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Review Article

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Pomegranate Peel Extract as a Natural Antimicrobial Agent: Extraction Methods, Biochemical Composition, Mechanism of Action, and Application in Food Packaging

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Abstract
Natural antimicrobial substances derived from plants are increasingly used in the food industry as safer and more sustainable alternatives to synthetic additives for food preservation. One such example is pomegranate peel extract (PPE), which is increasingly being used as a bioactive ingredient due to its antimicrobial and antioxidant properties, primarily attributed to the presence of phenolic acids, flavonoids, tannins, and other phytochemicals. The phytochemical composition and resulting antimicrobial activity of PPE are strongly influenced by the pomegranate cultivar, geographical origin, and the extraction method used for the peel. This underscores the need to further optimize PPE extraction methods. Additionally, PPE is being incorporated into edible films and coatings to enhance both food safety and quality. PPE has antimicrobial activity against variety of Gram-positive and Gram-negative bacteria. The addition of PPE to food packaging has been found to improve and maintain the physicochemical and organoleptic qualities of food during storage, while reducing microbial growth and extending shelf life. Incorporating PPE into food packaging materials aligns with sustainable packaging principles and meets ‘clean-label’ requirements. This article reviews PPE extraction methods, its phytochemical constituents, antimicrobial mechanisms, and applications in food packaging, highlighting its potential role in promoting sustainable food production.

Keywords:
foodborne pathogens; pomegranate peel extract; natural antimicrobial agents; edible coatings; food packaging

1. Introduction

Foodborne disease (FBD) represents a major global public health issue afflicting countless individuals. In the United States, contaminated food causes approximately 48 million illnesses each year, affecting about 1 in every 6 individuals becomes ill. This issue leads to the hospitalization of approximately 128,000 individuals and the deaths of around 3,000 people annually, representing a significant concern for public health and the economy [1]. This issue is not confined to the US. Central Asia and Europe report over 23 million cases and 5000 deaths each year due to FBD [2]. Australia estimates that the foodborne disease is estimated to cause over 4.1 million illnesses every year [3]. Understanding the major causes of FBD is critical for the development of natural antimicrobial solutions. This review examines pomegranate peel extract (PPE) as an antimicrobial agent for food packaging, focusing on its extraction methods, chemical composition, mechanisms of action, and potential applications in food preservation. At every stage of the food chain, from the farm to the

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table, microbial contamination poses a risk. At every stage of the food production process, food can become contaminated through various sources, including exposure to animal feces, inadequate sanitation during and after animal slaughter, contact with contaminated equipment or instruments, mishandling by food workers, or the use of unclean irrigation or washing water [4,5]. Among pathogenic microorganisms (MOs), bacteria such as *Campylobacter* spp., *Clostridium perfringens*, *Clostridium botulinum*, *Salmonella* spp., *Listeria monocytogenes*, *Staphylococcus aureus*, *Bacillus cereus*, *Vibrio* spp., *Escherichia coli*, and *Shigella* spp. account for most hospitalizations and fatalities [6]. Thus, maintaining food safety requires controlling foodborne pathogens (FBP) [7]. Symptoms can range from mild gastrointestinal issues to serious long-term consequences, such as cancer, neurological deficits, organ damage, and even death [8]. Despite advancements in food preservation technologies, foodborne illness remains a significant concern for both consumers and the food industry [8,9].

Clean-label and natural preservation methods are gaining popularity because, although synthetic antioxidants and antimicrobials effectively prevent foodborne pathogens, concerns remain regarding their potential long-term health risks and chemical residues [10–14]. Strong antibacterial and antioxidant activity, little sensory influence, broad availability, reduced cost, and comparatively easy extraction processes are just a few benefits of plant-derived antimicrobials [15–21]. Fruit peels, in particular, are rich in bioactive compounds with antibacterial and antioxidant properties [11,22]. Phenolic acids, flavonoids, and tannins contribute to the antimicrobial activity observed in many plants [11,23].

Despite being frequently thrown away, pomegranate peel provides a plentiful and sustainable source of bioactive compounds. Pomegranate peel has been extracted using various methods, with methanolic extraction consistently demonstrating superior antibacterial activity compared to petroleum ether, chloroform, and aqueous extracts [15,17,18,24,25].

To meet the increasing demand for natural and sustainable food preservation, this review summarizes the current evidence on pomegranate peel extract (PPE), covering its extraction methods, phytochemical composition, antimicrobial mechanisms, and applications in edible films and coatings to enhance food safety.

