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Pomegranate (*Punica granatum* L.) and Its Bioactive Components: Composition, Biological Activities, and Applications in Food, Pharmaceutical, and Nutraceutical Fields

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Abstract:

Pomegranate (*Punica granatum* L.) is a nutritionally rich fruit widely recognized for its diverse therapeutic properties and extensive applications in food, pharmaceutical, and cosmetic industries. This review provides a comprehensive overview of the composition, bioactive constituents, and biological activities of different parts of the fruit, including arils, seeds, and peel. Pomegranate is abundant in polyphenols such as ellagitannins (punicalagin and punicalin), ellagic acid, flavonoids, and anthocyanins, which contribute significantly to its pharmacological effects. The arils are a rich source of sugars, vitamins, and antioxidants, exhibiting strong antioxidant, antimicrobial, and prebiotic activities. Seeds contain bioactive lipids, particularly punicic acid, associated with anti-inflammatory, cardioprotective, antidiabetic, and anticancer effects. The peel, often considered agro-industrial waste, is highly enriched with phenolic compounds and demonstrates potent antioxidant, antimicrobial, antiviral, and anti-inflammatory properties. Recent advances in extraction techniques and nanoformulation strategies have further enhanced the bioavailability and applicability of these bioactive compounds. Overall, pomegranate and its by-products represent valuable natural resources with significant potential for the development of functional foods, nutraceuticals, and therapeutic agents. Further research is required to optimize extraction methods, understand molecular mechanisms, and explore clinical applications.

Keywords

Pomegranate (*Punica granatum*); Polyphenols; Ellagitannins; Punicalagin; Antioxidant activity; Antimicrobial activity; Pomegranate peel; Punicic acid; Nutraceuticals; Functional foods

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1. Introduction

Humans have been cultivating pomegranate (*Punica granatum* L.) since ancient times. It grows well in tropical and subtropical regions and belongs to the Punicaceae family. The term *Malum granatum*, meaning "granular apple" in Latin, is the origin of the word "pomegranate." This tree is characterized by elongated, smooth green leaves, a twisted and thorny stem, and brightly colored orange to crimson flowers. It exhibits remarkable adaptability to a wide range of environmental conditions. The fruit is typically spherical, with a diameter ranging from 6 to 12 cm. Its outer rind varies in color from yellow and green to pink, and may deepen to dark purple or bright red [1-2].

Approximately half of the fruit is edible, while the remaining portion consists of the peel. Of the edible fraction, the majority is juice, while the rest is composed of seeds. A longitudinal section of the pomegranate fruit highlights its key structural components, including the peel, arils, and seeds [3].

Fig. 1. Pomegranate (Punica granatum L.) fruit.

Pomegranate, originally native to Iran, is now widely cultivated across tropical and subtropical regions, including the United States, China, India, Tunisia, Turkey, Spain, Egypt, Morocco, and parts of Near and East Asia. Global production has reached millions of metric tons, with India emerging as the leading producer. A wide range of cultivars are grown, such as Bhagwa, Ganesh, Mridula, Maskat, Red Jodhpur, Jalore Seedless, and Red Ruby [3-4].

Pomegranate is well recognized for its significant medicinal properties, including antioxidant and anticancer activities. These effects are largely attributed to bioactive phytochemicals present in different parts of the plant. Among these, tannins play a crucial role. Tannins are naturally occurring phytochemicals found in a variety of plants and are known for their astringent properties and ability to form complexes with proteins and polysaccharides, thereby protecting plants from microbial infections and herbivores [5-6].

Tannins are structurally diverse compounds with molecular weights typically ranging from 500 to 3000 Da. They are broadly classified into four main categories: complex tannins, condensed tannins, gallotannins, and ellagitannins. Among these, ellagitannins are particularly important due to their complex structure and significant bioactivity. They are formed through oxidative coupling of galloyl groups, resulting in the formation of the hexahydroxydiphenic acid (HHDP) moiety. Upon hydrolysis, this moiety can spontaneously lactonize to produce ellagic acid [7-8].

