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The use of polyphenols in egg active packaging to extend its shelf life, a review

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ARTICLE INFO	ABSTRACT

ABSTRACT

Eggs are one of the superior value natural sources of protein and other nutrients, at the same time, they are vastly perishable. Consumers' concern about egg contamination and transmission of pathogens, especially salmonella, increased the desire to use safe and packaged eggs. The environmental hazards of synthetic polymers as packaging materials have become a global problem, for this reason, their replacement with biodegradable ones has been developed. To overcome some physical and mechanical weaknesses as well as increase bio-polymers performance, they are combined (composite) and/or reinforcing agents and natural agents are used in their fabrication. A variety of plant essential oils and extracts are widely used in active packaging materials. The results of the studies showed that the barrier and functional properties of active biopolymers are improved due to their hydrophobic nature, as well as the antioxidant and antimicrobial properties of polyphenols content of essential oils and extracts. Egg packaging with these active biopolymers preserves internal quality during storage and ultimately extends its shelf life. In this article, an attempt has been made to review the use of plant chemical compounds (phytochemical) in active biopolymers for egg packaging based on polysaccharide, protein and aliphatic polyester

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1- Introduction

Eggs are not only rich in vitamins, minerals, carotenoids, and essential fats, but they also serve as an excellent, cost-effective source of protein [1, 2]. However, due to their nutrient density, eggs can provide an ideal environment for the proliferation of microorganisms, including harmful pathogens such as *Salmonella enteritidis* and *Staphylococcus aureus*, making them susceptible to spoilage. The decline in egg quality begins immediately after they are laid and persists during storage, particularly in inappropriate (non-refrigerated) conditions. Consequently, it is crucial to assess the shelf life of eggs while ensuring their quality and safety for consumers [3]. Additionally, the integrity of the eggshell is a significant safety concern, as approximately 8% of total egg production consists of eggs with broken or cracked shells, which are more susceptible to bacterial contamination. Therefore, safeguarding the shells against mass transfer is essential, and it is reasonable that methods for protecting eggs focus on sealing the pores of the shell [4].

One of the most effective ways to maintain the internal quality and extend the shelf life of fresh eggs is by storing them at refrigerator temperatures. However, this practice, similar to washing eggs, is governed by specific regulations that vary by country. In the United States and several other nations, washing eggs is a standard procedure, and throughout the supply chain, eggs must be maintained at temperatures below 7.2ºC. Conversely, in the European Union, eggs should not be refrigerated before reaching the final consumer, and washing edible eggs is prohibited. Additionally, refrigeration can lead to increased production costs, which in turn raises the final price of the product [5]. In our country, there are no mandates regarding the washing or disinfection of edible eggs, nor is there a requirement to keep them at refrigerator temperatures during the supply chain.

In recent decades, there has been a growing interest in utilizing films and coatings for food packaging and preservation, aimed at enhancing quality, safety, and stability. Specifically regarding eggs, the application of a thin protective coating can serve as a barrier to mass transfer, while also preserving viscosity and certain functional properties, potentially leading to a reduction in cracks and an increase in the number of viable eggs [6]. Various biological materials, such as proteins, polysaccharides, lipids, and certain synthetic polymers like aliphatic polyesters, are effective for this coating process [4]. Furthermore, the shift towards natural bioactive agents over synthetic alternatives has led to an increased use of phytochemicals and naturally derived compounds with antimicrobial and antioxidant properties in active food packaging. In response to societal demands, packaging development must align with sustainable production practices, marketing strategies, consumer preferences, environmental considerations, and the advent of new technologies, particularly in the fields of biotechnology and nanotechnology [7]. Consequently, this study aims to assess the role of these active substances, with a particular focus on polyphenols, in the advancement of egg packaging to enhance safety and extend shelf life.

2 -Research method and theoretical framework

In this research, a review was conducted on articles and scientific literature concerning the application of phytochemicals and polyphenols in active food packaging, with a particular focus on eggs. The investigation involved searching for keywords such as biopolymer, phytochemical, polyphenol, active packaging, internal quality, eggshell, film, and biodegradable coating across various databases and search engines, including Science Direct, Scopus, Google Scholar, and internal article indexing databases like SID, as well as specialized journals relevant to the topic over the past five years.

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1-2 -Current packaging materials and related challenges

The worldwide output of plastic has risen dramatically, with 40% of the total production allocated for packaging purposes, and nearly half of that specifically for food packaging. Currently, plastics account for approximately 6% of global oil usage, a figure projected to rise to 20% by the year 2050 [8].

Plastic waste that is buried can leach toxic substances, contaminating both soil and water as it undergoes biological and abiotic degradation. The breakdown of plastic by microbes also releases methane and carbon dioxide, which further exacerbates global warming. Wildlife is at risk due to the ingestion of plastic debris. In response, various nations are exploring strategies to combat plastic pollution by minimizing waste, curbing production, enhancing recycling efforts, and considering alternative materials. Governments are implementing policy measures aimed at reducing plastic pollution in alignment with international regulations designed to safeguard terrestrial and marine ecosystems [9].