2. Literature Search Strategy

To gather relevant research on pomegranate peel extract (PPE), including its phytochemical composition, antimicrobial mechanisms, and applications in food packaging systems, a comprehensive literature search was conducted. We conducted a thorough search of several scientific databases, including PubMed, Scopus, Web of Science, ScienceDirect, and Google Scholar. The following keyword combinations were used to identify publications published between 2000 and 2025: 'pomegranate peel extract,' 'Punica granatum,' 'natural antimicrobials,' 'edible coatings,' 'edible films,' 'food packaging,' 'antimicrobial activity,' 'phenolic compounds,' 'solvent extraction,' and 'foodborne pathogens.'

Studies were included if they:

(1) investigated PPE extraction methods, biochemical composition, antimicrobial or antioxidant activity;

(2) evaluated in vitro or in vivo antimicrobial effects of PPE; or

(3) examined the incorporation of PPE into edible films or coatings in food systems.

Articles unrelated to PPE or its food applications, studies with unclear methodologies, and non-peer-reviewed sources were excluded. Additional relevant papers were identified by scanning the reference lists of selected articles. This narrative review provides a current overview of PPE and its potential in sustainable food preservation by synthesizing findings from the most pertinent and methodologically sound investigations.

3. Natural Antimicrobials

A compound or substance to be classified as a "natural antimicrobial" must exist naturally without adding any synthesized materials [26]. These natural antimicrobials can be derived from plants, animals, and beneficial MOs [26–30] (Figure 1).

Many of these compounds serve multiple functions, including enhancing sensory qualities, extending shelf life and nutritional value, and mitigating antibiotic resistance. These substances may exert antimicrobial effects by disrupting cell membranes, inducing cellular leakage, and inhibiting bacterial biosynthetic processes, including protein synthesis and folding, DNA and cell wall synthesis, and enzymatic activity [26,29,31,32]. Therefore, increasing public concern regarding the use of natural antimicrobial agents is largely driven by heightened awareness of the potential adverse effects associated with synthetic preservatives and additives commonly used in the food industry [26,27,30]. Natural substances such as essential oils, plant-derived extracts, and secondary metabolic byproducts from bacteria, plants, and even enzymes are becoming increasingly favorable [26,33]. In general, natural substances are recognized as safe (GRAS) and, when used appropriately, do not pose a risk to consumer health [33].

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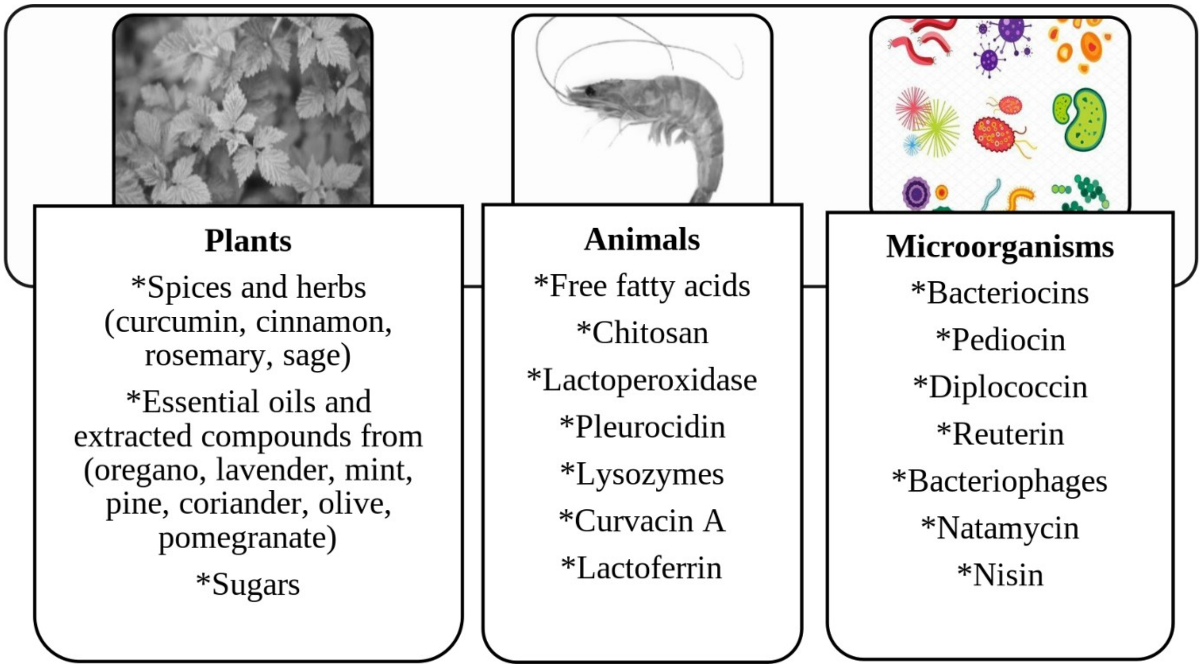

Figure 1: Sources of natural antimicrobials derived from plants, animals, and beneficial microorganisms.

