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**Review**

# **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 from plants are starting to be used in the food industry as more safe and sustainable alternatives to synthetic additives for food preservation. One of these is the pomegranate peel extract (PPE), which is starting to be used as a bioactive ingredient due to its antimicrobial and antioxidant properties driven from the phenolic acids, flavonoids, and tannins (among other phytochemicals) it possesses. The phytochemical composition, and resultant antimicrobial of PPE is particularly dependent on the pomegranate cultivar, geographical origin and extraction method of the peel. This highlights the need to further optimize extraction methods

of PPE. PPE is being incorporated into edible films and coatings to improve food safety and quality. PPE has antimicrobial activity against a number 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 the food (during storage) while causing less microbial growth and providing a longer shelf life. The addition of PPE to food packaging materials is consistent with sustainable packaging principles and 'clean-label' requirements. This article provides a review on the extraction methods of PPE, the antimicrobial mechanisms, phytochemical constituents of PPE and its use in food packaging to promote the use of PPE in sustainable food production.

## **Keywords**

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

## **1. Introduction**

Foodborne disease (FBD) represents a global issue afflicting countless individuals. In the United States, contaminated food causes roughly 48 million illnesses every year, meaning 1 out of every 6 people will become ill. This issue leads to the hospitalization of 128,000 individuals and the deaths of 3,000 people which is a significant issue 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 5,000 deaths each year due to FBD. [2]. Australia estimates that the FBD epidemic causes 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 analyzes pomegranate peel extract as an antimicrobial food packaging solution, assessing its extraction, composition, mechanisms, and

the potential for antimicrobial food packaging. During every part of the food chain, from the farm to the table, microbial contamination is a risk. At every single stage of microbiological contamination, food could potentially be contaminated by exposure to animal feces; during and after animal slaughter, there is insufficient sanitation, contamination of food by infected equipment or by instruments, irresponsible food handlers, or 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]. Mild gastrointestinal issues to serious long-term consequences, such as cancer, neurological deficits, organ damage, and even death, are among the symptoms [8]. Foodborne illness continues to be a major worry for consumers and the food business despite advancements in food preservation technologies [8,9].

Clean-label, natural preservation methods are becoming more popular despite the fact that synthetic antioxidants and antimicrobials successfully block FBP due to worries about their 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 chemicals with antibacterial and antioxidant properties [11,22]. Phenolic acids, flavonoids, and tannins have antimicrobial activity 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 a variety of methods,

although methanolic extraction has consistently shown better antibacterial activity than petroleum ether, chloroform, and aqueous extracts [15,17,18,24,25].

To address the growing need for natural and sustainable food preservation, this review summarizes current evidence on PPE extraction methods, phytochemical composition, antimicrobial mechanisms, and its applications in edible films and coatings for enhanced food safety.

## **2. Literature Search Strategy**

To gather pertinent research on pomegranate peel extract (PPE), its phytochemical makeup, antimicrobial processes, and its uses in food packaging systems, a thorough literature search was carried out. 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 in the search to find 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 food applications, research with unclear methodology, and non-peer reviewed sources were not included. Through reference list scanning, more pertinent papers were found. 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.