Food packaging serves multiple purposes, including safeguarding against environmental influences, enhancing quality and safety, extending shelf life, and simplifying usage, storage, and transportation. Historically, packaging materials have predominantly consisted of synthetic polymers such as polyamide, polypropylene, polyethylene terephthalate, ethylene vinyl alcohol, polystyrene, and polyvinyl chloride. These synthetic polymers are favored for their advantageous physicochemical and functional characteristics, including mechanical strength, flexibility, optical clarity, and barrier effectiveness, making them particularly well-suited for packaging applications. Consequently, the industrial production of these materials has seen significant growth over recent decades. Nevertheless, the extensive reliance on synthetic plastics for packaging poses serious environmental challenges, as these materials can persist in the environment for extended periods. When they do degrade, they can break down into microplastics or nanoplastics, leading to contamination of water, soil, and food sources [10].

2-2 -Possible solutions for current packaging materials

The increasing environmental concerns related to synthetic plastics have led to a heightened interest in the utilization of natural polymers, including polysaccharides and proteins, often combined with other natural elements such as lipids, phospholipids, surfactants, or natural nanoparticles, for the production of biodegradable packaging materials [11-13]. Innovations in biodegradable materials, including biopolymers, bioplastics, bionanocomposites, and edible coatings, are being pursued as alternatives to synthetic plastics. These biodegradable, renewable, non-toxic, biocompatible, and adaptable polymers exhibit a low carbon footprint [14]. Nevertheless, challenges such as viscosity, hydrophobicity, crystallization behavior, brittleness, water sensitivity, thermal stability, gas barrier properties, mechanical strength, processing complexities, and cost have impeded their broader industrial implementation [15].

To address the limitations of bio-polymers, extensive research has been conducted on the incorporation of reinforcing agents such as nanofillers, nanofibers, other biopolymers, softeners, and natural substances like essential oils and extracts. These enhancements contribute to improved food quality, safety, nutritional value, and sensory attributes. For instance, a study examining the use of 1.5% and 3% nanoclay in sodium alginate coating solutions demonstrated that increasing the proportion of nanoclay positively influenced the performance of the multi-structure nano coating. Furthermore, the addition of lemongrass extract (*Cymbopogon citratus*) to the composite coating significantly reduced the microbial load on chicken fillets during storage

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under cold conditions [16]. Additionally, research on biodegradable nanocomposite coatings made from carboxymethyl cellulose, oleic acid, and nanoclay assessed their impact on the internal quality and morphology of eggshells [17]. The findings indicated that eggs treated with the nanocomposite coating exhibited the least weight loss, the lowest thiobarbituric acid index, and the highest yolk index values compared to uncoated or simply coated eggs. Moreover, the coated eggshells displayed enhanced integrity and continuity, with fewer pores and fractures (Figure 1).

Figure 1. Scanning Electron Microscope (SEM) images of eggshell after 5 wks of storage at ambient temperature; Uncoated (right) coated with carboxymethyl cellulose/oleic acid/nanoclay (left)

Carboxymethyl cellulose/oleic acid biocomposite coatings were utilized as a medium for Mentha spicata L extract. The findings indicated that oleic acid enhanced the protective properties of carboxymethyl cellulose. Furthermore, the active composite coatings contributed to an extended shelf life of fish fillets during cold storage, attributed to the antioxidant and antimicrobial properties of the extract [18]. The incorporation of *Echinacea purpurea* L extract into carboxymethyl cellulose/oleic acid coatings, along with eucalyptus essential oil (*Eucalyptus globulus* L) and alpha-tocopherol in chitosan coatings, yielded favorable outcomes in prolonging the shelf life of fish fillets [19,20].

Bio-nanocomposites, which are composed of a bio-based polymer matrix and an organic or inorganic filler containing at least one nano-scale material, serve as effective active packaging materials. They exhibit enhanced mechanical, thermal, barrier, antimicrobial, and antioxidant properties, making them suitable for extending shelf life and minimizing microbial growth in food products [15]. Research has demonstrated that reinforcing chitosan-based polymer coatings with cellulose nanocrystals significantly reduces weight loss, Haugh unit, and yolk index in coated eggs [21]. Furthermore, incorporating 2% nano montmorillonite into a chitosan biopolymer coating solution in acetic acid markedly enhances the quality and functionality of the packaging material, ultimately benefiting the internal quality and shell integrity of the eggs over a storage period of five weeks [22]. Additionally, nano chitosan, as an economical biodegradable option, when combined with other biological compounds like polysaccharides or proteins, can enhance the functional properties of the resulting polymer nanocomposites [23]

The chemical properties of certain biopolymers, including molecular weight and degree of deacetylation, along with the preparation methods such as the choice of solvent and plasticizer, significantly influence their performance and effectiveness. Studies indicate that films made from high molecular weight chitosan exhibit superior physical and mechanical characteristics, while those made from low molecular weight chitosan demonstrate enhanced antimicrobial properties. Moreover, acetic acid has proven to be a more

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effective solvent than lactic acid or citric acid [24], and sorbitol has shown better performance compared to glycerol [25].