Ellagitannins are commonly found in fruits and seeds such as pomegranate, berries, walnuts, and almonds. In pomegranate peel, punicalagin is the predominant ellagitannin and contributes significantly to its polyphenolic content. Punicalagin can be converted into punicalin, and both compounds can further hydrolyze to form ellagic acid under specific conditions.

Although pomegranate is commonly consumed as a fresh fruit, its processed products, including juices, alcoholic beverages, jams, and jellies, have gained substantial industrial importance. The expansion of processing industries has led to a significant increase in by-products, particularly peels and seeds, highlighting their potential for value-added applications.

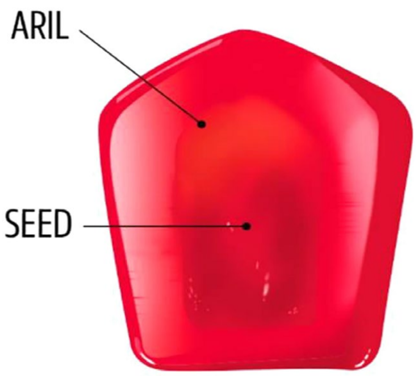
The buildup of this waste raises possible environmental issues, which highlights the need for sustainable approaches that make use of the bioactive substances present in these leftovers.The benefits of the pomegranate's peel, seed, and aril are examined in this article along with its bioactive makeup and combined biological qualities. Because of their bioactive source chemicals, the research that have been done on this fruit have mostly focused on its high added value, calculated the degree of valorization of these by-products, and examined their impact on advancements in food, medicine, cosmetics, and pharmacy [9-10].
The work with the pomegranate peel is highlighted in this study because it makes up half of the overall weight, is regarded as agro-industrial waste, and suggests a larger environmental issue. This could present a chance to develop new industrial uses in the food, pharmaceutical, or cosmetics industries. This article investigates the biological characteristics and bioactive makeup of the pomegranate fruit's various sections, particularly the peel, seed, and aril. Pomegranate research demonstrates its great added

value, especially when considering the worth of its by-products and their possible uses in pharmaceuticals, food, medicine, and cosmetics. The pomegranate peel, which makes up around half of the fruit's weight and is usually disposed of as agro-industrial waste, is given particular attention The peel offers a potential chance for the creation of novel applications in a variety of sectors because of its significant volume and environmental impact [11-12].

Taxonomy

Scientific classification of *Punica granatum.*

Kingdom: PLANTAE
Division: MAGNOLIOPHYTA
Class: MAGNOLIOPSIDA
Subclass: ROSIDAE
Order: MYRTALES
Family: PUNICACEAE
Genus and Specie: *Punica granatum* L.



2. Aril

The arils constitute more than half of the total weight of the pomegranate fruit and represent its edible portion. These arils are primarily composed of a high liquid content along with seeds. Structurally, the aril refers to a fleshy covering that partially or completely surrounds the seed and develops after fertilization. It originates from specific parts of the ovule or funiculus.

Arils are typically separated by thin membranes and inner white tissues and may appear transparent, pink, red, or whitish in color. Important quality parameters for industrial applications include acidity, total soluble solids, and aril color. The juicy and fleshy nature of arils arises from the outer epidermal cells of the seed, which elongate radially during development [13-14].

Nutritionally, arils are rich in water, natural sugars, and pectins. They also contain essential minerals such as potassium, phosphorus, calcium, iron, manganese, zinc, and copper, along with vitamin C and dietary fiber. In addition, arils are abundant in anthocyanins, which are water-soluble pigments responsible for their characteristic color. These include compounds such as delphinidin, pelargonidin, cyanidin, peonidin, petunidin, and malvidin. Besides anthocyanins, arils also contain various phenolic acids, including hydroxycinnamic acids (such as caffeic, p-coumaric, and chlorogenic acids) and hydroxybenzoic acids (such as ellagic and gallic acids).