## 2. 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).

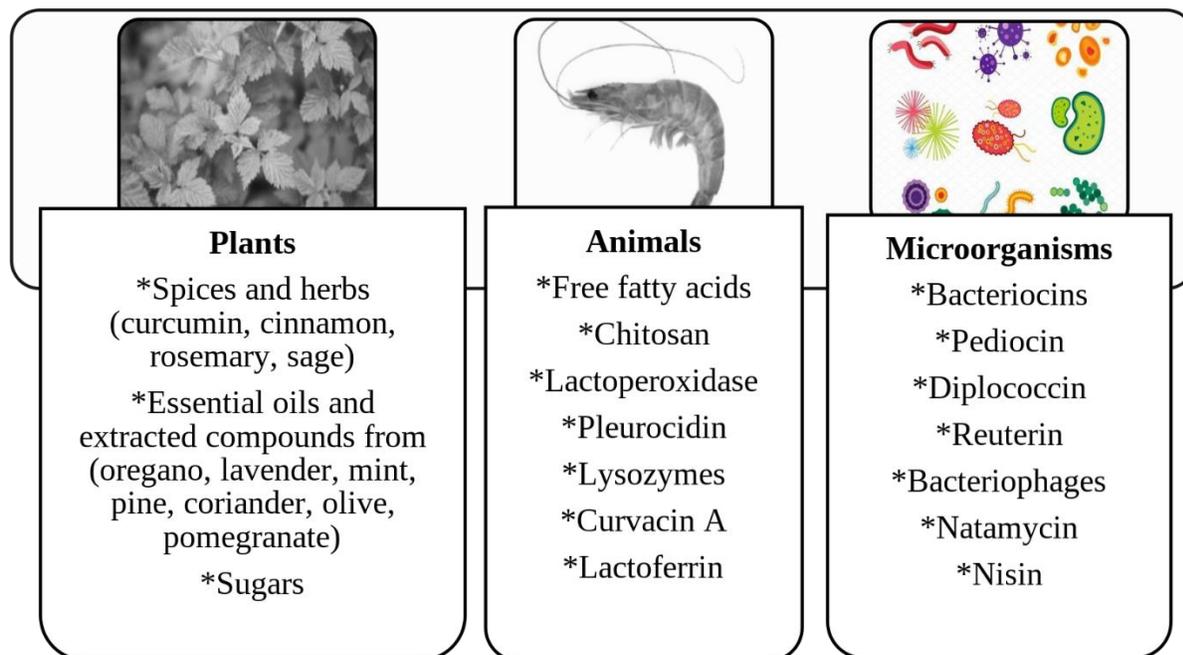


Figure 1. Sources of natural antimicrobials derived from plants, animals, and beneficial microorganisms.

Many of these substances have multiple functions, including improving the sensory qualities, extending the shelf life and nutritional value of food, and reducing antibiotic resistance. Such substances may act as antimicrobials by destroying cell membranes, causing cellular leakage, and

hindering biosynthetic bacterial processes such as protein synthesis and folding, DNA and cell wall synthesis, and enzymatic reactions [26,29,31,32]. Therefore, a growing public apprehension over the utilization of natural antimicrobial agents is primarily attributed to the growing knowledge of the adverse effects of artificially produced preservatives and additives that are utilized in the food sector [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]. Generally, natural substances are generally recognized as safe (GRAS) and do not endanger the well-being of consumers when used properly [33].

In addition, the widespread utilization of antibiotics has increased the number of diseases caused by bacteria resistant to the drugs [34]. By 2050, it is predicted that these antibiotic-resistant bacteria will probably kill 10 million people globally each year [34]. Also, human well-being is seriously threatened by the consumption of residual antibiotics in food, which build up in the human body and may kill or disturb the balance of the normal microflora in the human gut or may exacerbate the problem 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 demonstrated to decrease antibiotic resistance by encouraging synergistic interactions between antibiotics and naturally occurring antimicrobials [32]. So, the enormous effects of synthetic preservatives on food safety, environmental contamination, and human wellness rationalize the search for naturally occurring alternatives from plant-based materials and other natural sources [27,29, 34].

## **2.1. Plant-based natural antimicrobials**

Since natural antimicrobials can originate from diverse biological sources, plant-derived compounds represent the most extensively studied group due to their rich phytochemical profiles and established 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 possible antimicrobial mechanisms of plant extract against MOs include damaging to bacterial cells, impeding the function of cell enzyme structures, and destroying the phospholipid bilayer of the cell membrane [29, 32].

The molecular structure of plant substances greatly influences the antimicrobial activity; for example, the hydroxyl (–OH) groups are assumed to interact with the bacterial cell membrane, resulting in the disruption of its structures and allowing components to leak out of the bacterial cell [29,37]. Moreover, the plant flavonoids can cross bacterial cell membranes, causing pH variations between cells and damaging the membranes [32]. Furthermore, cellular composition leakage, interruption of metabolic or active transport processes, or loss of cellular energy as ATP are examples of membrane-disrupting chemicals [17,32]. Pomegranate peel is a viable option for food preservation since it is a plentiful and underutilized source of plant-derived phenolics and flavonoids, which have been shown to have potent antibacterial effects.