One significant challenge in developing biodegradable packaging materials from biopolymers is achieving films that possess mechanical, optical, and barrier properties comparable to those of conventional synthetic polymers. While it is often possible to produce biopolymer-based packaging materials with desirable performance characteristics in a laboratory setting, scaling this production economically remains a challenge, thereby restricting their commercial viability [26]. Biodegradable polymers can be categorized into three groups (Table 1). The first group consists of synthetic biodegradable polymers, which are made from renewable bio-based monomers. The second group includes natural biopolymers sourced from biomass, while the third group encompasses manufactured polymers that are genetically modified using microorganisms or bacteria [27].

Table 1. Classification of biodegradable polymers based on their source [27]

Bio-Based Polymers					
Synthetic Biodegradable Polymers			Natural Biopolymers Extracted from Biomass		Polymers Produced by Microorganisms
From Biomass	From Petrochemicals	Polysaccharides	Lipids	Proteins	Microbial
PLA	PCL PVA PGA	Starch, Cellulose, Aliginate, Carrageenan, Chitosan	Glycerides, Waxes	Gelatin, Casein, Whey protein, Soy protein, Zein, Wheat gluten	Bacterial cellulose PHAs PHB PHV PHBV

PLA: polylactic acid; PCL: polycaprolactone; PVA: polyvinyl alcohol; PGA: polyglycolic acid; PHAs: polyhydroxyalkonoates; PHB: polyhydroxybutyrate; PHV: polyhydroxyvalerate; PHBV: poly(3-Polyhydroxybutyrate-co-3-hydroxyvalerate

2-3 -Bioactive packaging

Active packaging materials commonly utilized in food packaging are designed to preserve the sensory attributes of products, thereby ensuring their quality. Notably, active packages that incorporate natural antioxidants and antimicrobials play a crucial role, as they not only extend the shelf life of packaged goods by mitigating adverse reactions but also inhibit the proliferation of foodborne pathogens. The European Union Commission characterizes active ingredients as any substance or agent that can enhance shelf life or maintain and improve the packaging environment. Consequently, an active agent may consist of a single substance or a combination of several substances. These compounds are integrated into the formulation of packaging materials, serving specific

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functions such as the release or absorption of carbon dioxide, oxygen, ethylene, odors, flavors, antioxidants, and antimicrobials [28,29].

Active ingredients can be categorized based on the type of active agent or its function. Various materials employed in food packaging can serve as active agents, making classification according to the purpose of active packaging more straightforward and practical for application. However, the multifunctionality of many active compounds adds complexity to their classification [30].

Active packaging materials incorporating food-safe synthetic active ingredients have been developed. Notably, among synthetic antimicrobials, films containing potassium sorbate, benzoate, and propionate are particularly significant. Additionally, synthetic antioxidants such as butylated hydroxytoluene (BHT) and butylated hydroxyanisole (BHA) are utilized in both polymeric and biodegradable film formulations as active packaging to inhibit lipid oxidation in food products [31].

Byproducts and waste generated from fruit and vegetable processing represent a valuable source of bioactive compounds rich in nutritional and functional benefits, including vitamins, minerals, antioxidants, and antimicrobial agents, despite often being discarded or repurposed for animal feed. The essential oils and plant extracts derived from these materials have been extensively researched for their antioxidant and antimicrobial properties, making them suitable additives for the creation of active food packaging. Consequently, utilizing active compounds sourced from agricultural by-products not only aids in recovering these valuable substances but also enhances their market value [32, 33].

4-2 -Plant chemical compounds in active food packaging

Researchers have explored the integration of phytochemicals—natural compounds derived from plants—into biopolymers as a sustainable alternative to conventional plastic packaging, aiming to reduce chemical contaminants in food. This approach utilizes plant-derived substances found in a variety of plants, vegetables, fruits, and herbs for food packaging applications. The most significant plant chemicals utilized in food packaging systems are detailed in Table 2.

Table 2. Phytochemical compounds involved in food packaging systems [7]

Phytochemicals				
Polyphenols	Glucosinolates	Carotenoids	Phytosterols	Bioactive compounds
Phenolic Acids gallic, vanillic, syringic, ferulic, caffeic, p-coumatic, chlorogenic and sinapic acids	glucobrassicanapin, progoitrin, gluconapin, glucoalyssin, glucobrassicin, gluconasturtiin	α and β carotenes, lycopene, lutein, zeaxanthin, astaxanthin, cryptoxanthin	β –sitosterol, campesterol, and stigmasterol	minerals, vitamins, peptides, enzymes, bacteriocins and unsaturated fatty acids

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Flavonoeids

anthocyanins, flavan-3-ols, flavones, and flavonols

1-4-2 -Polyphenols

Phenolic compounds present in plant-based foods have garnered significant interest. From a phytochemical perspective, polyphenols are structurally related to phenolic compounds and rank among the most prevalent natural substances found in plants. Chemically, polyphenols can be categorized into two main groups: flavonoids and non-flavonoids. Flavonoids represent the most crucial category, characterized by a distinctive diphenylpropane structure of the C6-C3-C6 type, which features two aromatic rings typically linked by an oxygenated heterocycle comprising three carbon atoms. They are also interconnected (Figure 2). Flavonoids can be further subdivided into several subclasses based on variations in the heterocyclic ring, with the most notable being flavonols, flavones, flavonones, isoflavones, flavonoids, and anthocyanins. The primary subclasses of non-flavonoids include phenolic acids, stilbenes, and lignans. This diverse array of compounds exhibits significant differences in bioavailability, structure, and biochemical characteristics. Their popularity has surged, particularly in the food industry, owing to their antioxidant properties and potential antibacterial effects, which remain partially understood [34]. The main classes of polyphenols are summarized in Table (3) [35].

