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THE POTENTIAL OF POMEGRANATE PEEL POLYPHENOLS IN THE DEVELOPMENT OF SAFE FUNCTIONAL FOODS: A SYSTEMATIC ANALYSIS

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Abstract: Pomegranate peel, which is usually generated as a by-product during juice and fruit processing, has recently attracted considerable scientific attention as a source of natural polyphenols, dietary fiber, organic acids, tannins, flavonoids, and mineral substances. The present article analyzes the potential of pomegranate peel as a functional food ingredient and natural biopreservative. The study was designed as a literature-based analytical review using scientific publications devoted to the phytochemical composition, antioxidant potential, antimicrobial activity, technological applicability, and safety aspects of pomegranate peel. The reviewed data show that pomegranate peel contains biologically active compounds such as punicalagin, ellagic acid, gallic acid, catechins, and hydrolysable tannins, which are responsible for its antioxidant, antimicrobial, anti-inflammatory, and preservative effects. These properties make pomegranate peel a promising natural alternative to synthetic additives in meat, dairy, bakery, and beverage products. At the same time, the practical application of pomegranate peel requires careful standardization of extraction methods, sensory acceptability, dosage, and toxicological safety. The findings support the concept of transforming pomegranate peel from agricultural waste into a high-value ingredient for functional food production and sustainable food technology.

Keywords: are pomegranate peel, Punica granatum, polyphenols, functional food, natural preservative, antioxidant activity, antimicrobial activity, sustainable food technology.

INTRODUCTION

The modern food industry is increasingly focused on the development of safe, natural, and biologically active ingredients that can improve both the nutritional value and shelf life of food products. This tendency is closely connected with consumer demand for products containing fewer synthetic additives and with global efforts to reduce food waste. In this context, fruit-processing by-products have become an important object of scientific and technological interest, because many of them contain concentrated amounts of bioactive compounds that remain underused in conventional production chains [1,2].

Pomegranate, known botanically as Punica granatum L., is one of the oldest cultivated fruits in the world. It is valued not only for its pleasant sensory properties but also for its traditional medicinal significance and its rich composition of polyphenols, organic acids, vitamins, minerals, and dietary fiber [3,4]. During the production of juice, concentrates, jams, and other processed products, a substantial amount of peel is separated from the edible arils. For many years, this peel was considered mainly as agricultural waste. However, recent studies have shown that pomegranate peel is often richer in phenolic compounds than the edible pulp and juice, which gives it considerable biological and technological value [1,5].

The peel of pomegranate contains hydrolysable tannins, especially punicalagin and punicalin, as well as ellagic acid, gallic acid, catechins, anthocyanins, and other phenolic substances. These compounds are associated with antioxidant, antimicrobial, anti-inflammatory, and potential therapeutic effects [6,7]. The antioxidant capacity of pomegranate peel has been confirmed by different in vitro methods, including DPPH, ABTS, FRAP, and ORAC assays [6,8]. Antimicrobial effects have also been reported against several foodborne microorganisms, including Escherichia coli, Staphylococcus aureus, Salmonella species, and other pathogens relevant to food safety [9].

The use of pomegranate peel as a food ingredient is scientifically attractive for several reasons. First, it may serve as a natural antioxidant capable of slowing lipid oxidation in products with high fat content. Second, its antimicrobial activity may contribute to the control of microbial spoilage. Third, the dietary fiber fraction of pomegranate peel may improve the functional value of foods. Fourth, its use is consistent with the principles of circular economy and sustainable food production, because it transforms a low-value by-product into a functional raw material [1,2,10].

Despite these advantages, pomegranate peel cannot be introduced into food production without critical evaluation. The high tannin content may influence taste, color, astringency, and consumer acceptance. In addition, different drying methods, extraction solvents, temperature regimes, and storage conditions may change the concentration and stability of bioactive compounds [2,11]. Therefore, a scientifically grounded approach is required to determine where and how pomegranate peel can be used most effectively.

Morphologically, the pomegranate fruit has a complex structure consisting of a hard outer peel, internal membranes, and seeds. The fruit contains carbohydrates, organic acids, vitamins (mainly vitamin C), mineral substances, and biologically active compounds [3,4]. In addition, numerous studies have reported that pomegranate fruit has high nutritional and dietary value [4,5]. (Figure 1)

The purpose of this article is to analyze the potential of pomegranate peel polyphenols as natural biopreservatives and functional ingredients in food products. The article also discusses the phytochemical basis of its biological activity, reviews its possible applications in different food systems, and evaluates the main technological and safety-related limitations.