## 2.2. 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, a small tree that can thrive in a variety of agro-climatic environments [19,24]. It has been extensively cultivated in the Mediterranean region, Southeast Asia, and the US, and it is utilized as an herbal remedy for managing a variety of illnesses [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 was mentioned in the Holy Qur'an along with other fruits such as dates as they are fruits of paradise [24,40]. This plant is composed of edible or inedible parts that have been used for treating and preventing a variety of infectious medical conditions and to bring about many benefits in food applications [17, 24, 40, 41, 42].

Focusing on the inedible part of pomegranate (primarily the peels), which comprises 30-60% of the whole fruit, has higher biologically active substances compared to the edible components [19, 43–46]. Several studies reported higher total phenolic content and antibacterial and antioxidant activities of pomegranate peels compared to the edible parts, including 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.

### **2.2.1. Extraction Methods and Biochemical Composition**

The overall effectiveness of natural antimicrobial compounds is significantly influenced by the extraction process. So, various extraction techniques (e.g., solvent extraction, direct extraction, enzymatic extraction, and high-pressure extraction) have been used to extract and purify active substances for multiple purposes [17, 32, 47]. Considering the solvent extraction method, various solvents such as water, ethanol, methanol, and acetone are utilized [17, 28, 41, 47, 48].

The solvents employed for pomegranate peel extraction have a significant impact on the amount of phytochemicals and antioxidant activity [17]. According to earlier research, using methanol as an extraction solvent is more potent than 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 reaped from the methanol extract of pomegranates compared to ethanol. While several methods have been investigated for pomegranate extraction, it has been found that heating using high temperatures could degrade the extracts and hence diminish the components' functionality, reducing the total amount of active components, or altering the natural properties [17].

Comparative analyses across studies indicate that methanol consistently produces PPE with higher phenolic content and stronger antimicrobial potency due to its superior ability to solubilize hydrolysable tannins and other phenolic compounds responsible for membrane-disruptive activity [17,18,37,42]. In contrast, aqueous extractions generally yield lower phenolic concentrations and weaker antimicrobial effects because many bioactive compounds in pomegranate peel exhibit limited water solubility [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 emphasize how crucial it is to choose extraction techniques that balance antibacterial efficacy, safety, and scalability according 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, pomegranate peels' biochemical makeup varies widely among varieties and is impacted by climate, cultivation practices, and geographic location [17, 48]. Additionally, a higher concentration of phenolic acid and flavonoids, primarily anthocyanins, is responsible for the pomegranates' deep red color, which is crucial for consumer appeal in pomegranate advertising [17,19]. When compared to water, ethanol, petroleum ether, or chloroform-based extractions, methanol has continuously yielded PPE with a greater phenolic content and stronger antibacterial activity in published investigations [17,18,37,42]. Methanol's high polarity, which increases the solubility and recovery of hydrolysable tannins such punicalagin and ellagic acid, which are closely linked to antibacterial action, is the main cause of this improved performance [19, 38].

However, because of their reduced toxicity and broader regulatory acceptance, ethanol–water combinations are thought to be more appropriate for food-grade applications, even though they frequently produce slightly lower total phenolic contents and antibacterial activity than 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.

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, gallagylidilactone, and tellimagrandin.

### 2.2.2. Antioxidant and Antimicrobial Activity of Pomegranate Peel Extract

Once extracted, the biochemical composition of PPE directly determines its antimicrobial efficacy, which has been evaluated 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 the use of PPE by methanol-water (50: 50 v/v) extraction in different concentrations (0, 0.25, 0.5, 1, and 2%) was effective in eradicating lipid oxidation in tahini during 6 months of storage compared with the control (untreated with PPE), due to the presence of phenolic compounds (gallic acid, ellagic acid, and punicalagin).