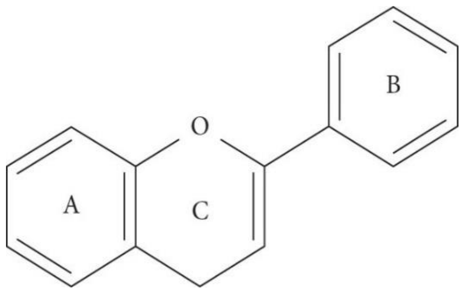

Figure 2. The main skeleton of flavonoids (C6-C3-C6)

Table 3. Polyphenolic classes, compounds and plant sources [7]

Group	Class	Compounds
Flavonoid-polyphenols	Flavonols	Quercetin, kaempferol, isorhamnetin
	Flavones	Apigenin, luteolin, diosmin
	Flavanols	Catechin, proanthocyanidins,

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		epicatechin, epigallocatechin
	Flavanones	Naringenins, hesperetin, eriodictyol
	Anthocyanins	Cyanidin, perlargonidin, delphinidin
	Isoflavones	Genistein, daidzein, equol
Non-flavonoied-polyphenols	Phenoloc acids	Caffeic acid, chlorogenic acid, ferulic acid
	Lignans	Pinoresinol, podophyllotoxin, stegananic, matairesinol
	Stilbenes	Resveratrol, pterostilbene
Tannins		Tannic acid, Chinese tannin, Turkish tannin, acer tannin, ellagitannin, chebulagic acid

Several mechanisms contribute to this process, such as alterations in cell membrane fluidity, modifications in intracellular activities associated with phenolics that interact with enzymes, and a decrease in cell wall integrity resulting from membrane interactions. Many plants are rich in polyphenols, and their potential as a natural substitute for traditional food preservatives is particularly promising. Polyphenols have the ability to suppress the growth of bacteria and fungi, highlighting their significance in food production. It is crucial to comprehend the antimicrobial characteristics of polyphenols, as their efficacy is affected by the sensitivity of pathogens and their chemical makeup [36].

Plant extracts are frequently incorporated into packaging materials and films. The phenolic compounds present in plants, particularly polyphenols and flavonoids, serve as antimicrobial and antioxidant agents. Active packaging that utilizes plant-derived substances, while not coming into direct contact with food or altering its nutritional content, helps to prevent contamination and spoilage. Extracts rich in polyphenols (both flavonoids and non-flavonoids) and alkaloids with antioxidant properties can be effectively utilized as additives in food packaging [37].

2-4-2- The role of plant-derived chemical compounds in active packaging systems to enhance product longevity

Food packaging that incorporates plant-based and bioactive chemical compounds recognized for their antioxidant properties plays a crucial role in neutralizing oxygen radicals. Conversely, certain active compounds utilized as preservatives in the food sector or incorporated into packaging polymers may pose health risks to consumers. Consequently, researchers are increasingly focused on identifying and substituting synthetic antioxidants with natural alternatives derived from biological sources deemed safe for human consumption [7]. The presence of free radicals in food packaging can lead to the oxidation of lipids and other food components, resulting in spoilage and diminished food quality. Mechanisms that inhibit free radical species, including those of oxygen and active nitrogen, work by lowering local oxygen concentrations, decreasing the oxidation potential of molecular oxygen, converting lipid peroxides into non-radical products, and chelating metal ions to hinder free radical formation. Additionally, certain phytochemical compounds exhibit chelating abilities that prevent transition metals from functioning as oxidizing agents [7, 38].

Moreover, plant-derived chemical and bioactive compounds can serve as components of antimicrobial packaging systems. Antioxidants and antimicrobials are frequently integrated into packaging materials during production, allowing for their gradual release and distribution within the packaged food through controlled methods. To enhance antioxidant efficacy, the release of phytochemicals and bioactive compounds on food surfaces should be regulated through compounding or encapsulation techniques. Antioxidants are employed in food packaging to mitigate lipid oxidation and protein denaturation [39]. Research has demonstrated that nanoencapsulation significantly enhances the antioxidant properties of sour tea extract (*Hibiscus sabdariffa* L), with carboxymethyl cellulose coatings and sour tea nanocapsule extracts effectively reducing oxidative spoilage in chicken nuggets [40].

