Agri Articles
(e-Magazine for Agricultural Articles)
Volume: 06, Issue: 06 (NOV-DEC, 2026)
Available online at http://www.agriarticles.com
©Agri Articles, ISSN: 2582-9882

Pomegranate Peel Powder in Sustainable Food Packaging: Antioxidant and Antimicrobial Properties, Functional Applications, and Future Perspectives

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The increasing amount of waste from traditional plastic packaging has aided in the development of sustainable and bio-based food packaging materials. Pomegranate (*Punica granatum* L.) peel, a major fruit processing by-product, is a promising source of naturally occurring bioactive compounds that can be utilized in active food packaging systems. The peel contains polyphenols, tannins, flavonoids, and other compounds with antioxidant and antimicrobial qualities. To improve the functional performance of packaging materials and raise the value of agricultural waste, pomegranate peel powder can be added to biodegradable film-forming matrices. Pomegranate peel powder and its extracts have previously been investigated in protein-based, chitosan, fish gelatin, and synthetic biodegradable polymer films. The effects that have been documented include free-radical scavenging activity, inhibition of particular microorganisms, changes in the film's color and opacity, and modifications to its mechanical and barrier qualities. However, the outcomes are influenced by the peel material concentration, polymer composition, processing conditions, and interactions between the bioactive compounds and the packaging matrix. This review summarizes the phytochemical properties of pomegranate peel, its role in active packaging, the key findings of published research, and the challenges with practical application. Further research is required to ascertain the food safety, migration behaviour, biodegradability, sensory acceptability, and commercial viability of pomegranate peel-based packaging systems.

Keywords: Pomegranate peel powder; active food packaging; biodegradable films; antioxidant activity; antimicrobial activity; agricultural waste valorization; sustainable packaging.

Introduction

Food packaging is crucial for shielding food items from microbial contamination, oxygen exposure, moisture transfer, and physical harm. The low cost, flexibility, and barrier performance of conventional plastic materials make them popular. However, interest in renewable and biodegradable substitutes has grown due to the persistence of plastic waste in the environment. For some food applications, bio-based packaging materials made from proteins, polysaccharides, lipids, and agricultural byproducts are being researched as possible substitutes. Large amounts of peels, seeds, and other residues are produced by the fruit processing industries. These materials contain compounds that can be recovered and used in food, pharmaceutical, cosmetic, and packaging applications, despite the fact that many of them are thrown away. the packaging industry is increasingly embracing bio-based and biodegradable materials. These sustainable alternatives are designed to decompose naturally, minimizing their impact on landfills and reducing the accumulation of microplastics in the environment. Bio-based packaging materials such as edible films, biodegradable films, and

compostable materials derived from plant sources have emerged as promising solutions due to their ability to blend environmental safety with functional properties required for effective food preservation. Edible coatings and films can be directly applied to food surfaces, providing an additional layer of protection against oxidation, moisture loss, and microbial contamination while enhancing the product's shelf life. Moreover, recent advancements in active and intelligent packaging systems further enhance the functionality of bio-based materials. As defined in the European regulation (EC) No 450/2009, active packaging comprises packaging systems that interact with the food in such a way as to "deliberately incorporate components that would release or absorb substances into or from the packaged food or the environment surrounding the food." Active packaging materials, which incorporate additives like antioxidants and antimicrobial agents, help maintain food quality and safety over extended periods. Recently, particular interest has been given to the development of antioxidant and antimicrobial enriched active packaging. Intelligent packaging systems, on the other hand, monitor and communicate food freshness through indicators, providing consumers with real-time information about the product's condition. Bioactive compounds from natural sources, such as plant extracts and essential oils, are frequently incorporated into these packaging systems to replace synthetic additives, creating "natural" active packaging solutions that meet consumer preferences for clean-label products for an extended period of time.