Moreover, the widespread use of antibiotics has contributed to a rise in bacterial infections caused by drug-resistant strains [34]. By 2050, it is projected that antibiotic-resistant bacteria could cause approximately 10 million deaths worldwide annually [34]. Additionally, human health is significantly threatened by the consumption of residual antibiotics in food, which can accumulate in the body, disrupt the balance of normal gut microflora, and further contribute to the development of antibiotic resistance [29,34]. Therefore, plant-based compounds appear to be a plausible solution to the growing problem of antibiotic resistance. Furthermore, plant extracts have been shown to mitigate antibiotic resistance by promoting synergistic interactions between conventional antibiotics and naturally occurring antimicrobial compounds [32]. Thus, the significant impacts of synthetic preservatives on food safety, environmental pollution, and human health justify the pursuit of naturally derived alternatives from plant-based materials and other natural sources [27,29,34].

3.1. Plant-Based Natural Antimicrobials

Among natural antimicrobials from diverse biological sources, plant-derived compounds are the most extensively studied owing to their rich phytochemical profiles and proven safety in food applications.

Several plant-based parts, including seeds, flowers, peels, leaves, and pulps, can be extracted to obtain antimicrobial compounds [26,35]. In particular, fruit and vegetable processing wastes may provide useful supplies of phenolic compounds such as thymol (thyme), benzoic acid (cranberries), and eugenol (cinnamon) [26,35], as well as organic acid compounds such as citric acid (citrus fruit), and malic acid (apple) [26,36]. The potential antimicrobial mechanisms of plant extracts against microorganisms include damaging bacterial cells, disrupting the function of cellular enzymes, and compromising the phospholipid bilayer of the cell membrane [29,32].

The molecular structure of plant compounds significantly influences their antimicrobial activity. For instance, hydroxyl (−OH) groups are believed to interact with bacterial cell membranes, disrupting their integrity and causing cellular contents to leak out [29,37]. Moreover, the plant flavonoids can cross bacterial cell membranes, causing pH variations between cells and damaging the membranes [32]. Furthermore, membrane-disrupting compounds may cause leakage of cellular contents, interruption of metabolic and active transport processes, and loss of cellular energy in the form of ATP [17,32]. Pomegranate peel represents a promising option for food preservation, as it is an abundant and underutilized source of plant-derived phenolics and flavonoids, which exhibit strong antibacterial properties.

3.2. Pomegranate

Building on the general antimicrobial potential of plant extracts, pomegranate peel has received particular attention for its high phenolic content and potent activity against foodborne pathogens. The pomegranate (*Punica granatum* L.) is a member of the *Punicaceae* family, and is a small tree that can thrive in a variety of agro-climatic environments [19,24]. Pomegranate has been widely cultivated in the Mediterranean region, Southeast Asia, and the United States, and it has long been used as an herbal remedy for managing a variety of ailments [19]. It has recently been referred to as nature's power fruit due to its delicious flavor and superior health advantages [38,39]. In addition, pomegranate is mentioned in the Holy Qur'an alongside other fruits, such as dates, as fruits of paradise [24,40]. This plant consists of both edible and inedible parts, which have been used to prevent and treat various infectious diseases, as well as to provide numerous benefits in food applications [17,24,40–42].

The inedible part of the pomegranate, primarily the peel, comprises 30–60% of the whole fruit and contains higher levels of biologically active substances than the edible components [19,43–46]. Several studies have reported that pomegranate peels possess higher total phenolic content, as well as greater antibacterial and antioxidant activities, compared to the edible parts, including the pulp [17,24,45,46]. Therefore, the fruit processing sector noticed that this inedible layer could be a novel natural source of bioactive substances due to its significant financial advantages [19,25,28]. Understanding the antimicrobial potential of pomegranate peel requires examining how extraction techniques influence the yield and activity of its bioactive compounds.

3.2.1. Extraction Methods and Biochemical Composition

The overall effectiveness of natural antimicrobial compounds is significantly influenced by the extraction process. Thus, a variety of extraction techniques, such as solvent extraction, direct extraction, enzymatic extraction, and high-pressure extraction, have been employed to isolate and purify bioactive compounds for diverse applications [17,32,47]. In the solvent extraction method, a range of solvents including water, ethanol, methanol, and acetone are commonly used [17,28,41,47,48].