5-2 -Examining the extraction methods of bioactive compounds

Selecting the optimal extraction technique for both quantitative and qualitative analyses of plant bioactive compounds is crucial. The extraction process serves as the foundational step in any research involving medicinal plants, significantly influencing the results obtained. The effectiveness of analyzing bioactive substances is heavily reliant on the chosen extraction methods, the input variables, and the specific characteristics of various plant parts. Fortunately, advancements in spectroscopic and chromatographic techniques have simplified this process considerably. Key variables that influence extraction include the plant matrix characteristics, pressure, temperature, solvent choice, and duration of extraction. A variety of extraction techniques are available for isolating plant components. In recent decades, innovative methods have emerged that are more sustainable, utilizing fewer synthetic and organic solvents, operating more efficiently, and yielding higher quality extracts. Techniques such as ultrasound-assisted extraction, pulsed electric fields, enzymatic digestion, extrusion, microwave heating, ohmic heating, supercritical fluid extraction, and accelerated solvent extraction have been explored to enhance the production and specificity of bioactive compounds in plant materials. Traditional methods, like Soxhlet extraction, continue to serve as a standard for assessing the efficacy of these newly developed techniques [41].

3 -Results and discussion

1-3 -Polymers based on polysaccharides

Polysaccharide-based biopolymers are natural, non-toxic materials that are abundantly available and highly suitable for use in packaging applications. They exhibit remarkable mechanical and structural characteristics while allowing selective permeability to gases such as carbon dioxide and oxygen. However, their ability to act as a barrier against water vapor is limited. To enhance the properties of biodegradable films, various reinforcing agents can be incorporated. The addition of antioxidants, antimicrobials, essential oils, phenolic compounds, and plant extracts transforms biopolymers into appealing, active, and intelligent packaging solutions, thereby extending the shelf life of food products. Furthermore, the inclusion of plasticizers like glycerol and sorbitol can enhance the flexibility of biopolymers, improve their process ability, increase the mobility of starch chains, and decrease moisture

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absorption. Nonetheless, it is important to note that the introduction of plasticizers may compromise the mechanical strength of biodegradable polymers [42].

In earlier research, the use of biodegradable wrappers made from polysaccharides for egg packaging was thoroughly examined. Innovative packaging materials derived from pectin, starch, chitin, chitosan, cellulose and its derivatives, as well as gums and mucilages, were developed in the form of films and edible coatings. These materials were often combined with other polysaccharides, proteins, lipids, and incorporated with antibacterial agents, antioxidants, and enzymes to enhance the internal quality of eggs and their shells, thereby extending their shelf life, yielding promising outcomes. Furthermore, the favorable results from utilizing cellulose derivative films and coatings in bio-packaging—such as reducing microbial contamination, mitigating chemical spoilage factors, preserving quality, and prolonging the shelf life of livestock products—indicate the potential for addressing legal considerations, lowering costs, and tackling challenges related to mass production and commercialization. This underscores the importance of developing production standards and regulations, enhancing awareness and marketing efforts, and promoting the broader adoption of biodegradable packaging solutions [43].

The significant antioxidant potential of *Origanum vulgare* L is linked to the presence of phenolic monoterpenes, including thymol and carvacrol, as well as phenolic compounds like origanoside and rosmarinic acid. Research examining the impact of the minimum inhibitory concentration of marjoram essential oil on aerobic heterotrophic bacteria demonstrated its inhibitory effects, taking into account various storage conditions and production times. Additionally, the study explored the effects of washing and applying an active nanocomposite coating made from carboxymethyl cellulose infused with marjoram extract on egg quality during storage at both room and refrigeration temperatures. The findings indicated that the use of this active nanocomposite coating, which combines carboxymethyl cellulose, nano montmorillonite, and marjoram extract, enhances the shelf life of eggs by four weeks at both ambient [44] and refrigerated temperatures [45].

Garlic (*Allium sativum* L) is rich in organic sulfur compounds, particularly thiosulfates, with allicin being a key antibacterial agent. A study on the physicochemical changes in eggs coated with a nanomultistructure (polyvinyl alcohol/chitosan/nano clay) infused with garlic extract during storage revealed that the antimicrobial efficacy of garlic extract at concentrations of 2% and 4% was more pronounced against *Staphylococcus aureus* compared to *Escherichia coli*. Notably, higher concentrations of the extract significantly extended the shelf life of the eggs by an additional 2-3 weeks [46].

Ginger essential (*Zingiber officinale*) oil possesses a diverse chemical profile that includes gingerol, aromatic alcohols, and terpenoids. Similarly, lemongrass essential oil (*Cymbopogon citratus*) is characterized by the presence of citral, ketones, alcohols, and esters. The chemical composition of Tahitian lemon essential oil (*Citrus aurantifolia*) features monoterpene hydrocarbons, notably limonene and myrcene. In a study assessing the shell microbiota and internal quality of eggs coated with a cassava starch biopolymer infused with essential oils, it was observed that the total count of aerobic mesophilic bacteria on the egg shells with active coatings remained consistent on both day 0 and day 35 of storage. Consequently, the cassava starch coatings enriched with essential oils effectively preserved the internal quality of the eggs throughout the storage period while also reducing the microbiota on the egg shells, maintaining it at low levels [47].