2.1 Biological Properties and Applications of Arils

2.1.1 Antioxidant Activity

Pomegranate arils possess strong antioxidant properties, largely attributed to the presence of ellagitannins and other polyphenolic compounds. These bioactive compounds play a significant role in neutralizing free radicals and reducing oxidative stress. Experimental studies have demonstrated that pomegranate extracts can suppress tumor development, modulate inflammatory pathways, and inhibit oxidative damage at the cellular level.

Additionally, bioactive compounds such as punicalagin, ellagic acid, and urolithins have shown protective effects against oxidative stress by reducing reactive oxygen species and preventing cellular damage. These antioxidant properties contribute to the potential use of pomegranate in disease prevention, including cancer and inflammatory disorders.

2.1.2 Antimicrobial and Prebiotic Effects

Pomegranate arils and their extracts exhibit notable antimicrobial activity against a variety of microorganisms. Studies have shown that pomegranate extracts can inhibit the growth of both vegetative cells and spores of harmful bacteria, as well as prevent microbial contamination in food systems.

Beyond antimicrobial effects, pomegranate also demonstrates prebiotic potential by promoting the growth of beneficial gut microbiota such as *Lactobacillus* and *Bifidobacterium*. At the same time, it inhibits harmful bacterial populations, contributing to improved gut health. Certain bioactive compounds present in pomegranate can be metabolized by gut microbiota into beneficial metabolites, enhancing their biological activity.

Furthermore, compounds such as catechins and other polyphenols improve antioxidant activity and bioaccessibility during digestion, reinforcing the functional and therapeutic value of pomegranate arils [14-15].

2.2 Applications of Arils

Pomegranate arils are widely utilized in the food industry due to their high nutritional value and appealing taste. They are commonly used in the preparation of juices, jams, jellies, canned beverages, and pastes. In addition to their industrial use, arils play an important role in global cuisine. For instance, they are frequently added to salads and desserts in Mediterranean regions and are a key ingredient in traditional dishes such as *chiles en nogada* in Mexican cuisine.

Recent research highlights the growing potential of pomegranate-based food products, particularly due to their health-promoting properties. Pomegranate juice powder has been explored as a functional ingredient in food formulations. Its incorporation into products such as yogurt has been shown to enhance nutritional value, increase phenolic content, and improve textural properties including viscosity, consistency, and cohesion.

Pomegranate extracts have also demonstrated effectiveness in food preservation. Their incorporation into dairy products has been associated with improved oxidative stability, extended shelf life, and enhanced sensory attributes. These benefits are largely attributed to the antimicrobial, antioxidant, and anti-inflammatory properties of pomegranate-derived compounds. Such findings suggest promising applications in the development of functional and therapeutic food products.

Beyond food applications, pomegranate aril juice has been associated with several health benefits. It has been shown to reduce oxidative stress and inhibit lipid peroxidation, contributing to improved cholesterol profiles by lowering total cholesterol and low-density lipoprotein levels while improving high-density lipoprotein balance.

In cardiovascular health, pomegranate juice has demonstrated the ability to reduce blood pressure by inhibiting angiotensin-converting enzyme activity. It may also improve myocardial perfusion and reduce stress-induced ischemia in individuals with coronary heart disease [16-17.]

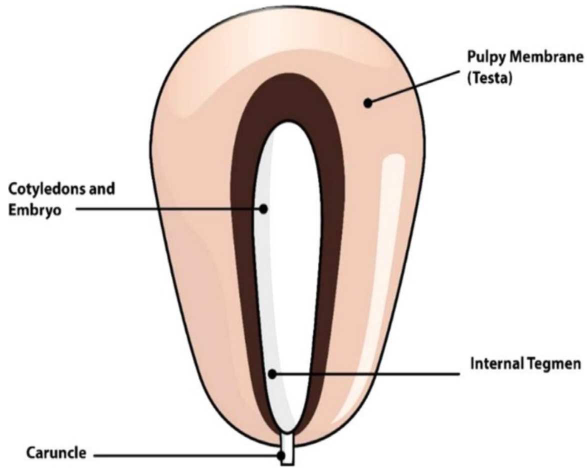
In the context of metabolic health, consumption of pomegranate juice has shown beneficial effects in diabetic individuals. Despite containing natural sugars, it does not adversely affect glycemic parameters and may reduce atherogenesis through its antioxidant properties.