The antimicrobial effect of PPE most likely comes from the interactions between the OH group of phenolic compounds and the bacterial cell membrane, which can result in membrane destabilization, leading to the leakage of cytoplasmic materials, which causes 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]. Together, these multilevel interactions contribute to the broad-spectrum antimicrobial profile consistently reported for PPE against foodborne pathogens [19, 37, 41].

For example, the inhibition zones of methanolic PPE extract using 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 *Pseudomonas stutzeri* strain by broth dilution assay. The PPE effect was measured by computing the cell numbers in plates, indicating the control was >300 CFU with a  $10^{-1}$  dilution factor compared to 36 CFU in 1% PPE, while the numbers of cells were not detected in broth treated with 5% and 10% of 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 compared with Gram-negative bacteria like *E. coli* or *Salmonella spp.* [37, 46]. This pattern may be explained by structural variations in the bacterial cell envelope; the outer lipopolysaccharide layer of Gram-negative bacteria functions as a permeability barrier that restricts the penetration of numerous hydrophobic antimicrobial

compounds, while the thick peptidoglycan layer of Gram-positive bacteria enables phenolic compounds to interact with and disrupt membrane integrity more effectively [35,36,50]. These structural variations demonstrate the specific antibacterial action of pomegranate peel extract (PPE) and the need to take pathogen type into account when calculating appropriate application concentrations [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, against *S. Enteritidis* and 12.50 and 12.75 mg/ml, respectively, against *S. Kentucky*. Furthermore, the *in vitro* examination of PPE extracted by diethyl ether, 80% methanol, and water showed that the MIC was 0.5 and 4 mg/ml for *L. monocytogenes* and *S. Enteritidis*, respectively. While the *L. monocytogenes* numbers of 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, it was noticed that the MIC and MBC of methanol PPE against *E. coli* O157:H7 were 15 and 20 mg/ml, respectively [37].

PPE extracted by different types of solvents also possesses antifungal effects. For example, the minimum fungicidal concentration (MFC) and MIC of methanolic PPE against *Fusarium sambucinum* were 120 and 20 mg/ml, respectively. While 1.25 and 20 mg/ml reduced the growth of *F. sambucinum* by 23.7% and 75.5% respectively, on potato tubers, noting a full elimination of its spore development at a concentration of 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 test circumstances, PPE has antibacterial potency that is comparable to or higher than that of other plant-based antimicrobials including 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. While clove and thyme essential oils have strong broad-spectrum antimicrobial activity but often impart strong flavor and aroma that restrict their use in sensitive food matrices, citrus peel extracts, which are rich in limonene and organic acids, usually show stronger activity against Gram-negative bacteria [10,12,13,29]. PPE, on the other hand, is better suitable for incorporation into edible coatings because it provides strong antibacterial and antioxidant benefits with less sensory disturbance [41,47,48]. Furthermore, compared to plant extracts whose antimicrobial activity mainly depends on one or two dominant compounds, PPE's high tannin and phenolic content permits a multimechanistic mode of action, including membrane disruption, metal ion chelation, and enzyme inhibition [19,35–37,50].

## **Natural antimicrobial agents in food Packaging**

### **2.3. 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.

A suitable packaging material is essential for preserving the food's quality and safety as well as preventing food loss [54].

Nearly 30% of the food produced ends up in waste dumps as a result of rotting during harvesting, shipping, or other processes [45,55]. The primary purpose of food packaging is to safeguard and prevent food from any potential hazards that could affect its safety and/or quality [56]. Edible and inedible (conventional) packaging material could be utilized to contain and preserve foods [54]. Typically, inedible food packaging is a single-use material that is thrown away when eating the packaged food or upon delivery to the consumer [55]. Although several materials are commonly utilized in conventional food packaging, such as paper, plastic, glass, steel, cardboard, and aluminum, such materials are not environmentally friendly and contribute to pollution in the form of packaging waste [55,56]. Furthermore, most of these materials are dependent on non-renewable petroleum resources and have a high possibility of toxic reactions [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 and environmentally compatible, less toxic packaging materials is on the increase as there is a growing concern about the detrimental implications of conventional packaging materials on their well-being, as well as on 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 yet to be resolved disadvantages of the edible packages are the sensitivity to high or fluctuating temperatures, the

need for an additional outer package, not being cost-effective sometimes, and producing allergic responses in people with allergies [55,58].