The choice of solvent for pomegranate peel extraction greatly influences the yield of phytochemicals and the resulting antioxidant activity [17]. Previous studies have shown that methanol is a more effective solvent for extracting bioactive compounds from pomegranate peel compared to other solvents [17,49]. Orak et al. [50] reported that the greatest tannin content was found in the methanol extract compared to water and ethanol extracts. Also, Hanafy et al. [28] reported that the greatest antibacterial activity was observed with the methanol extract of pomegranates compared to the ethanol extract. Although various methods have been explored for pomegranate peel extraction, it has been observed that high-temperature heating can degrade the extracts, thereby reducing the functionality of their components, decreasing the total amount of active compounds, or altering their natural properties [17].

Comparative analyses across studies show that methanol consistently yields pomegranate peel extract with higher phenolic content and greater antimicrobial potency, owing to its superior capacity to solubilize hydrolyzable tannins and other phenolic compounds responsible for disrupting microbial cell membranes [17,18,37,42]. In contrast, aqueous extractions typically produce lower phenolic concentrations and weaker antimicrobial effects, as many of the bioactive compounds in pomegranate peel have limited solubility in water [19,38,44]. Due to their lower toxicity and regulatory acceptability, ethanol–water combinations generally exhibit an intermediate extraction efficiency, delivering slightly less antibacterial activity than methanol but greater appropriateness for food-grade applications [15,17,28]. These solvent-dependent variations highlight the importance of selecting extraction methods that optimize antibacterial efficacy while ensuring safety and scalability, tailored to the intended food application. The antibacterial and antioxidant qualities of pomegranate peels are attributed to a wide range of phytochemicals and bioactive compounds, mainly phenolic acids, flavonoids, and hydrolyzable tannins (Table 1) [17,43,46,47,51,52]. Olaimat et al. [47] used gas chromatography-mass spectrometry (GC-M) to identify the phytochemical components present in methanolic PPE. Twelve chemicals in methanolic PPE were identified, and 5-Hydroxymethylfurfural (5-HMF) was the most common constituent.

However, the biochemical composition of pomegranate peels varies considerably among different cultivars and is influenced by factors such as climate, agricultural practices, and geographic origin [17,48]. Additionally, higher concentrations of phenolic acids and flavonoids, particularly anthocyanins, are responsible for the deep red color of pomegranates, which is important for consumer appeal [17,19]. Compared to extractions using water, ethanol, petroleum ether, or chloroform, methanol has consistently produced pomegranate peel extract with higher phenolic content and more potent antibacterial activity, as reported in published studies [17,18,37,42]. Methanol's high polarity, which increases the solubility and recovery of hydrolysable tannins such as punicalagin and ellagic acid, which are closely linked to antibacterial action, is the main cause of this improved performance [19,38].

Table 1: Major bioactive constituents identified in pomegranate peel extract. Adapted from [17,43,46,51,52].

Bioactive Substance	Examples
Phenolic acids	cinnamic, ellagic, gallic, caffeic, ferulic, vanillic, syringic, chlorogenic, hydroxycinnamic, hydroxybenzoic, sinapic, and p-coumaric acids
Flavonoids	anthocyanins such as pelargonidin, delphinidin, and cyanidin, in addition to their derivatives such as catechin, epicatechin, rutin, and quercetin
Tannins	punicalagin, punicalin, castalagin, corilagin, pedunculagin, granatins, gallagyldilactone, and tellimagrandin.

However, due to their lower toxicity and wider regulatory acceptance, ethanol–water mixtures are considered more suitable for food-grade applications, even though they often yield slightly lower total phenolic content and antibacterial activity compared to methanol [15,17,28]. These solvent-dependent variations show that the choice of extraction solvent has a major impact on PPE's chemical profile and antibacterial efficiency; as a result, extraction conditions should be customized for the intended food application.

3.2.2. Antioxidant and Antimicrobial Activity of Pomegranate Peel Extract

Once extracted, the biochemical composition of pomegranate peel extract directly influences its antimicrobial efficacy, which has been assessed in numerous in vitro and in vivo studies. PPE has been used to increase the antioxidant capacity of food products [17,43,44]. For example, PPE showed great potential to extend the shelf life and increase the antioxidant capacity of meat and chicken products, ice cream, and wheat noodles [44]. Ghasemi et al. [43] reported that PPE extracted with methanol–water (50:50, v/v) at different concentrations (0, 0.25, 0.5, 1, and 2%) was effective in reducing lipid oxidation in tahini during 6 months of storage compared with the control (untreated with PPE), owing to the presence of phenolic compounds such as gallic acid, ellagic acid, and punicalagin.