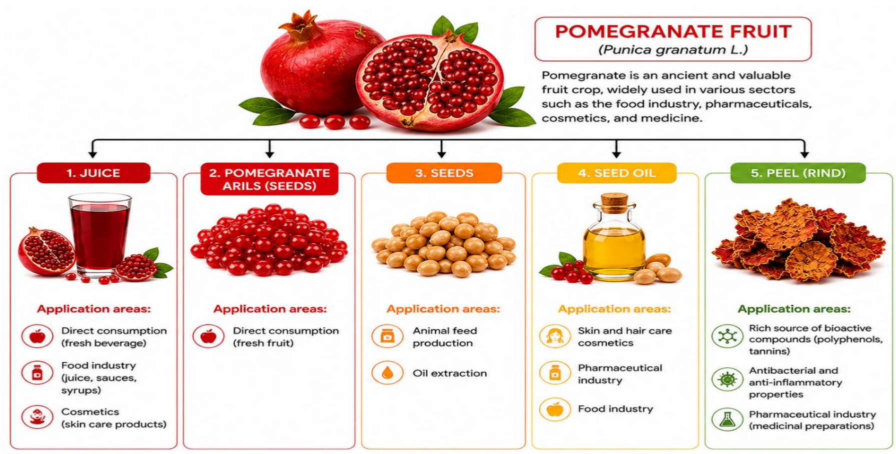

Figure 1. Products obtained from pomegranate fruit and their characteristics

MATERIALS AND METHODS

This article was prepared as a literature-based analytical review. Scientific publications on pomegranate peel, Punica granatum L., polyphenols, antioxidant activity, antimicrobial properties, functional foods, natural preservatives, and sustainable food processing were analyzed. The review included experimental studies, review articles, and applied food technology studies published in peer-reviewed journals.

The selection of literature was guided by thematic relevance. Priority was given to studies that described the chemical composition of pomegranate peel, the role of phenolic compounds, antioxidant and antimicrobial assays, food preservation effects, extraction and drying methods, and potential health-related applications. The analysis also included publications discussing the wider concept of using agro-industrial by-products in functional food development.

The methodological approach was based on comparative interpretation of published data rather than on laboratory experimentation. The reviewed studies were grouped into several analytical directions. The first direction concerned phytochemical composition. The second direction focused on antioxidant and antimicrobial activity. The third direction considered the technological use of pomegranate peel in food products. The fourth direction addressed safety, dosage, sensory acceptability, and future research needs.

LITERATURE REVIEW

Scientific interest in pomegranate peel has increased because this by-product contains a broad spectrum of biologically active substances. Azmat et al. emphasized that pomegranate peel and its extracts may be used as functional foods, food additives, and nutraceutical components due to their phenolic acids, flavonoids, minerals, and hydrolysable tannins [1]. Magangana et al. further noted that processing conditions, including drying and extraction, significantly affect the preservation of phytochemicals and nutritional properties in pomegranate peel waste [2].

Earlier reviews also described pomegranate as a fruit with multiple functional components related to human health. Viuda-Martos et al. reported that pomegranate contains several compounds with antioxidant and anti-inflammatory potential, and that its by-products may be important for the food industry [3]. Akhtar et al. analyzed the chemistry and food-related features of pomegranate peel and concluded that it has promising value as a functional ingredient because of its polyphenol-rich profile [4].

The antioxidant activity of pomegranate peel has been repeatedly confirmed. Singh et al. demonstrated strong antioxidant activity of pomegranate peel and seed extracts using in vitro models, showing that the peel fraction is an especially important source of radical-scavenging compounds [6]. Li et al. compared pomegranate peel extract with pulp extract and showed that peel extract had stronger antioxidant properties, which supports the view that processing waste may have higher bioactive value than some edible parts of the fruit [7].

Antimicrobial activity is another key reason for considering pomegranate peel as a natural preservative. Al-Zoreky found that pomegranate peel extracts inhibited several pathogenic and spoilage microorganisms, indicating their possible use in food preservation [9]. Gullón et al. also showed that pomegranate peel flour obtained from juice extraction co-products had a valuable polyphenolic profile and antibacterial activity [5]. These findings are particularly relevant because modern food production seeks safer and more acceptable alternatives to synthetic preservatives.