2.3 Seed

The pomegranate seed is located within the aril and typically exhibits a prismatic shape. It is enclosed by a protective outer covering known as the testa, which serves as a barrier against environmental stress. The testa consists of two distinct layers: the sarcotesta and the mesotesta. The sarcotesta is the soft, fleshy, and edible portion, while the mesotesta forms the harder inner layer.

Surrounding the core of the seed is another protective structure known as the tegument, which plays a crucial role in regulating water movement between the seed and its external environment. This structural organization contributes to the seed’s protection, viability, and overall functional properties [18-19].

Fig. 3 The pulpy membrane, called the testa, that surrounds the embryo and cotyledons is visible



3. Pomegranate Seed

Pomegranate seeds are an important component of the fruit and have gained increasing attention due to their nutritional composition and potential industrial applications. Proximate analysis has revealed that the seeds contain a significant amount of oil, averaging around 12–13%, which can be extracted and utilized for health-promoting purposes. This oil is rich in beneficial fatty acids and bioactive compounds, making it valuable for both pharmaceutical and industrial uses.

In addition to lipids, pomegranate seeds contain a wide range of phytochemicals, including anthocyanins, flavonoids, coumarins, and phenolic acids. Major anthocyanins present include derivatives of cyanidin, pelargonidin, and delphinidin. Other bioactive compounds such as flavonoids (genistein, rutin, gallocatechin), coumarins, nucleosides, and essential amino acids further enhance the functional properties of the seeds.

Pomegranate seed oil is particularly notable for its high content of tocopherols and unique fatty acids. Among these, punicic acid, a conjugated linolenic acid, is the most abundant and biologically significant component. The oil also contains other fatty acids such as palmitic, stearic, oleic, and linoleic acids, along with sterols and vitamin E. Additionally, compounds such as squalene contribute to its antioxidant and skin-protective properties [20-21].

The oil content of pomegranate seeds can vary depending on factors such as cultivar, ripeness, and environmental conditions, typically ranging between 7% and 27%. Various extraction techniques, including conventional methods like solvent extraction and cold pressing, as well as advanced methods such as ultrasound-assisted and supercritical fluid extraction, influence both the yield and quality of the oil.

3.1 Biological Properties of Seeds

Pomegranate seeds exhibit a wide range of biological activities, largely attributed to punicic acid and other bioactive compounds.

Anti-cancer Activity

Pomegranate seed oil and extracts demonstrate inhibitory effects against multiple cancer types, including breast, prostate, skin, colon, lung, and liver cancers. These effects are mediated through mechanisms such as inhibition of cell proliferation, induction of apoptosis, and suppression of inflammation and metastasis-related pathways.

Antioxidant and Anti-inflammatory Activity

The seeds are rich in natural antioxidants that help neutralize free radicals and reduce oxidative stress. Their anti-inflammatory effects contribute to the prevention of various chronic diseases by modulating inflammatory pathways.

Metabolic and Anti-diabetic Effects

Pomegranate seed oil has shown potential in improving insulin sensitivity, regulating glucose metabolism, and preventing obesity. It also contributes to improved lipid profiles and helps reduce the risk of metabolic disorders [23-24].

Cardiovascular and Skeletal Protection

The bioactive compounds present in seeds exhibit cardioprotective effects by reducing cholesterol levels and preventing lipid peroxidation. Additionally, they support bone health by improving bone mineral density and calcium levels.

Neuroprotective Effects

Pomegranate seed oil has demonstrated protective effects against oxidative stress in the brain, suggesting its potential in delaying neurodegenerative diseases and improving cognitive function.