Fruit and vegetable by-products are increasingly recognized for their potential as sources of bioactive compounds for sustainable packaging applications. It has been observed that around 25%–30% of waste is generated from fruit processing industries. These by-products contain a high concentration of valuable phytonutrients, including phenolic compounds, flavonoids, and dietary fibers, often in higher concentrations than those found in the edible portions of the fruit. Researchers have demonstrated that these compounds can effectively replace artificial additives in packaging materials, providing antioxidant and antimicrobial effects that help extend the shelf life of food products while reducing the reliance on petrochemical-derived components. Among these by-products, pomegranate peel (PoP), a common waste from the pomegranate juice industry, has emerged as a particularly promising material for sustainable packaging. In India, most of the produce is used for table consumption, and around 15%–20% of the fresh pomegranate produce loses marketability and consumer acceptability due to postharvest losses. Pomegranate's rind and seeds, which account for roughly 54% of the fruit, are the waste components of pomegranate after juice extraction. Fruits with disorders such as cracks or splits, sunburned husks, etc., which reduced the overall appearance of the fruit, can be directly used for processing into value added products due to their health-promoting properties like antioxidant, antimicrobial, antiviral, and anti-inflammatory activities. By harnessing bioactive compounds present in waste or byproducts, sustainable packaging alternatives can be developed that not only enhance food preservation but also contribute to reducing the reliance on synthetic packaging materials. Furthermore, many researchers found that the antioxidant activity of PoP was higher than the flesh. The incorporation of such compounds modifies the structure of films which improves their functionality for food applications. This dual function of reducing waste and creating eco-friendly packaging solutions is a crucial step toward a circular economy in the food industry. While numerous studies have explored the extraction and application of bioactive compounds from PoPs in sustainable packaging solutions, several key areas remain underexplored. Most studies focus on optimizing extraction techniques and evaluating the basic mechanical and antibacterial properties of PoP-based materials. However, there is limited research on the scalability of these extraction processes for industrial applications. Moreover, the long-term stability, shelf-life, and real-world performance of packaging materials made from PoPs compounds, especially in different food storage environments, have not been thoroughly investigated. Additionally, there is a lack of studies on the integration of PoPs extracts with other bioactive materials to further enhance functional properties such as antioxidant and antimicrobial activity. The economic viability and potential regulatory hurdles for widespread adoption in the packaging industry also require more attention. The objective of this review is

to provide a comprehensive analysis of the extraction methods used for isolating bioactive compounds from PoP, evaluating both conventional and eco-friendly approaches. The review aims to compare the extraction efficiency, yield, and the qualitative and quantitative characteristics of the recovered compounds to identify the most suitable methods for various applications. Furthermore, the paper seeks to explore the current and potential applications of these bioactive compounds in sustainable packaging solutions, including biodegradable films, coatings, and bioactive additives. By analyzing the performance and properties of these materials, the review will highlight key areas for future research, focusing on improving scalability, stability, and market integration of PoP-based packaging solutions.

Phytochemical Composition of Pomegranate Peel

Pomegranate peel contains a variety of phenolic compounds, including hydrolysable tannins, ellagitannins, punicalagin-related compounds, ellagic acid, and flavonoids. These constituents are associated with the antioxidant potential of pomegranate-derived materials. Phenolic compounds may contribute to free-radical scavenging through their chemical structures and their capacity to participate in oxidation-reduction reactions. Certain phenolic compounds may also interfere with microbial growth under appropriate experimental conditions. The concentration and composition of these compounds are influenced by cultivar, fruit maturity, growing conditions, drying temperature, storage conditions, particle size, and extraction procedure. Consequently, peel powder obtained from different sources may not demonstrate identical functional properties. In food packaging, the bioactive compounds may interact with the film-forming material through hydrogen bonding and other intermolecular interactions. Such interactions can influence film structure, strength, flexibility, water sensitivity, and the release of bioactive substances. It is important to distinguish between the chemical composition of the original peel and the properties of a finished packaging film. The presence of phenolic compounds in raw peel does not automatically establish that the final film will provide sufficient antioxidant or antimicrobial protection during food storage.