The antimicrobial activity of pomegranate peel extract is primarily attributed to interactions between the hydroxyl groups of its phenolic compounds and the bacterial cell membrane, which can destabilize the membrane, cause leakage of cytoplasmic contents, and ultimately lead to cell death [17,28,37]. A conceptual diagram illustrating the antimicrobial mechanism of PPE would typically depict three primary actions: (1) adsorption of phenolic compounds onto the bacterial cell surface, (2) disruption of membrane phospholipid organization leading to increased permeability and leakage of intracellular components, and (3) inhibition of key microbial enzymes through protein binding and metal ion chelation [35–37,50]. Collectively, these multi-level interactions contribute to the broad-spectrum antimicrobial activity consistently observed for PPE against foodborne pathogens [19,37,41].

For example, the inhibition zones of the methanolic PPE extract, as determined by the agar well diffusion method against four different bacterial species, including *Enterobacter aerogenes*, *Salmonella typhi*, *Staphylococcus aureus*, and *Klebsiella pneumoniae*, were 18.2, 18.3, 24.5, and 11.3, respectively [46]. Moreover, Devatkal et al. [53] studied the antibacterial effect of aqueous PPE at 1%, 5%, and 10% against the *Pseudomonas stutzeri* strain by broth dilution assay. The PPE effect was measured by counting cells on plates, indicating that the control was >300 CFU with a $10-1$ dilution factor, compared to 36 CFU in 1% PPE, while cells were not detected in broth treated with 5% or 10% PPE. When comparing microbial susceptibility patterns, Gram-positive bacteria such as *Staphylococcus aureus* and *Listeria monocytogenes* often exhibit larger inhibition zones and lower MIC values than Gram-negative bacteria such as *E. coli* or *Salmonella* spp. [37,46]. This pattern can be attributed to structural differences in the bacterial cell envelope. The outer lipopolysaccharide layer of Gram-negative bacteria acts as a permeability barrier that limits the penetration of many hydrophobic antimicrobial compounds, whereas the thick peptidoglycan layer of Gram-positive bacteria allows phenolic compounds to interact with and more effectively disrupt membrane integrity [35,36,50]. These structural variations highlight the specific antibacterial activity of pomegranate peel extract (PPE) and underscore the importance of considering the pathogen type when determining the appropriate application concentration [37,41].

Wafa et al. [20] also studied the antibacterial effect of PPE extracted by a mixture of solvents (water, methanol, and ethanol) using the broth microdilution method against *S. enterica* (Kentucky and Enteritidis serotypes). The minimum inhibitory concentration (MIC) and the minimum bactericidal concentration (MBC) were 10.75 and 12.75 mg/mL, respectively, against *S.* Enteritidis and 12.50 and 12.75 mg/mL, respectively, against *S.* Kentucky. Furthermore, the in vitro examination of PPE extracted with diethyl ether, 80% methanol, and water showed that the MICs were 0.5 and 4 mg/mL for *L. monocytogenes* and *S.* Enteritidis, respectively. The *L. monocytogenes* numbers in fresh chilled fish dipped for 15 min in a solution containing 300 mL of 10 mg/mL PPE and stored at 4 °C were reduced by >1 log CFU/g after 6 days of refrigerated storage [38]. Moreover, the MIC and MBC of methanol PPE against *E. coli* O157:H7 were 15 and 20 mg/mL, respectively [37].

Pomegranate peel extract (PPE) obtained using different solvents also exhibits antifungal activity. For example, the minimum fungicidal concentration (MFC) and MIC of methanolic PPE against *Fusarium sambucinum* were 120 and 20 mg/mL, respectively. Concentrations of 1.25 and 20 mg/mL reduced the growth of F. sambucinum on potato tubers by 23.7% and 75.5%, respectively, while complete inhibition of spore development was observed at 20 mg/mL [25]. Also, the antifungal activity of PPE extracted by methanol, ethanol, and water against *Penicillium digitatum* isolated from yellow citrus fruits was investigated. According to the findings, methanol, ethanol, and water demonstrated greater efficiency, with inhibition zones of 22–24 mm, 20–23 mm, and 18–20 mm, respectively [40]. Depending on the extraction solvent and experimental conditions, pomegranate peel extract (PPE) exhibits antibacterial activity comparable to or exceeding that of other plant-derived antimicrobials, such as thyme oil, clove phenolics, and citrus peel extracts [11,22,23].