Other Therapeutic Effects

The seeds have also been associated with protective effects against nephrotoxicity and improvements in reproductive health. Traditionally, they have been used in the management of liver-related disorders.

3.2 Applications of Seeds

Pomegranate seeds and their oil have diverse applications across multiple industries. They are widely used in the food industry as functional ingredients due to their nutritional and antioxidant properties. The oil is also utilized in nutraceutical formulations for its health benefits, including hepatoprotective, anticancer, and neuroprotective effects [25-26].

In animal nutrition, pomegranate seed oil has been incorporated into feed to enhance the quality of meat and dairy products by improving fatty acid composition. In addition, seed-derived products have been explored in the development of functional foods such as fortified dairy products and snack formulations.

The oil also finds applications in cosmetics due to its moisturizing, antioxidant, and skin-conditioning properties. Bioactive compounds such as squalene and phytosterols contribute to its effectiveness in skincare formulations.

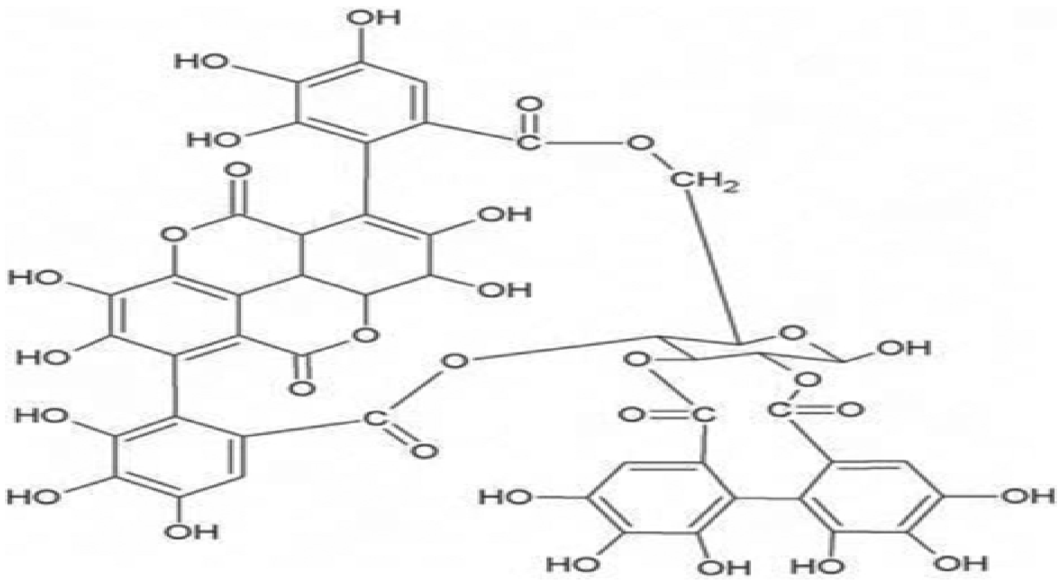
Furthermore, pomegranate seed derivatives have been used in food preservation and packaging applications due to their antioxidant and antimicrobial properties. Encapsulation techniques have also been explored to improve the stability and delivery of bioactive compounds in pharmaceutical and food systems.

4. Pomegranate Peel

Pomegranate peel constitutes a significant portion of the fruit and is often considered a by-product of juice processing. However, it is a rich source of dietary fiber, particularly insoluble fiber, and contains high levels of bioactive compounds.

The peel exhibits a wide range of colors, including yellow, green, pink, red, and purple, depending on the variety and pigment composition. It is especially rich in phenolic compounds and flavonoids such as catechin, quercetin, epicatechin, and procyanidins. Additionally, it contains various anthocyanins and phenolic acids, contributing to its strong antioxidant potential.

Despite being traditionally considered waste due to its bitter taste and rigid texture, pomegranate peel has gained attention for its potential applications in food, pharmaceutical, and nutraceutical industries due to its high bioactive content and functional properties [27-28].



4.

Fig. 4. Punicalagin molecular structure.

