualified Presumption of Safety (QPS) status in the USA and EU.

2.3 Essential Oils and Their Components

According to the International Organization for Standardization (ISO) (ISO DIS9235.2), an essential oil is "a product made by distillation with either water or steam or by mechanical processing of citrus rinds or by dry distillation of natural materials," meaning that an extract can only be named essential oil if it is obtained by either steam or hydrodistillation. EOs can be obtained from distinct plant materials such as flowers, buds, leaves, stem, bark and seeds.

3. Advances in Packaging Materials

3.1 Edible Packaging Material and its limitation

Edible packaging material is a kind of sustainable material that takes natural, edible and digestible "food" as raw material and is processed by modern material forming technology. It has excellent biocompatibility and biodegradability and can be consumed by animals or humans along with the food, while satisfying the basic functions of packaging (e.g., protection and transport), thus avoiding packaging waste pollution. The design of edible packaging was originally inspired by the "peel/skin" of fruits and vegetables, and now edible packaging has been widely applied to various forms of food packaging (e.g., films, coatings, sheets, bags, cups, trays, and lids), as shown in Figure 1

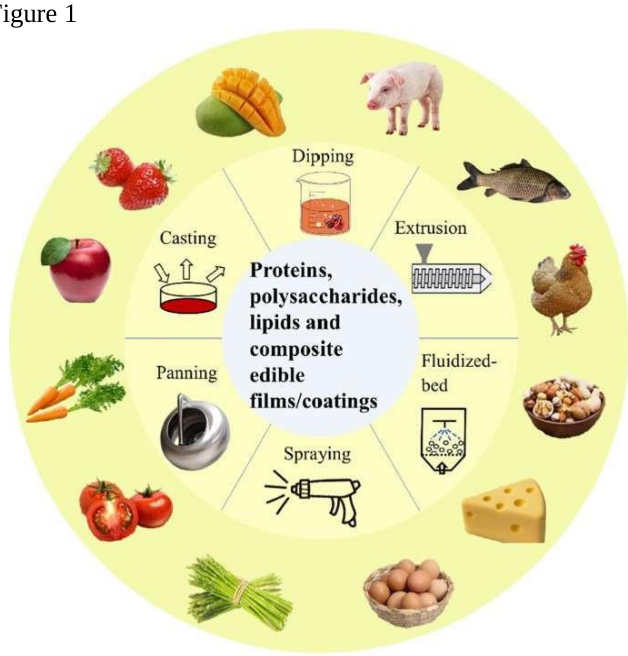

Figure - 1

Polysaccharides are complex carbohydrates with varying degrees of polymerization and are composed of monosaccharaides linked by α- 1,4-, β-1,4-, or α-1,6-glycosidic bonds [16]. The polysaccharides commonly applied in edible packaging are cellulose, hemicellulose, starch, chitosan, and polysaccharide gums, which are used as the main matrix of packaging materials, and processed into polysaccharide based edible films or layers by casting, coating, electro spinning, or extrusion technologies

Compared with traditional packaging materials (such as paper, plastic, metal, and glass), polysaccharide-based materials have two significant advantages: Edibility and environmentally friendly performance. developing polysaccharide-based materials effectively reduces the dependence on petroleum resources, decreases the carbon footprint of the "product-packaging" system, and meets the strategic requirements of global sustainable packaging.

However, compared with traditional petroleum-based polymers and plastics, polysaccharide-based materials still have many disadvantages, mainly including the following:

(A) The chemical and thermal stability of polysaccharides are poor, which is not conducive to their subsequent molding processing. In particular, the materials formed by only one kind of polysaccharide are often brittle, easy to crack or wrinkle, have high shrinkage after molding, and have poor mechanical properties.

(B) Polysaccharide-based materials contain many hydroxyl, amino or carboxyl groups, which result in high hydrophilicity, easy swelling by moisture, and poor water vapor barrier and moisture resistance. Moreover, they are sensitive to water, and their hydrogen bonding actions, microstructures and internal stress would change after moisture absorption; which resulted in a significant decrease in the mechanical strength of polysaccharide-based materials at high relative humidity.

(C) Cellulose, hemicellulose, starch, agar, and other polysaccharides (except chitosan, pectin, and their derivatives) would provide nutrients and facilitate the growth and reproduction of microorganisms, which is not conducive to food storage.