### **3.2. Edible Films and Coatings**

Among the various forms of active packaging, edible films and coatings provide an effective vehicle for delivering PPE to food surfaces. Edible films and coatings are contemporary food safety systems that tend to represent the most commonly utilized 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 a thin layer of edible material that covers the food surface and taking into account that all the components and ingredients included in the edible coating are allowed and safe to eat [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 made of thin sheets that are utilized as food wrappers and are designed not to be removed from the food product by casting or extrusion method, while edible coatings are biodegradable liquid edible materials applied as a part of the whole food product by dipping, spraying, panning, brushing, or fluidized bed method [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 technique for applying edible coatings in food packaging is dipping; a technique in which the product is immediately dipped into a liquid coating solution, followed by a dry process, to create a

thin membrane that covers the food surface, since it is cost-effective, and easy to use, in addition to the ability for applying on irregular food surfaces [58,61,62].

The standard edible film should be ingestible by humans, inexpensive, non-contaminated, with strong mechanical, sensory, and microbiological stability and activity [58]. In addition, the thickness of edible films and coatings is a crucial physical characteristic, and it should be  $\leq 0.3$  mm [58]. Further, other characteristics of films and coatings, including surface tension, viscosity, density, applying method, food product size, and shape, play a significant role in the determination of film/coating thickness [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].

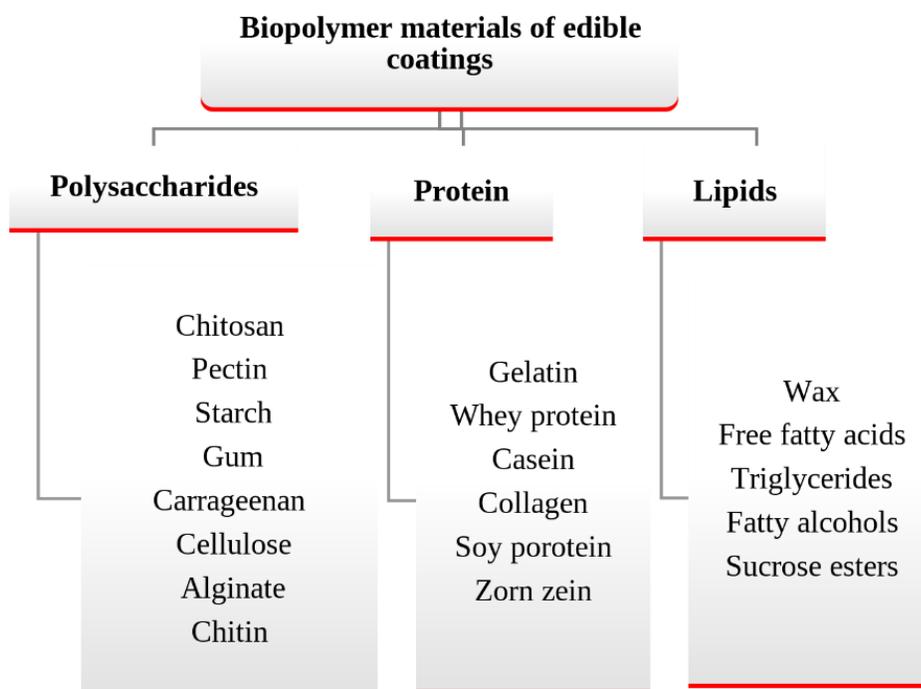


Figure 2. Major biopolymer components used in edible films and coatings. Adapted from [55,58,63].

### 3. 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 investigated the addition of PPE as an antimicrobial agent in food packaging materials to improve the shelf life, safety, quality, antioxidant, and organoleptic characteristics of food products [41, 47,48, 52,54,55, 64]. Accordingly, recent studies suggested that the food sector may use PPE as an alternative to the artificial antimicrobials that are currently utilized 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.

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.