Pomegranate Peel (Continued)

Pomegranate peel contains substantial quantities of microelements and bioactive compounds with significant biological activities, including antimutagenic, antioxidant, apoptotic, and antibacterial properties. Among these, polyphenols are the most abundant constituents, with punicalagin isomers representing the dominant fraction of total tannins. The peel is particularly rich in hydrolyzable tannins, especially ellagitannins, which are known for their strong antioxidant capacity demonstrated through various in vitro studies.

The efficiency of recovering these bioactive compounds largely depends on the extraction method employed. Conventional techniques such as hydrodistillation, Soxhlet extraction, and maceration have been widely used. However, these methods often require longer processing times and higher solvent consumption. In contrast, modern green extraction technologies, including microwave-assisted extraction and ultrasound-assisted extraction, have gained attention due to their efficiency, reduced processing time, and lower solvent usage.

Ultrasound-assisted extraction enhances the recovery of polyphenols by improving mass transfer, while microwave-assisted extraction significantly reduces extraction time and increases yield. These advanced methods not only improve extraction efficiency but also preserve the integrity of heat-sensitive bioactive compounds. As a result, extracts obtained through these techniques exhibit high polyphenol content and strong antioxidant activity.

In addition to extraction technologies, biotechnological approaches such as fermentation have been explored for the valorization of pomegranate peel. Solid-state fermentation has shown potential as an eco-friendly method for producing valuable secondary metabolites with minimal waste generation. During fermentation,

ellagitannins are biodegraded into ellagic acid, a compound well known for its potent antioxidant and therapeutic properties. Enzymatic activities involved in this process, including tannase and related enzymes, play a crucial role in converting complex tannins into bioactive compounds [29-32].

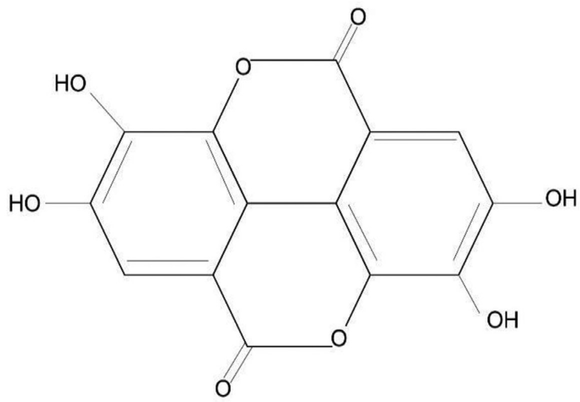
4.1 Biological Properties of Pomegranate Peel

Pomegranate peel has been traditionally used in various medicinal systems for the treatment of several ailments, including inflammation, gastrointestinal disorders, and reproductive issues. In recent years, scientific studies have validated and expanded upon these traditional uses.

The peel exhibits a wide range of biological activities, including strong antioxidant, antimicrobial, anti-inflammatory, antiproliferative, and anticancer effects. These properties are primarily attributed to its high concentration of polyphenols, flavonoids, and other bioactive compounds. Due to these diverse therapeutic effects, pomegranate peel has gained considerable attention as a potential natural source for the development of functional foods, nutraceuticals, and pharmaceutical formulations

4.1.1 ***Antioxidant Activity***

During normal cellular metabolism, reactive oxygen species (ROS)—such as superoxide



anion, Fig.5. Ellagic acid molecular structure

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4.4 Pomegranate peel applications

Because of the significant amount of peel waste produced, the increasing demand for pomegranate-based goods has raised environmental concerns. However, because pomegranate peel is high in bioactive compounds, this byproduct offers a significant industrial application possibility.

Substances that continue to pique scientific curiosity due to their diverse biological characteristics. These characteristics have spurred attempts to increase the possible uses of pomegranate peel, as was previously covered in this work. To increase this waste's attractiveness to various markets and provide financial gains, researchers are actively looking for ways to turn it into valuable products. Several uses for pomegranate peel and its constituent parts are described in the sections that follow.