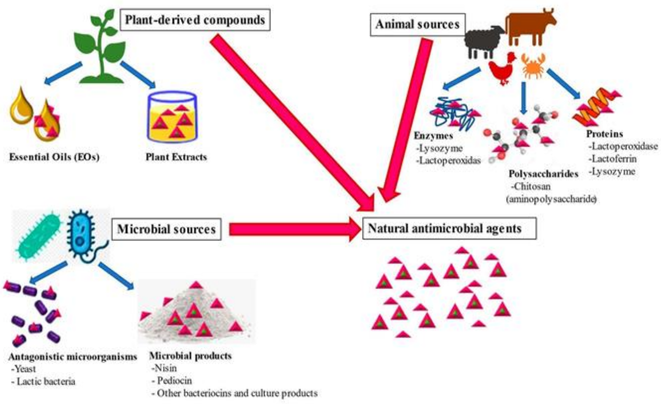

Figure 2. Sources of antimicrobial agents

3.2. Film/Coating Formation Methods

3.2.1. Casting Method

A lab or pilot scale method, also known as solvent casting, is a rather simple and one of the most common techniques of edible film formation. This method has been adapted at an industrial scale with various animal and plant-based materials as the main source of biopolymers. Starch, cellulose, pectin, gums, chitosan, agar, alginate, dextran, gelatin, casein, whey protein, waxes, paraffin and glycerides are the common biopolymers used in the manufacture of edible films by solvent casting, along with plasticizers such as glycerol, aloe, resins; and chaotropic agents like urea. After selection of suitable ingredients, the biopolymer is solubilized in a suitable solvent along with the NAMAs, followed by casting of solution the mold. Post this step is followed by degassing and drying is completed before the film is, finally, peeled off from the surface as depicted in Figure 3a. This method has the advantage of being simple, easy in operation, low cost and environment friendly. The outcome of the casting process is a function of various factors like atmospheric conditions, equipment, time and temperature combination used.

3.2.2. Compression Molding

Either thermo-compression or ultrasonic compression binds the film-forming materials into a desirable shape and thickness. An ultrasonic welder is used for welding the film materials, which have been previously refined, as depicted in Figure 2b. Post compression, the welded materials are cut and processed to elaborate sustainable edible packaging systems. Various raw materials to form Nano composites can be used, but starches, particularly, cassava starch have excellent properties and show less degenerative changes when subjected to compression molding. This technique has not yet gained popularity for manufacturing edible films but is a fast and economical method and needs to be adapted to suit the edible film packaging industry

3.2.3 Extrusion Method

To improve the mechanical and water vapor barrier properties of the polysaccharide-based films, lipids are added to enhance the hydrophobicity of the films. Co-extrusion blowing is a suitable technique to attain the desired results when multiple sources of biopolymers, most commonly lipids and starches, are being used along with other additives.

4. Conclusions and Future Trends

In conclusion, natural antimicrobial packaging is an innovative concept in food packaging which is gaining increasing interest among researchers as well as among producers and representatives of the packaging industry, as they allow the highest quality and safety of food. natural antimicrobials has expanded in recent years in response to consumer demand for greener additive. recent advancements in natural antimicrobial food packaging represent a significant leap forward in the quest safer, more sustainable food packaging solutions. development of natural antimicrobial packaging materials environmentally-safe, environmentally-friendly, biodegradable, low cost, low carbon foot print,

The integration of natural antimicrobials agents, such as essential oils, plant extracts, antimicrobial peptides, and bacteriocins, into packaging material has demonstrated remarkable efficacy in inhibiting microbial growth and preserving the quality of packaged foods. As consumers increasingly demand safer and more sustainable food products, natural antimicirobial presents a viable solution to meet these expectations while also addressing environmental concerns. This review has shown that natural antimicrobials have the potential to replace chemical additives in food products to extend shelf-life as well as safety and quality

The natural antimicrobial agents are likely to grow steadily in the future because of greater consumer demands for minimally processed foods and those containing naturally derived preservation ingredients. The impact of advanced formulation, smart packaging technologies, Ecofriendly packaging.