In addition to food preservation, pomegranate peel has a long history in traditional medicine. Lansky and Newman reviewed the ethnopharmacological and biomedical significance of pomegranate and described its potential role in inflammation-related conditions [12]. Seeram et al. showed that punicalagin, ellagic acid, and total pomegranate tannin extract possess antioxidant and antiproliferative activities in vitro [13]. However, these biomedical findings should be interpreted carefully, because food application does not automatically mean therapeutic efficacy in humans.

From the technological perspective, the preservation of bioactive compounds depends strongly on processing methods. Mphahlele et al. showed that drying can influence antioxidant, antibacterial, and other bioactivities of pomegranate peel [11]. This means that the same raw material may have different functional value depending on whether it is shade-dried, oven-dried, freeze-dried, extracted with water, extracted with ethanol, or processed into powder. Therefore, standardization is one of the central conditions for practical application.

RESULTS

The literature analysis demonstrates that pomegranate peel has four main characteristics that make it suitable for functional food and natural preservation technologies. These characteristics are its high polyphenol content, strong antioxidant capacity, antimicrobial action, and compatibility with sustainable use of agro-industrial by-products.

The first major finding is that pomegranate peel is a concentrated source of phenolic compounds. Punicalagin, ellagic acid, gallic acid, and other tannins are repeatedly mentioned as the main contributors to its biological activity [1,4,6]. These compounds can donate electrons or hydrogen atoms, neutralize free radicals, and reduce oxidative chain reactions. This mechanism is especially important in foods that are sensitive to lipid oxidation, such as meat products, dairy products enriched with fats, and some bakery formulations.

The second finding is that pomegranate peel has strong antioxidant activity in laboratory models. Studies using DPPH, ABTS, FRAP, and related methods consistently show that peel extracts possess high radical-scavenging and reducing capacity [6,7,8]. Although values differ between studies, the general trend is clear. Extracts with higher total phenolic content usually show stronger antioxidant activity. This relationship supports the use of pomegranate peel as a natural antioxidant ingredient.

The third finding is related to antimicrobial properties. Pomegranate peel extracts have shown inhibitory effects against several microorganisms associated with food spoilage and foodborne disease [5,9]. The antimicrobial mechanism is usually explained by the ability of tannins and phenolic compounds to interact with microbial cell walls, disturb membrane permeability, bind proteins, and interfere with microbial enzymes. Such effects may reduce the growth of bacteria and fungi in selected food systems.

The fourth finding is that processing conditions determine the final quality of pomegranate peel products. Drying temperature, particle size, solvent type, extraction time, and storage conditions may either preserve or reduce the concentration of bioactive substances [2,11]. High temperatures may accelerate degradation of heat-sensitive compounds, whereas inappropriate storage may reduce antioxidant potential. Therefore, the practical use of pomegranate peel requires controlled technological procedures.

The fifth finding concerns the functional food value of pomegranate peel. Besides polyphenols, it contains dietary fiber and mineral substances, which may contribute to the nutritional profile of enriched products [1,3]. When used in appropriate amounts, pomegranate peel powder may improve the fiber content of bakery products, fermented dairy products, and other foods. However, excessive addition may negatively affect taste and texture due to bitterness and astringency.

DISCUSSION

The transformation of pomegranate peel from waste into a functional food ingredient reflects one of the most important directions in modern food science. Food systems are under pressure to become safer, healthier, and more sustainable. At the same time, food manufacturers must maintain sensory quality, economic efficiency, and consumer acceptance. Pomegranate peel offers a promising but complex solution to these challenges.

The strongest argument for the use of pomegranate peel is its antioxidant potential. Lipid oxidation is one of the main causes of quality deterioration in many food products. It leads to unpleasant flavor, color changes, nutrient loss, and reduced shelf life. Synthetic antioxidants have been widely used to control oxidation, but consumer preference is shifting toward natural alternatives. Pomegranate peel polyphenols may help address this demand because they can neutralize free radicals and slow oxidative processes [6,7].

The antimicrobial potential of pomegranate peel is also important. Food spoilage and contamination remain major problems in the food industry. Natural antimicrobial agents are especially valuable when they can reduce microbial growth without introducing undesirable chemical residues. The inhibitory effects reported for pomegranate peel extracts suggest that they may be useful in selected food systems, particularly when combined with other preservation methods such as refrigeration, modified atmosphere packaging, fermentation, or mild heat treatment [5,9].