The formulation of basil essential oil (*Ocimum basilicum* L) within a starch-based coating enhances its effectiveness in prolonging the shelf life of food and minimizing its microbial contamination. Upon interaction with microorganisms, basil essential oil can compromise the integrity of cell membranes, cytoplasm, enzymes, proteins, fatty acids, ions, and metabolites. Research was conducted on a corn starch coating infused with basil essential oil to address the swift spoilage of quail eggs under non-refrigerated conditions. The findings indicated that the active corn starch/basil essential oil coating significantly reduced the overall growth of aerobic mesophilic bacteria, *Enterobacteriaceae*, molds, and yeasts on the surface of quail eggs to below 2 log CFU/mL by the fourth week of storage, in contrast to the control group. Furthermore, the average number of units and eggs exhibiting the active coating was notably greater than that of the control [48].

Thyme essential oil (Thymus vulgaris) exhibits significant antimicrobial properties against Salmonella species. In a research study, eggs were treated with edible coatings derived from sweet potato starch, incorporating varying concentrations of thyme essential oil: none (control), 2%, 4%, and 6%. The findings indicated that the application of thyme essential oil in these potato-based coatings preserved the quality and safety of the eggs for an additional two weeks compared to the control group. The active coatings notably inhibited the proliferation of Salmonella during the storage period. The antimicrobial efficacy of thyme essential oil is primarily due to its constituents, particularly the terpene thymol (5-methyl-2-[1-methylethyl)phenol]. Thymol is particularly effective against Gram-negative bacteria, as it disrupts the bacterial cell membrane, leading to the release of lipopolysaccharides. Thyme essential oil is rich in phenolic compounds (terpenoids) such as thymol and carvacrol, which demonstrate activity against a broad spectrum of microorganisms. Consequently, it is anticipated that the antimicrobial properties of these phenolic compounds, including thymol and carvacrol, result in both structural and functional impairment of the cytoplasmic membrane [49].

Peppermint (*Mentha piperita*) typically comprises 0.3-0.4% essential oil, which includes menthol, menthone, menthyl acetate, menthofuran, and 1.8-cineole, along with trace amounts of other compounds such as limonene, polygon, caryophyllene, and pinene. Additionally, mint is rich in terpenoids and flavonoids, including eriocitrin, hesperidin, and kaempferol 7-O-rutinoside. The antimicrobial properties of this essential oil have been recognized for an extended period. Its lipid characteristics may enhance barrier properties when incorporated into polymers. Research has indicated that carboxymethyl cellulose/nanoclay nanocomposites infused with peppermint essential oil can enhance egg quality parameters while regulating the release of moisture and carbon dioxide, thereby mitigating weight loss. Furthermore, the Haw index and yolk index in eggs treated with active coatings demonstrated a lesser decline compared to those without the essential oil [50].

The primary constituent of *Cassia angustifolia* essential oil has been identified as cinnamaldehyde [51]. Research has examined the impact of this essential oil on the characteristics of composite films made from pectin and sodium alginate, revealing beneficial effects on the film's physical and mechanical properties. Comparable positive outcomes were noted in the physical, mechanical, and antioxidant attributes of sodium alginate hydrogel films and acacia gum infused with cinnamon essential oil (*Cinnamomum verum*) [52]. Hydrosol, a byproduct of essential oil extraction, possesses distinctive qualities, such as a low concentration of essential oil (under 1 g/l) and water solubility. Hydrosols demonstrate excellent stability for over a year. Investigations have highlighted the antimicrobial and antifungal capabilities of herbal hydrosols. Findings indicated that applying a coating of pectin and cinnamon hydrosol to eggs resulted in reduced weight loss during storage. Coated eggs exhibited higher

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Haw units and yolk indices compared to their uncoated counterparts. While the bacterial count in uncoated eggs reached 3 log CFU/mL by the sixth week of storage, coated eggs maintained a bacterial count of zero throughout the entire storage duration. [53].

2-3 -Protein-based polymers

Protein biopolymers consist of amino acid copolymers and can be categorized into those derived from plants, such as gluten and soy, and those from animals, including whey, collagen, and keratin. These biopolymers exhibit numerous advantageous characteristics, including strong mechanical properties, excellent gas barrier capabilities, effective film-forming abilities, nutritional benefits, and elasticity, making them ideal for food packaging applications. However, their hydrophilic nature results in limited water barrier performance. Protein-based biopolymers hold significant promise for use in biomedicine and food packaging. Various protein-based polymers, including whey protein, gelatin, wheat gluten, corn zein, and soy protein, have been utilized to create edible films that enhance the mechanical and barrier properties of food packaging. Additionally, biopolymers like keratin, casein, zein, gelatin, and soy protein are crucial in the production of a range of industrial items, such as shopping bags, protective films, and health-related products. The mechanical and other properties of protein biopolymers can be enhanced through the combination with other biopolymers (both protein and non-protein) or with various reinforcing agents. These protein biopolymers can serve as coating layers, providing an alternative to synthetic polymers in food packaging [54].