4.2.1 Applications in Food Products

In recent years, fruit peels have gained considerable attention in animal nutrition and health, with their use as feed supplements becoming increasingly popular. These peels are rich in essential nutrients, including minerals, proteins, carbohydrates, and dietary fiber, making them valuable for supporting animal growth and development. Pomegranate peel, in particular, has been explored for its potential use as a feed preservative, stabilizer, and quality enhancer.

Beyond animal feed, pomegranate peel extract has shown significant promise in food packaging applications. It has been incorporated into biopolymer films that act as protective barriers against environmental factors such as oxygen, heat, moisture, and ultraviolet radiation. When combined with film-forming agents like gelatin, zein, and chitosan, pomegranate peel extracts enhance the functional properties of these films, including their antioxidant capacity.

The strong antioxidant activity of these films is attributed to bioactive compounds such as punicalagin, ellagic acid, and flavonoids, which possess phenolic hydroxyl groups capable of neutralizing free radicals. These properties make pomegranate peel extracts highly suitable for extending the shelf life and improving the quality of food products [37-38].

Encapsulation techniques have also been widely used to improve the stability and application of pomegranate peel extracts in food systems. Encapsulated extracts have demonstrated high efficiency in preserving phenolic content and extending the shelf life of products such as nut-based pastes and baked goods. Compared to crude extracts, encapsulated forms retain higher levels of bioactive compounds during processing, making them more effective for functional food applications.

The growing demand for functional foods has further encouraged the incorporation of plant-based additives into food products. Pomegranate peel extract has been successfully used as a functional ingredient in various food matrices, enhancing both nutritional value and shelf life. These applications highlight its potential as a natural alternative to synthetic additives in the food industry.

5. Future Perspectives

Pomegranate peel and other fruit by-products represent valuable sources of bioactive compounds with significant potential in nutraceutical and pharmaceutical applications. Polyphenols present in the peel exhibit strong antioxidant properties and can be effectively utilized in the formulation of dietary supplements through advanced encapsulation techniques.

In addition, recent developments in nanotechnology have opened new avenues for the application of pomegranate-derived compounds. These bioactive molecules can be incorporated into nanostructures such as nanoemulsions, nanoparticles, nanoliposomes, phytosomes, and nanovesicles, which are widely used in advanced drug delivery systems [39-40].

The juice, seeds, and peel of pomegranate have all demonstrated substantial health benefits, making the fruit a valuable functional resource. Among these, the peel is particularly significant due to its high concentration of ellagitannins and other polyphenolic compounds. Despite its potential, further research is required to better understand the enzymatic mechanisms involved in the biodegradation of these compounds and to develop efficient extraction and purification techniques.

Comparative studies with other fruit by-products have also highlighted the potential of utilizing agricultural waste for value-added applications. Similar to other bioactive-rich fruit residues, pomegranate peel can be transformed into functional dietary supplements, including capsules and gummies, catering to a wide range of consumers.

Although the use of advanced extraction technologies may involve higher initial costs, their benefits in terms of improved yield, reduced solvent usage, and enhanced safety make them a worthwhile investment. With increasing awareness of health and wellness, along with advancements in food and pharmaceutical technologies, pomegranate peel holds significant promise as a sustainable and valuable resource for the development of functional and therapeutic products [41-42].

2. Conclusion

Cultivation of pomegranates (Punica granatum L.) extensively because of their capacity to withstand a variety of climates. The fruit's many biological properties, which are ascribed to the presence of bioactive substances such as ellagic acid, punicalagin, punicalin, and punicic acid, have drawn a lot of scientific attention. These substances have been shown to have positive health effects and have been studied in vitro and in vivo for their potential to prevent or treat diseases like inflammation, cancer, obesity, diabetes, bacterial infections, and viral infections like influenza. Despite these encouraging results, more investigation is required to fully comprehend their in vivo metabolism and methods of action. This involves determining safe and effective dosage ranges for these substances' use in the food, pharmaceutical, and cosmetic sectors.

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