<b>Film/ Coating Type</b>	<b>Pomegranate peel/ concentration</b>	<b>Application</b>	<b>Main findings</b>	<b>Reference</b>

<b>Chitosan film</b>	80% Methanol PPE/ (10 g/L)	<i>In vitro</i>	The inhibition zone was 2.5 mm against <i>Staph. aureus</i> . It was not effective against <i>E. coli</i> .	[65]
<b>2% Chitosan coating</b>	70% ethanol PPE/ (0.5, 1.0, 1.5, and 2.0%)	<i>In vivo</i> (Nile tilapia fillets)	During storage at 4 °C for 30 days, the coating of the fillets caused a significant drop in the total microbial counts.	[66]
<b>Chitosan coating</b>	Water PPE / (0.361 g/ml) of dry PPE	<i>In vitro</i> and <i>in vivo</i> (Orange)	Inhibition zones were 3.1 mm against <i>P. digitatum</i> . The organism was significantly reduced in oranges.	[49]
<b>Chitosan coating</b>	80% ethanol PPE /(1%)	<i>In vivo</i> (Capsicum)	<i>Colletotrichum gloeosporioides</i> was reduced by 1.1 log CFU/g on capsicum after 25 d at 10 °C.	[67]
<b>Fish gelatin film</b>	Pomegranate peel powder (PPP) / (5%)	<i>In vitro</i>	Inhibition zones were 7.0, 5.1, and 4.1 against <i>Staph. aureus</i> , <i>L. monocytogenes</i> , and <i>E. coli</i> , respectively.	[68]

<b>Chitosan film</b>	Pomegranate peel powder/ (3%)	<i>In vivo</i> (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]
<b>Chitosan-starch films (CH-S)</b>	70% Ethyl alcohol and distilled water PPE / (0.5%, 1%)	<i>In vivo</i> (Fresh beef)	The CH-S films with 0.5% and 1% PPE reduced the numbers of <i>L. monocytogenes</i> on fresh beef stored at 4 °C by 1.0 log CFU/g after 21 d.	[70]
<b>Chitosan film</b>	20% Methanol PPE/ (0.03%)	<i>In vitro</i>	Inhibition zones were 8.0 and 8.5 against <i>E. coli</i> and <i>Bacillus cereus</i> , respectively.	[71]
<b>Fish Gelatin- κ-Carrageenan coatings (Gf-Cr)</b>	PPE (1.5, 2.0%)	<i>In vivo</i> ( Fish Fillet)	The Gf-Cr coatings with 1.5, 2.0% PPE caused complete inhibition of psychrotrophic bacteria, yeast, and mold, and <i>Enterobacteriaceae</i> throughout a 30 d of storage time at 4 °C.	[72]

**2% Methanol PPE/ Chitosan coating, 9% Gelatin coating** (2.5,5.0, and 10.0%) (Medjool dates) *In vitro* and *in vivo*

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]

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**2% Methanol PPE/ Chitosan coating, 9% Gelatin coating** (2.5,5.0, and 10.0%) (Medjool dates) *In vitro* and *in vivo*

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* was significantly decreased by 1.3 log CFU/g to >4.5 log CFU/g [48]

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by day 56. While the pathogen was not detected (<1 CFU/15 g) at 24°C.

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When adding PPE to edible films and coatings, a number of practical restrictions must be taken with account despite its proven antibacterial capabilities. 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, phenolic chemicals in PPE may interact with biopolymer matrices like chitosan, gelatin, or starch, thereby influencing the final coating's mechanical characteristics, flexibility, and barrier effectiveness [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].

## **Conclusion**

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 position PPE as a valuable bioactive ingredient for the development of eco-friendly packaging systems that align with the increasing global demand for sustainable food solutions.

Despite its promising potential, several knowledge gaps 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 explore large-scale extraction feasibility, encapsulation or controlled-release systems, migration behavior in packaging materials, and comprehensive sensory and shelf-life assessments across diverse food categories.

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). Advancing our understanding of PPE's functional properties will further strengthen its role in the development of safer, more sustainable, and environmentally responsible food packaging systems.

## List of Abbreviations

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

## Author Contributions

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## Conflict of Interest

The authors declare no competing financial or personal interests.

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