Research has been conducted on the surface maintenance and disinfecting capabilities of essential oils, both independently and as components in biopolymer coatings. Additional investigations could enhance the understanding of how to effectively incorporate these essential oils into egg coatings, as well as their potential advantages and disadvantages regarding egg preservation and microbiological safety. Coatings made from proteins infused with essential oils may serve as an effective means to keep the Haugh unit within the optimal range for classifying eggs (AA) stored at ambient temperatures. A study aimed at examining the impact of coating formulations that included water-cheese protein isolate (WPI) and garlic essential oil on the internal quality, microbiological, and sensory attributes of quail eggs over a 28-day period at room temperature revealed that eggs with the active coating exhibited lower levels of active aerobic mesophilic bacteria, *Enterobacteriaceae*, molds, and yeasts on their shells. Furthermore, the Haw units in eggs with the active coating during storage were found to be higher compared to those with WPI coatings or uncoated eggs [55].

Tea (*Melaleuca alternifolia*) essential oil is a diverse blend of terpenes and tertiary alcohols, with terpinen-4-ol and 1,8-cineole being its primary constituents. Copaiba essential oil (*Copaifera langsdorffii*) is composed of approximately 80% sesquiterpenes and 20% diterpenes. Thyme (*Thymus vulgaris*) is rich in phenolic compounds, including carvacrol, thymol, p-cymene, and terpinene. These compounds enable essential oils to be utilized in various applications, particularly for their antimicrobial and antioxidant properties. In a study examining the effectiveness of rice protein coatings infused with these essential oils for preserving the internal quality of fresh eggs stored at 20°C for six weeks, it was found that the coatings not only maintained but also enhanced the internal quality characteristics of the eggs. The rice protein coating demonstrated adequate water repellency and sealing capabilities, significantly minimizing water loss during room temperature storage for up to six weeks. Incorporating lipid materials into the coating may further enhance its moisture barrier properties. The lipophilic nature of essential oils can also help mitigate mass and oxygen loss [56].

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The primary phenolic constituents found in cinnamon (*Cinnamomum verum*) essential oil consist of phenolic acids, phenolic volatile oils (such as 2-hydroxycinnamaldehyde and cinnamylaldehyde derivatives), and flavan-3-ols. In a spectrophotometric analysis of antioxidant capacity, cinnamon essential oil demonstrated significantly greater antioxidant potential compared to ginger (*Zingiber officinale*) essential oil, attributed to the lower concentration of phenolic volatile oils in the latter. However, it was noted that neither essential oil enhanced the protective properties of sodium caseinate films against lipid oxidation [57].

In the study of gelatin films, including gelatin-bacterial cellulose films and gelatin-bacterial cellulose-magnesium oxide nanocomposite films, it was observed that the incorporation of bacterial cellulose resulted in a film with a reduced number of smaller pores, lower water vapor permeability, and an increased breakpoint length. The addition of magnesium oxide nanoparticles further contributed to a denser and more uniform cross-section of the film, enhancing the hydrophobicity of its surface. When eggs were coated with these films, they exhibited lower weight loss, reduced total volatile nitrogen content, and increased hardness compared to uncoated eggs [58].

3-3 -Aliphatic polyesters

All non-aromatic hydrocarbons are classified as aliphatic compounds. Aliphatic polyesters are a type of biopolymer characterized by repeating units that yield metabolites such as poly(beta hydroxyalkanoate) and poly(alpha hydroxyalkanoate) upon decomposition. Their structure, featuring ester bonds within flexible chains, renders them susceptible to hydrolysis, facilitating biodegradability. Common aliphatic polyesters utilized in food packaging include polylactic acid, poly(butylene adipate terephthalate), polyhydroxyalkanoate, polybutylene succinate, polyhydroxybutyrate, and polycaprolactone. Aliphatic polyesters constitute a significant portion of bioplastics, with global production reaching 2.11 million tons in 2020. The packaging sector represents the largest market segment, accounting for 47% of this total, or approximately 0.99 million tons [59, 30].

Polyvinyl alcohol is a prominent polymer known for its exceptional film-forming capabilities, high tensile strength, and good chemical stability, although it has limited water barrier properties. Research indicates that the incorporation of chitosan enhances the characteristics of polyvinyl alcohol films. Composite films made from polyvinyl alcohol and chitosan exhibit superior physical properties and antioxidant activities. The physical and mechanical attributes of chitosan films are influenced by factors such as the surface characteristics and molecular weight of chitosan, as well as the type of acidic solvent used. Edible coatings composed of chitosan and polyvinyl alcohol, particularly when the polyvinyl alcohol content is higher (75% compared to 25%), demonstrate improved barrier properties and durability compared to the individual components, with enhancements lasting for at least two weeks [60, 61].

A study was conducted to examine a composite film made from polyvinyl alcohol, sodium alginate, and chitosan, focusing on how this coating influences the internal quality of duck eggs during storage. The findings indicated that the double-layer film exhibited superior storage stability in terms of mechanical properties, solubility, and water barrier performance when compared to single-layer films. Furthermore, the double-layer coating proved to be effective in preserving the internal quality of duck eggs stored at room temperature, thereby extending their shelf life [62].

Polylactic acid (PLA) films are entirely biodegradable. PLA is derived from the fermentation of organic waste produced by the agricultural and food sectors, such as corn, to extract sugars. These sugars are then converted into lactic acid, which is subsequently purified and polymerized to form polylactic acid.