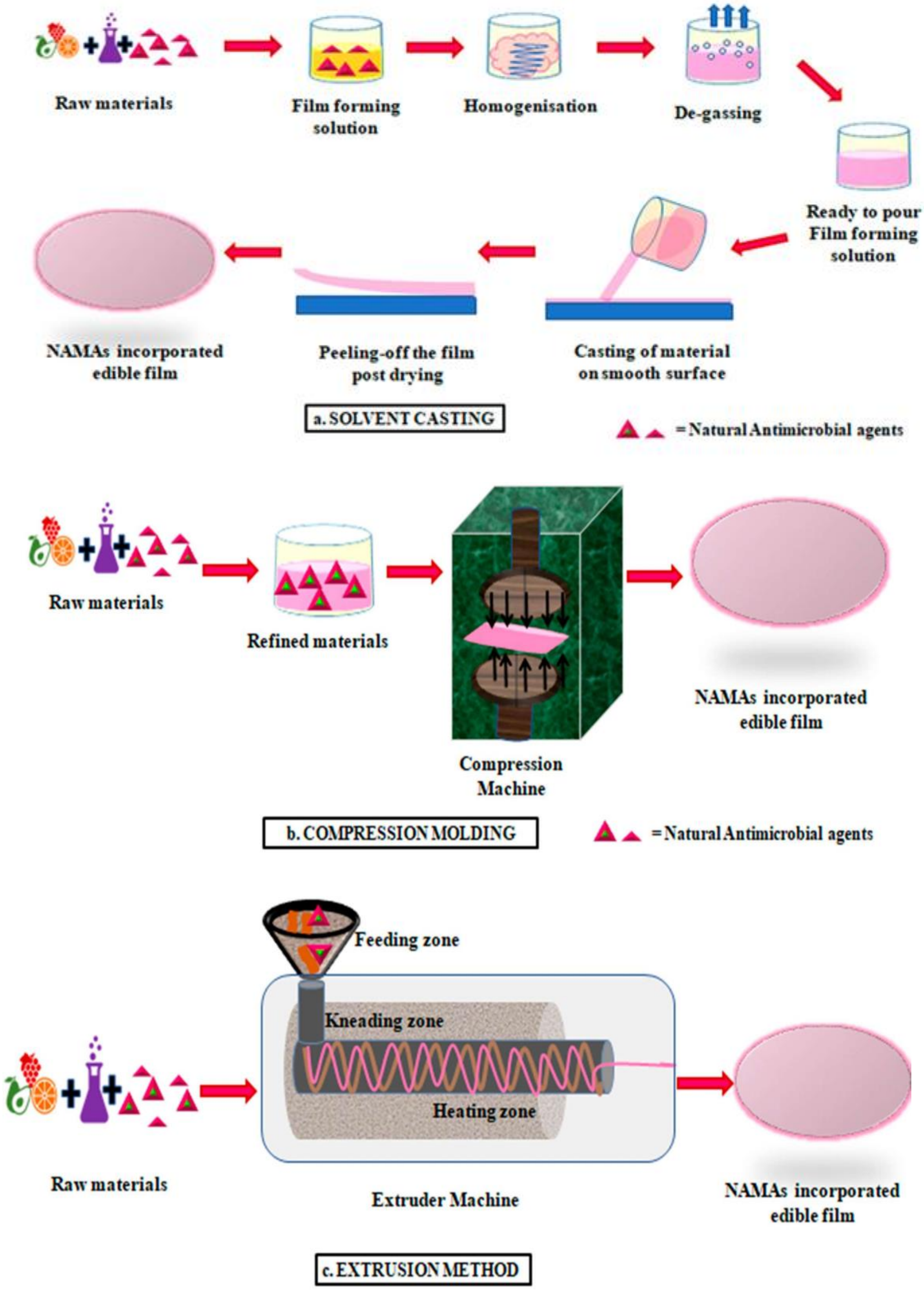

Figure 3. Various methods of film formation (a) solvent casting (b) compression moulding (c) extrusion method

Table 1. Examples of bacteriocins used in food packaging

Bacteriocin	Characteristics	Producer	Target Microorganisms
Nisin	Heat stable at 121 ◦C (pH =2) Less stable at pH 5–7	Lactobacillus lactis subsp. lactis	Streptococcus thermophilus Lactobacillus spp. Listeria monocytogenes Lactobacillus lactis Staphylococcus aureus Clostridium botulinum Bacillus cereus
Lacticin 3147A	Heat stable at 100◦C (10 min at pH5) Stable at room and low temperature Most stable at acid and neutral pH	Lactobacillus lactis DPC3147	Bacillus subtilis Staphylococcus Aureus Listeria monocytogenes Lactobacillus fermentum
Pediocin PA-1	Stable at pH 4 to 6, becomes less stable as pH increases. Heat stable at 80 ◦C (10 min)	Pediococcus acidilactici	Lactobacillus helveticus Pediococcus pentosaceus Listeria monocytogenes
Enterocin AS-48	Remarkably stable to extremes of pH and denaturing agents Inactivated by heat at 65°C and alkaline pH Compatible with several chemical compounds such as EDTA, lactic acid and sodium hypochlorite	Enterococcus faecalis subsp. liquefaciens S-48	Corynebacterium spp. Mycobacterium spp. Nocardia spp. Micrococcus spp. Staphylococcus spp. Listeria monocytogenes Brochothrix thermosphacta Lactic acid bacteria Bacillus cereus Bacillus coagulans Bacillus subtilis Clostridium perfringens Clostridium sporogenes Clostridium tetani Myxococcus spp. Escherichia coli Rhizobium spp. Agrobacterium spp. Salmonella spp. Shigella spp. Pseudomonas spp. Klebsiella spp
Sakacin-A	Heat-stable (100◦C, 20 min) Active at pH 2– 9 Most stable at pH 3–5 Stable during frozen storage	Lactobacillus sakei Lb706	Listeria monocytogenes Listeria innocua Lactic acid bacteria