PPE offers broad-spectrum antimicrobial activity with relatively little sensory impact, making it more suitable for use in edible coatings and films where flavor neutrality is desired, in contrast to essential oils, which frequently have strong aromas and may negatively affect the sensory qualities of foods [27,41,50]. PPE exhibits competitive or better inhibitory activity against a variety of foodborne pathogens when compared to other plant-derived antimicrobials. Although clove and thyme essential oils exhibit strong broad-spectrum antimicrobial activity, their intense flavor and aroma often limit their use in sensitive food matrices. In contrast, citrus peel extracts, which are rich in limonene and organic acids, generally demonstrate stronger activity against Gram-negative bacteria [10,12,13,29]. PPE, on the other hand, is more suitable for incorporation into edible coatings, as it offers strong antibacterial and antioxidant benefits while causing minimal sensory impact [41,47,48]. Furthermore, unlike plant extracts whose antimicrobial activity largely relies on one or two dominant compounds, PPE's high tannin and phenolic content enable a multi-mechanistic mode of action, including membrane disruption, metal ion chelation, and enzyme inhibition [19,35–37,50].

4. Natural Antimicrobial Agents in Food Packaging

4.1. Food Packaging

Although PPE clearly has antimicrobial potential, its use in active food packaging systems best demonstrates its usefulness. An essential part of the food production process is food packaging. An appropriate packaging material is crucial for maintaining food quality and safety while minimizing food loss [54].

Nearly 30% of food produced is lost due to spoilage during harvesting, transportation, or other handling processes [45,55]. The primary purpose of food packaging is to protect food from potential hazards that could compromise its safety or quality [56]. Both edible and conventional inedible packaging materials can be used to contain and preserve food [54]. Typically, inedible food packaging is single-use and is discarded either when the packaged food is consumed or upon delivery to the consumer [55]. Although conventional food packaging commonly uses materials such as paper, plastic, glass, steel, cardboard, and aluminum, these materials are not environmentally friendly and contribute significantly to pollution through packaging waste [55,56]. Furthermore, most of these materials rely on non-renewable petroleum resources and may pose toxicological risks [55]. Even though certain materials (e.g., paper) have very high recycling rates, nearly above 20%, conventional packaging continues to have a significant environmental impact. On the other hand, other materials (e.g., plastics) typically have poor recycling rates of less than 20% [55].

Consumer demand for safe, environmentally friendly, and less toxic packaging materials is increasing due to growing concerns about the adverse effects of conventional packaging on both human health and the environment [57,58]. Therefore, novel edible packaging has grown significantly as a potential alternative to conventional packaging in the past few decades, achieving eco-friendly packaging, reducing food waste, and guarding against potential food contamination or spoilage [45,54,55,58]. On the other hand, some unresolved drawbacks of edible packaging include sensitivity to high or fluctuating temperatures, the occasional need for an additional outer package, lack of cost-effectiveness in certain cases, and the potential to trigger allergic reactions in susceptible individuals [55,58].

4.2. Edible Films and Coatings

Among the various forms of active packaging, edible films and coatings provide an effective vehicle for delivering

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PPE to food surfaces. Edible films and coatings are modern food safety solutions and represent the most commonly used form of edible food packaging [45,58,59]. Edible packaging materials are being commercially developed in the food sector, primarily in the US, with an expected annual expansion rate of 14.31% from 2022 to 2030; while the global edible packaging usage was estimated to be worth \$0.84 billion in 2021 and expected to increase to reach \$2.8 billion by 2030 [58]. Generally, edible films and coatings are thin layers of edible material applied to the food surface, with all components and ingredients being safe and approved for consumption [59,60]. Furthermore, two main categories that distinguish edible films from coatings are the physical structure and the application method [57,58]. Edible films are thin sheets used as food wrappers and intended to remain on the food, typically produced by casting or extrusion. In contrast, edible coatings are biodegradable liquid materials applied directly to the entire food product using techniques such as dipping, spraying, panning, brushing, or fluidized bed methods [58]. Moreover, the application of coating methods on food products is determined by the food type, surface characteristics, and the coating's primary goal [61]. The most traditional and widely used method for applying edible coatings in food packaging is dipping. In this technique, the product is immersed in a liquid coating solution and then dried to form a thin layer covering the food surface. Dipping is cost-effective, easy to perform, and particularly suitable for coating irregularly shaped food products [58,61,62].

A standard edible film should be safe for human consumption, cost-effective, free from contaminants, and possess strong mechanical, sensory, and microbiological stability and functionality [58]. In addition, the thickness of edible films and coatings is a crucial physical characteristic, and it should be $\leq$ 0.3 mm [58]. Additionally, other characteristics of films and coatings, such as surface tension, viscosity, density, application method, and the size and shape of the food product, play a crucial role in determining the thickness of the film or coating [58,61]. Usually, the major components of edible coatings and films are biopolymer materials, including polysaccharides, proteins, or lipids (Figure 2), solvents (e.g., alcohol, water, citric acid, acetic acid, lactic acid, and hydrochloric acid), and additives (e.g., plasticizers, emulsifiers, antioxidants, and antimicrobials) [55,58,63].