Incorporation of Pomegranate Peel Powder into Packaging Films

Integrating pomegranate peel extract (PPE) into biodegradable packaging materials offers promising potential for sustainable and eco-friendly food preservation. Derived from pomegranate peel, a byproduct of juice production, PPE is rich in bioactive compounds such as polyphenols, flavonoids, and tannins, which are known for their potent antioxidant effects. These compounds help extend the shelf life of packaged food by delaying oxidative degradation, thus enhancing packaging functionality. Studies have highlighted the antioxidant potential of PPE-enriched films; for instance, reported that incorporating PPE into edible chitosan films increased antioxidant activity to 66.42% effectiveness, compared to 27.44% in films treated with standard butylated hydroxyanisole. Similarly, Bertolo et al.118 found that chitosan/gelatin gels with PPE displayed significantly enhanced antioxidant capacity due to the high PC of the extract. Further research by showed improved antioxidant effects when pomegranate peel powder (PPP) was incorporated into chitosan films. Likewise, It was demonstrated that k-carrageenan films with PPE exhibited higher DPPH radical scavenging activity than those containing pomegranate flesh extract (PFE), highlighting the potent antioxidant properties of PPE. Studies by found that apricots treated with nano-chitosan coatings containing PPE had greater antioxidant activity, largely due to biologically active compounds such as phenolic compounds, anthocyanins, and punicalagin. Beyond antioxidant protection, PPE also provides strong antimicrobial benefits, which contribute to food safety and extended freshness. The antimicrobial activity of PoP is attributed to its polyphenolic compounds, including flavonoids, phenolic acids, and tannins (e.g., punicalagins, gallic acid, and alginic acid), which work synergistically to inhibit microbial growth. These polyphenols disrupt bacterial cell walls and interfere with bacterial proteins, leading to cell death. Additionally, hydroxyl groups in these compounds reduce the pH around bacterial cells, further hindering microbial metabolism. In practical applications, PPE-enriched coatings have demonstrated substantial antimicrobial efficacy. For example, a nano-chitosan coating with

PPE applied to apricots significantly reduced decay, weight loss, and maintained firmness and antioxidant activity over a 30-day period at 4°C. Likewise, pectin based PPE edible coatings on energy bars have shown to extend shelf life by leveraging PPE's natural antimicrobial properties, effectively inhibiting spoilage-causing bacteria such as *Staphylococcus aureus* and *Escherichia coli*. Yang et al. reported that chitosan films with 10 g/L of PPE exhibited significant inhibitory effects against *S. aureus*, enhancing the preservation of food items. In another study, observed that active films composed of chitosan and polyvinyl alcohol with aqueous PPE not only improved UV protection but also reduced *S. aureus* counts by 2 log cycles and inhibited B. cereus growth. Tarkhasi found that incorporating a 5% PPE concentration in coatings for silver carp fish effectively extended shelf life by lowering the total viable bacterial count and delaying lipid oxidation. Incorporating PPE into biodegradable packaging also supports sustainability and circular economy goals by repurposing an agricultural byproduct that would otherwise go to waste. By turning PoP into biodegradable packaging materials, environmental waste is reduced, offering an eco-friendly alternative to traditional plastics. Biodegradable materials derived from plant-based polymers or algae naturally decompose, minimizing non-biodegradable waste accumulation and promoting an eco-conscious solution. Baniasadi et al. developed PoP extract-infused carboxymethyl cellulose composite films. The life cycle assessment highlighted the reduced environmental impact, showing a 59% reduction in ecological footprint due to the functional improvements from polyethylene (PE) and clay.