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However, a significant drawback of PLA films is their unsuitability for products that are sensitive to external elements like oxygen and moisture, and they also exhibit limited flexibility. Consequently, the application of PLA-based packaging remains restricted, primarily due to inadequate gas barrier properties. To enhance the permeability of these films, researchers have explored coating them with bio-polymers, including chitosan, gelatin, and other hydrocolloids, to preserve their biodegradability while improving barrier performance [63]. Additionally, a PLA film infused with cinnamon essential oil (*Cinnamomum verum*) was developed by Khanjari *et al.* [64], demonstrating a reduction in bacterial growth, total volatile nitrogen, and thiobarbituric acid-reactive substances.

Polyhydroxybutyrate is a known biodegradable poly-beta-hydroxyalkanoate that is synthesized by many bacteria as internal carbon or energy storage. Polyhydroxybutyrate is one of several biodegradable polymers that has reached commercial production, and due to its non-toxicity and having good thermal resistance and water barrier properties, it has wide applications in packaging to biomedical items. It is complicated. In several studies, the potential capacity of polyhydroxybutyrate-based films and coatings for food packaging applications has been investigated; Active nanocomposite film based on polyhydroxybutyrate combined with nano silica and clove essential oil showed high antibacterial activity against Escherichia coli, Aspergillus niger and Staphylococcus aureus. Active films based on polyhydroxybutyrate enriched with different essential oils such as grape seed oil, ginger and bergamot were prepared and their desirable mechanical, thermal, barrier and antimicrobial properties were determined. Also, polylactic acid-polyhydroxybutyrate active composite films coated with methyl cellulose and chitosan along with olive leaf extract, polylactic acid-polyhydroxybutyrate active composite film enriched with alpha-tocopherol and containing essential oil. Fennel was used to increase shelf life of food products and was associated with positive results [63].

4 -Conclusion

Biopolymers serve as biodegradable, non-toxic, renewable, and biocompatible alternatives to synthetic packaging materials, effectively mitigating the environmental pollution associated with synthetic polymers. They possess the capability to form films, and by addressing certain physical and mechanical limitations through combinations with other biopolymers and the incorporation of reinforcing agents, they can facilitate the development of active, intelligent, and efficient packaging solutions. Additionally, polyphenols, recognized as significant plant-derived chemical compounds with antioxidant and antibacterial properties, play a crucial role in the creation of active packaging materials. The application of biopolymer coatings derived from polysaccharides, proteins, and aliphatic polyesters—either individually or in combination—has shown promising outcomes in egg packaging, whether utilized in a simple or active manner. Biopolymer wraps employed in egg packaging effectively prevent mass exchange by sealing the small pores of the shell. Furthermore, the production of active biopolymeric packaging materials that incorporate plant extracts and essential oils has enhanced the antioxidant, antimicrobial, and barrier characteristics of the wraps. This enhancement is attributed to the hydrophobic nature and unique properties of phenolic compounds, which contribute to preserving the internal quality of the eggs (including weight loss, pH variations, changes in Haw and indexed units, and indices of oxidative and microbial spoilage) while ultimately extending their shelf life.

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مقاله علمی_پژوهشی

مروری بر بکارگیری پلی‌فنول‌ها در بسته‌بندی فعال تخم‌مرغ با هدف افزایش ماندگاری

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چکیده

تخم‌مرغ یکی از بهترین منابع طبیعی پروتئین با کیفیت بالا و سایر مواد مغذی بوده و در عین حال مستعد فساد است. نگرانی مصرف‌کنندگان از آلودگی و انتقال بیماری‌زاها به‌ویژه *سالمونلا*، موجب شد تا تمایل به استفاده از تخم‌مرغ‌های ایمن و بسته‌بندی شده افزایش یابد. مشکلات زیست‌محیطی پلیمرهای مصنوعی به‌عنوان مواد بسته‌بندی به معضلی جهانی تبدیل شده است، به‌همین دلیل جایگزینی آنها با پلیمرهای زیست تخریب‌پذیر توسعه یافته است. برای غلبه بر برخی از ضعف‌های فیزیکی و مکانیکی و افزایش عملکرد زیست-پلیمرها، آنها را با یکدیگر ترکیب نموده (کامپوزیت) و/یا عوامل تقویت‌کننده و عوامل طبیعی در ساخت آنها بکار می‌رود. اسانس و عصاره‌های گیاهی مختلف به‌طور گسترده‌ای در مواد بسته‌بندی فعال مورد استفاده قرار می‌گیرد. نتایج مطالعه‌های انجام شده نشان داد خواص سدی و عملکردی زیست‌پلیمرهای فعال به‌دلیل ماهیت آب‌گریزی، خواص ضد اکسیدانی و ضد میکروبی پلی‌فنول‌های موجود در اسانس و عصاره بهبود می‌یابد. بسته‌بندی تخم‌مرغ با این زیست‌پلیمرهای فعال موجب حفظ کیفیت داخلی طی دوره نگهداری و در نهایت افزایش ماندگاری آن می‌شود. در این مقاله سعی شده است بکارگیری ترکیبات شیمیایی گیاهی در زیست‌پلیمرهای فعال بسته‌بندی تخم‌مرغ بر پایه پلی‌ساکارید، پروتئین و پلی‌استر آلیفاتیک مرور شود.