However, the effectiveness of pomegranate peel should not be overstated. Results obtained in laboratory assays do not always translate directly into complex food matrices. Proteins, fats, carbohydrates, pH, water activity, and storage temperature can influence the behavior of polyphenols. For example, tannins may bind to proteins, which may reduce antimicrobial activity or change texture. Therefore, each product type requires separate optimization.

Meat products are among the most relevant areas for application. Oxidation and microbial spoilage are common quality problems in meat systems. Pomegranate peel extract may reduce oxidative rancidity and contribute to microbial control. Its natural reddish-brown pigments may also influence product color. This can be beneficial in some formulations, but undesirable in others. Therefore, the concentration of the extract must be selected carefully.

Dairy products represent another promising direction. Fermented milk products enriched with plant polyphenols may gain improved antioxidant value. At the same time, interactions between polyphenols and milk proteins can affect viscosity, stability, and taste. Pomegranate peel may support the development of functional yogurts or fermented beverages, but its astringent taste must be balanced through formulation design.

Bakery products may benefit from pomegranate peel powder as a source of dietary fiber and phenolic compounds. Small amounts may improve antioxidant value and contribute to the development of healthier products. However, high levels may darken the product, change crumb structure, and reduce consumer acceptability. This means that technological trials are required before industrial application.

Beverages are another area of interest because pomegranate peel extracts can provide color, acidity, and antioxidant capacity. Nevertheless, bitterness and astringency are significant limitations. Encapsulation, controlled extraction, blending with fruit juices, or fermentation may reduce these sensory problems and improve acceptability.

The safety aspect deserves special attention. Natural origin does not automatically mean complete safety. Pomegranate peel contains high levels of tannins, and excessive consumption may cause undesirable effects. In addition, extracts prepared with different solvents may contain different concentrations of active compounds. Therefore, food-grade extraction, toxicological evaluation, and dosage standardization are necessary before large-scale use [4,11].

Another important issue is standardization. Different studies use different pomegranate varieties, extraction methods, drying temperatures, and analytical methods. This makes comparison difficult. A peel extract obtained by ethanol extraction from one variety cannot be considered identical to a water extract obtained from another variety. For this reason, future research should focus on developing standardized indicators such as total phenolic content, punicalagin concentration, antioxidant capacity, microbial inhibition values, and sensory thresholds.

From an environmental perspective, the use of pomegranate peel has strong advantages. It reduces organic waste and creates additional value for fruit-processing enterprises. This is consistent with the concept of circular economy, where by-products are returned to the production chain as valuable resources rather than discarded [10]. For countries where pomegranate cultivation is common, including Central Asian regions, this approach may also have local economic importance.

The medical and nutraceutical potential of pomegranate peel should be discussed cautiously. Many studies describe antioxidant, anti-inflammatory, antimicrobial, and metabolic effects of pomegranate compounds [12,13,14]. However, food products enriched with pomegranate peel should not be presented as medicines unless clinical evidence and regulatory approval support such claims. A scientifically correct approach is to describe pomegranate peel as a functional ingredient with potential health-supporting properties rather than as a direct therapeutic agent.

CONCLUSION

Pomegranate peel is a valuable agro-industrial by-product with considerable potential for functional food development and natural preservation technologies. Its biological and technological value is mainly related to its high content of polyphenols, including punicalagin, ellagic acid, gallic acid, catechins, and hydrolysable tannins. These compounds provide antioxidant and antimicrobial properties that may help improve food stability, reduce oxidative deterioration, and support the development of natural preservative systems.

The literature analysis shows that pomegranate peel may be used in meat, dairy, bakery, and beverage products as a source of natural antioxidants, antimicrobial substances, dietary fiber, and bioactive compounds. At the same time, practical use requires careful attention to extraction method, drying conditions, dosage, sensory acceptability, and safety. Excessive tannin content may negatively influence taste and consumer acceptance, while insufficient standardization may lead to unstable technological results.

Overall, pomegranate peel represents a scientifically promising raw material for the “waste-to-value” approach in food technology. Its use may contribute to healthier food products, reduced dependence on synthetic additives, and more sustainable processing of fruit by-products. Future studies should focus on standardized extraction methods, clinical safety evaluation, product-specific formulation, and industrial-scale application.

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