Antioxidant Properties of Pomegranate Peel-Based films

One of the essential chemical elements which is very important in the metabolism of aerobic organisms is oxygen, but it can also cause adverse reactions. Free radicals, which are reactive oxygen species (ROS), often react with different molecules such as proteins, lipids, DNA, and RNA and can damage them. They can also cause diseases such as cancer, diabetes, arthrosclerosis, neurodegenerative diseases and premature aging. In addition to the human body, oxidation reactions occur in many food products that are exposed to oxygen, light, or heat, leading to reduced shelf-life and nutritional value of products, as well as changes in their taste and color. Antioxidants can protect cells by various mechanisms such as forming non-radical species from ROS and reducing oxygen concentration, thus being very important in maintaining the quality of products. Food products are not available to consumers for consumption immediately after production; rather this process takes time and these products must maintain their original quality and be safe when consumed. Since oxidation affects product quality, delaying the oxidation of biomolecules by antioxidants is an effective strategy in maintaining product quality and can be used as a protective mechanism in food storage. Synthetic antioxidants such as tert-butyl hydroquinone (TBHQ), propyl gallate (PG), butylated hydroxytoluene (BHT), and butylated hydroxyanisole (BHA) have been used excessively in the food industry due to their higher stability and performance, low cost, and availability However, recent studies have shown that their long-term use can cause skin allergies, gastrointestinal tract problems, cancer, premature aging, and DNA damage. Natural antioxidants can be good alternatives to synthetic antioxidants. They are mostly extracted from plant materials such as vegetables, spices, fruits, and herbs they are classified into three main categories: phenolic compounds, carotenoids, and vitamins. Some studies have reported that non-edible parts of fruits often have higher bioactive contents than edible parts. Pomegranate is a fruit rich in antioxidants; with each ton of pomegranate juice producing 9 tons of by-products that are a good source of functional com pounds. Pomegranate peel, which is considered as an agricultural waste, is a great source of bioactive compounds and has several health benefits due to its polyphenolic components such as tannins and flavonoids, anthocyanins, alkaloids, and organic acids. These natural antioxidants, which are found in various parts of the plants including leaves, roots, stems, fruits, seeds and peels, should be extracted for further uses. The most common method is extraction with organic solvents. Other methods such as extraction with supercritical fluids, microwaves, high hydrostatic pressure, and ultrasound can also be employed. Utilization of antioxidants in the food industry as

preservatives can be in food matrices, food packaging coatings, and films High amounts of oxygen transfer in the packaging cause oxidation and affect the taste, color, as well as texture of the food product. As a solution, antioxidant active packaging can remove oxygen from the head space or release antioxidants into the package. This type of active packages can be in the form of independent antioxidant devices (sachets, pads, or labels with antioxidant agents) or antioxidant pack aging materials which can be placed into the walls of the films or inside the product container. To measure the antioxidant capacity, the oxidation rate of chemicals such as DPPH (2,2-diphenyl-2-picrylhydrazyl), TBARS (2-thiobarbituric acid substances), AAPH (2,2′-azobis(2-methyl-propionamidine) dihydrochloride), and ABTS (2,2′-azino-bis(3-ethyl benzothiazoline-6-sulfonic acid)) which are exposed to antioxidants is determined. According to the points mentioned above, it is important to prevent oxidation of food products where pomegranate peel extract (PPE) have been demonstrated to be a good source of antioxidants and can be used in active packaging.

Antimicrobial Properties and Food Preservation

Pomegranate peel extract (PPE) is rich in bioactive compounds, especially polyphenols, flavonoids, phenolic acids, and tannins, it has strong antimicrobial activity. By compromising the integrity of cell walls, increasing the permeability of cell membranes, interfering with cellular metabolism, and preventing microbial adhesion, these substances prevent the growth of microorganisms. PPE is effective against a variety of Gram-positive and Gram-negative bacteria, including Bacillus subtilis, Escherichia coli, and Staphylococcus aureus, as well as fungi like Aspergillus niger, according to numerous studies. Additionally, adding PPE to edible coatings and biodegradable films—especially those made of chitosan, gelatin, has demonstrated encouraging outcomes in lowering microbial growth and prolonging food product shelf life. PPE is therefore a promising natural antimicrobial agent for enhancing food safety, maintaining quality, and reducing dependence on artificial preservatives.

Effects on Physical and Mechanical Properties

Physical and Mechanical Properties: The change of the physical and mechanical properties of edible packaging, such as tensile strength, Young's modulus and elongation at break, are dependent on the interactions between the polymers and additives. The decreasing strength of mechanical properties can be attributed to free volume and molecular mobility in these systems (He, Lan, Ahmed, Qin, & Liu, 2019). Previous findings have indicated that incorporating pomegranate peel extract increases the moisture and swelling index of edible.

Thickness of the film: The thicknesses of the fish gelatin films containing PPP are presented in Table 1. The results showed that the thickness of the film increased significantly ($p < 0.05$) when the content of PPP was increased from 1% to 2%, and the thicknesses were 72.50 and 83.75 µm, respectively. Increasing the concentration of PPP from 3% to 5% also increased the thickness, from 103.75 to 106.25 µm, but no significant difference ($p > 0.05$) was observed.