Table 2- Natural extracts and compounds (with the exception of essential oils and their components) used for the development of active food packaging. NA-not applicable

Natural Compound	Packaging Material	Antimicrobial Activity	Food Preservation Data
Gallic acid	Chitosan coating	Total viable counts	The addition of 0.2% gallic acid to chitosan films for pork loin coating showed antioxidant and antimicrobial properties under high oxygen MAP storage at 4˚C
Lignign	Hydroxypropylmethylcellulose composite	Brochotrix thermosphacta Pseudomonas fluorescens	NA
Green tea extract	Chitosan	Total viable counts, Yeasts Moulds Lactic acid bacteria	Decreased number of total viable counts, lactic acid bacteria, yeasts and moulds in film-wrapped pork sausages stored at 4˚C for 20 days
Allium ursinum L. extract	Poly(lactic acid) (PLA) film	Staphylococcus aureus Escherichia coli	NA

Table 3. Essential oils and their components and their use for the development of active food packaging.

Essential oil Component	Encapsulation Strategy	Packaging Material	Food Product	Antimicrobial Effectiveness in vivo
Cinnamon	NA	Polyvinyl alcohol electrospun fibres	Strawberries	When compared to control films, EO films stopped fungal rotting for up to 6 days of storage at 21˚C
Oregano	Nanoemulsion	Mandarin fibre edible coating	Low-fat cut cheese	Decreased Staphylococcus microbial population by 1.4 and 1.5 log CFU/g in coated cheese pieces containing 2.0% or 2.5% w/w of EO, respectively, during 15 days of refrigerated storage
Ginger	NA	Soy protein/zein electrospun fibres	Fresh Minas cheese	Decay incidence of tomatoes within cyclodextrin−EOs boxes was reduced from 9−15% to 2% after a storage period of 6 days/8˚C+12 days/ 25˚C
Carvacrol	Halloysite tubes	Chitosan-coated polyethylene	Chicken meat	Active films caused a 1.5 log reduction on total viable counts on chicken meat surface following 24h of incubation at 4˚C

Table 4. Sources, compositions, structures, and outstanding characteristics of polysaccharides for edible packaging application.

Polysaccharides	Sources	Molecular Structure Characteristics	Functional Advantages
Cellulose	Major: wood and cotton Minor: certain peels, husks, bagasse, algae, vegetables, tunicates fungi, invertebrates, and bacteria	Comprise anhydroglucose units connected by β-glycosidic bonds Contains numerous hydroxyl groups	Good chemical stability, gelation, and film-forming properties Good mechanical properties, and barrier capacities to oxygen and lipids Renewable, biodegradable, biocompatibility Soluble dietary fiber and food additive Compared with ordinary cellulose, nanocellulose has a higher elastic modulus, tensile strength, crystallinity, lower coefficient of thermal expansion, large specific surface area, high reactivity, and small size effects
Chitosan	Major: the shells of crustaceans such as shrimps, crabs, insects • Minor: the cell walls of lower plants, bacteria, and fungi	Composed of N-acetyl-D-glucosamine and D-glucosamine (occupies a larger proportion, generally > 55%) connected by β-(1→4) glycosidic bonds • Contains numerous amino and hydroxyl groups, and a few acetylamino	Good gelation, film-forming properties and processing suitability • Good mechanical, oxygen and lipids barrier, and adsorptive properties (The tensile strength and swelling power of chitosan films prepared at higher drying temperatures and solute concentrations improved relatively) • Renewable, biodegradable, biocompatibility • Food additive The high specific surface area, large aspect ratio, and small size effect of nano-chitosan can further improve the biological activity, biocompatibility, and adsorption properties of ordinary chitosan [55,56]_------------Good antioxidant activity; and excellent antimicrobial activity, with effective inhibition of most gram- negative and -positive bacteria and fungi (These properties differ from those of cellulose, hemicellulose and starch)_____

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