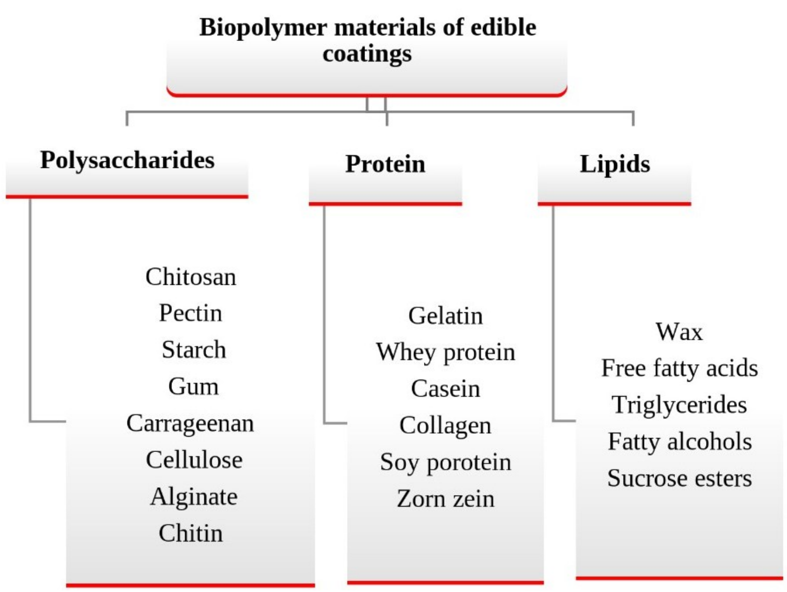

Figure 2: Major biopolymer components used in edible films and coatings. Adapted from [55,58,63].

5. Incorporation of Pomegranate Peel Extract as an Antimicrobial Agent in Edible Coatings

Integrating PPE into edible packaging has been widely studied, and the following section summarizes key findings across different food models. Several studies have investigated the addition of PPE as an antimicrobial agent in food packaging materials to improve the shelf life, safety, quality, antioxidant activity, and organoleptic characteristics of food products [41,47,48,52,54,55,64]. Accordingly, recent studies have suggested that the food industry could use PPE as the synthetic antimicrobials currently employed in food packaging materials [41,43,47,48]. Table 2 shows the use of PPE as an antimicrobial agent in edible coatings and films against several foodborne and spoilage MOs [65–72].

Table 2: In vitro or in vivo antimicrobial activity of pomegranate peel extract incorporated into edible packaging.

Film/ Coating Type	Pomegranate Peel/Concentration	Application	Main Findings	Reference
Chitosan film	80% Methanol PPE/ (10 g/L)	In vitro	The inhibition zone was 2.5 mm against *Staph. aureus*. It was not effective against *E. coli*.	[65]
2% Chitosan coating	70% ethanol PPE/(0.5, 1.0, 1.5, and 2.0%)	In vivo (Nile tilapia fillets)	During storage at 4 °C for 30 days, coating the fillets resulted in a significant reduction in total microbial counts.	[66]
Chitosan coating	Water PPE/(0.361 g/mL) of dry PPE	In vitro and in vivo (Orange)	The inhibition zones were 3.1 mm against *P. digitatum*. The organism was significantly reduced in oranges.	[49]
Chitosan coating	80% ethanol PPE/(1%)	In vivo (Capsicum)	*Colletotrichum gloeosporioides* was reduced by 1.1 log CFU/g on capsicum after 25 d at 10 °C.	[67]
Fish gelatin film	Pomegranate peel powder (PPP) /(5%)	In vitro	Inhibition zones were 7.0, 5.1, and 4.1 against *Staph. aureus*, *L. monocytogenes*, and *E. coli*, respectively.	[68]
Chitosan film	Pomegranate peel powder/(3%)	In vivo (Chicken breasts)	Reduced the total bacterial count, psychrotrophic, and coliform bacteria on chicken breasts by 2, 2.5, and 3.0 log CFU/g, respectively, after 15 d at 4 °C.	[69]
Chitosan-starch films (CH-S)	70% Ethyl alcohol and distilled water PPE/(0.5%, 1%)	In vivo (Fresh beef)	The CH-S films with 0.5% and 1% PPE reduced the numbers of *L. monocytogenes* on fresh beef stored at 4 °C by 1.0 log CFU/g after 21 d.	[70]
Chitosan film	20% Methanol PPE/(0.03%)	In vitro	Inhibition zones were 8.0 and 8.5 against *E. coli* and *Bacillus cereus*, respectively.	[71]
Fish Gelatin-κ-Carrageenan coatings (Gf-Cr)	PPE (1.5, 2.0%)	In vivo (Fish Fillet)	The Gf-Cr coatings with 1.5, 2.0% PPE caused complete inhibition of psychrotrophic bacteria, yeast, and mold, and *Enterobacteriaceae* throughout a 30 d of storage time at 4 °C.	[72]
2% Chitosan coating, 9% Gelatin coating	Methanol PPE/(2.5,5.0, and 10.0%)	In vitro and in vivo (Medjool dates)	PPE's MIC and MBC against *L. monocytogenes* at 37 °C were 3.91–7.81 and 15.63–31.25 mg/mL, respectively. On PPE-coated dates, *L. monocytogenes* was significantly decreased (1.8 log–2.9 log CFU/g) by day 56 at 4 °C, while the pathogen was not detected (<1 CFU/15 g) at 24 °C.	[47]
2% Chitosan coating, 9% Gelatin coating	Methanol PPE/(2.5,5.0, and 10.0%)	In vitro and in vivo (Medjool dates)	PPE's MIC and MBC against *S. enterica* at 37 °C were 7.81–15.63 and 15.63–31.25 mg/mL, respectively. At 4 °C, on PPE-coated dates, S. enterica levels decreased significantly by 1.3 log CFU/g, reaching >4.5 log CFU/g by day 56. At 24 °C, however, the pathogen was not detected (<1 CFU/15 g).	[48]