Edible packaging enriched with pomegranate peel extract – A case of active packaging: Edible coatings and films enriched with pomegranate peel extract can also enhance the shelf life of food products due to the control of the respiration rate, minimization of oxidative stress, decreased loss of color, flavour, and other sensory attributes of packed items.

Applications in Food Packaging

1. **Meat and Meat Products:** Meat and meat products are high moisture content, nutrient composition, and environmental sensitivity, meat and meat products are particularly vulnerable to microbial deterioration and lipid oxidation during storage. Thus, pomegranate peel powder (PPP) or pomegranate peel extract (PPE) active packaging has been studied as a possible strategy for preserving meat quality and prolonging storage life. Phenolic compounds with antimicrobial and antioxidant qualities found in pomegranate peel can be added to edible coatings and biodegradable films.
2. **Fresh-Cut Fruits and Vegetables:** After cutting, the internal tissues of fresh-cut fruits and vegetables are exposed to air, moisture loss, and microbial contamination, which quickly

degrades their quality. Pomegranate peel powder or extract-containing edible coatings and active packaging may help preserve the quality of these goods by adding antibacterial or antioxidant compounds and providing a protective barrier.

3. **Dairy Products and Other Perishable Foods:** In order to prevent microbial contamination, oxidation, and unwanted changes during storage, dairy products and other perishable goods need to be packaged appropriately. Because pomegranate peel extract can have antibacterial and antioxidant properties when added to a suitable polymer matrix, it has drawn attention as an active component in edible films. Products whose quality is impacted by oxidation or surface microbial development may benefit from such films.

Environmental Benefits and Waste Valorization

Pomegranate peel presents an opportunity to transform an agricultural by-product into a more valuable material when used as a packaging ingredient. This strategy promotes the recovery and use of materials that might otherwise be thrown away, which is consistent with the principles of the circular economy. However, just because a movie uses natural ingredients doesn't mean it will be environmentally beneficial. Energy consumption during drying and processing, solvent use, transportation, packaging performance, end-of-life treatment, and whether the material is truly biodegradable under pertinent circumstances all affect the final result. Moreover, a film that contains peels is not always suitable for edible use or composting. Appropriate testing and adherence to relevant standards and regulations are necessary for these claims.

Conclusion

Increasing demands for consumption safe food products had led to emergence of developed packaging methods. Packaging is one of the main processes in food production that is effective in maintaining food quality and safety, prolonging shelf-life and enhancing its organoleptic properties. Active packaging using functional compounds of plants, is a new packaging technology. PPE contains large amounts of phenolic and bioactive substances that have functional properties such as antioxidant and antimicrobial properties. This has been proven many times in numerous studies. The presence of these substances has led to the use of this extract in applications related to human health as supplements and therapeutic properties, as well as use in food science, including food packaging. PPE increases the shelf life of meat, dairy products, fruits, etc. For this reason, this combination has been used many times as an effective ingredient in the composition of food packaging films or coatings. This review summarizes the effect of using PPE as a bioactive compound on the antioxidant, antimicrobial, microstructure and physical properties including thickness, WVP, mechanical properties, optical properties and thermal properties of packaging films. Results of the research indicate that produced films' properties have been affected by PPE and have been improved in some cases. Pomegranate peel is a waste that is not normally consumed by humans. The analyzes carried out by the researchers have shown that the pomegranate peel waste has materials with suitable properties for use in food packaging. PPE has shown high potential in the production of packaging films, both in physical and mechanical properties, as well as in antioxidant and antimicrobial properties. Considering that this material is a waste and the cost of its preparation is low, and it also has the capability of a conversion process, its use in the food industry, especially in food packaging, to maximize the advantageous properties of pomegranate peel in relation to emerging trends in active edible packaging and sustainable food processing technology, it is imperative that future research concentrates on ascertaining the most favorable levels or proportions of pomegranate peel extract, as well as its potential synergistic effects with different edible matrices. The use of this material on an industrial scale for this purpose and also to reduce the produced waste should also be considered. In addition, via the reduction of biowaste items within supply chains, the need for landfill disposal will be reduced.

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