Despite its proven antibacterial properties, several practical limitations must be considered when incorporating PPE into edible films and coatings. Particularly in light-colored foodstuffs, the naturally dark pigmentation of PPE may change the color, opacity, or visual appearance of coated meals, potentially affecting customer acceptance [41,55,60]. Furthermore, the phenolic compounds in PPE can interact with biopolymer matrices such as chitosan, gelatin, or starch, affecting the mechanical properties, flexibility, and barrier performance of the final coating [58–60,65]. Furthermore, uniformity and reproducibility of antimicrobial activity may be hampered by variations in phenolic composition resulting from variations in pomegranate cultivar, harvest season, geographic origin, and extraction technique [19,42,44]. To overcome these obstacles and maintain the structural integrity and sensory quality of edible coatings while achieving consistent antimicrobial activity, formulation optimization, controlled-release techniques, or encapsulation approaches will be needed [56,59,60].

6. Conclusions

This review synthesized current evidence on PPE, with emphasis on its extraction methods, phytochemical composition, antimicrobial mechanisms, and its incorporation into edible films and coatings for food preservation. Collectively, the reviewed studies demonstrate that PPE is a promising natural antimicrobial agent capable of enhancing food safety, extending shelf life, and contributing to clean-label preservation strategies. These advantages make PPE a valuable bioactive ingredient for developing eco-friendly packaging systems that meet the growing global demand for sustainable food solutions.

Despite its promising potential, several gaps in knowledge still remain. The antimicrobial efficacy of PPE varies with extraction method, solvent polarity, cultivar, and food matrix, and standardized extraction protocols are still lacking. In addition, limited information exists regarding the stability of phenolic compounds during storage, their interactions with biopolymers in edible coatings, and their impact on sensory qualities in different food products. Future research should investigate the feasibility of large-scale PPE extraction, the development of encapsulation or controlled-release systems, migration behavior in packaging materials, and comprehensive evaluations of sensory attributes and shelf life across various food products.

The broader adoption of PPE-based antimicrobial coatings may contribute to global sustainability efforts by reducing reliance on synthetic preservatives, minimizing agricultural waste, and supporting United Nations Sustainable Development Goals, particularly SDG2 (Zero Hunger), SDG3 (Good Health and Well-Being), and SDG13 (Climate Action). Enhancing our understanding of PPE's functional properties will further reinforce its potential in developing safer, more sustainable, and environmentally responsible food packaging systems.

List of Abbreviations

CFU	Colony Forming Unit
FBD	Foodborne Disease
FBP	Foodborne Pathogens
MBC	Minimum Bactericidal Concentration
MIC	Minimum Inhibitory Concentration
MOs	Microorganisms
PPE	Pomegranate Peel Extract

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Conceptualization: A.N.O; Visualization: S.H. and A.N.O; Writing—original draft: S.H; Writing—review & editing: S.H., A.N.O., and M.A.-H; Supervision: M.A.-H. All authors have read and agreed to the published version of the manuscript.

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AI Declaration

The authors confirm that no AI tools were used to generate any content of this manuscript.

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