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Pomegranate (*Punica granatum L.*) as a Sustainable Source of Bioactive Compounds: Phytochemistry, Biological Activities, Extraction Technologies, and Industrial Applications

J.Muneer Ahamath[1*], J. Sirajudeen[1], R.Abdul vahith[1], Rajasekar. P[1], Nainar Zakkariya S[1]

[1]Department of Chemistry, Jamal Mohamed College (Autonomous), Tiruchirappalli - 620 020, Tamil Nadu, India

***Corresponding Author E-mail: jm@jmc.edu**

Abstract:

Punica granatum L. (pomegranate) is a nutritionally valuable fruit renowned for its rich phytochemical composition and broad spectrum of biological activities. Owing to its significant therapeutic potential, pomegranate has attracted considerable attention in the food, pharmaceutical, nutraceutical, and cosmetic industries. This review comprehensively summarizes the phytochemical profile, bioactive constituents, and health-promoting properties of different fruit components, including the arils, seeds, and peel. Pomegranate is particularly rich in polyphenolic compounds such as ellagitannins (punicalagin and punicic acid), ellagic acid, flavonoids, anthocyanins, and other phenolic metabolites that contribute substantially to its pharmacological activities. The arils constitute a valuable source of natural sugars, vitamins, minerals, and antioxidants, exhibiting potent antioxidant, antimicrobial, and prebiotic effects. Pomegranate seeds contain bioactive lipids, especially punicic acid, which have demonstrated anti-inflammatory, cardioprotective, antidiabetic, and anticancer properties. The peel, which represents a major agro-industrial by-product, is exceptionally rich in phenolic compounds and displays remarkable antioxidant, antimicrobial, antiviral, anti-inflammatory, and chemopreventive activities. Recent advances in extraction technologies, encapsulation approaches, and nano formulation strategies have significantly improved the stability, bioavailability, and therapeutic efficacy of pomegranate-derived bioactive compounds, thereby expanding their potential industrial and biomedical applications. Furthermore, valorising pomegranate processing by-products offers a sustainable approach for developing high-value functional ingredients and reducing environmental waste.

Overall, pomegranate and its by-products represent promising natural resources for developing functional foods, nutraceuticals, cosmeceuticals, and novel therapeutic formulations. Future research should focus on optimizing extraction processes, elucidating molecular mechanisms of action, enhancing clinical translation, and exploring innovative applications of pomegranate-derived bioactives in health and disease management.

Keywords: *Punica granatum*; pomegranate peel; pomegranate seeds; ellagitannins; punicalagin; ellagic acid; bioactive compounds; antioxidant activity; nutraceuticals; functional foods.

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1. Introduction

Pomegranate (*Punica granatum* L.) is one of the oldest cultivated fruit crops and has been valued for centuries because of its nutritional and medicinal properties. It belongs to the family Juncaceae and is widely distributed throughout tropical and subtropical regions of the world. The name "pomegranate" is derived from the Latin term *Malum granatum*, meaning "granular apple," referring to its characteristic seed-filled structure. The plant is a deciduous shrub or small tree characterized by glossy green leaves, thorny branches, and attractive orange-red flowers. Owing to its remarkable adaptability, pomegranate can thrive under diverse climatic and environmental conditions. The fruit is generally spherical, measuring approximately 6–12 cm in diameter, and exhibits rind colours ranging from yellow-green to deep red or purple depending on cultivar and maturity stage[1,2].

Structurally, approximately 50% of the fruit consists of the peel, while the remaining edible portion is composed of arils and seeds. The arils contain a large proportion of juice and represent the major edible fraction of the fruit. A longitudinal section of the pomegranate reveals three principal anatomical components: peel, arils, and seeds, each possessing distinct phytochemical compositions and biological functions[3].

Although pomegranate is believed to have originated in the region extending from modern-day Iran to northern India, its cultivation has expanded globally. Today, it is extensively grown in countries including India, China, the United States, Turkey, Spain, Tunisia, Egypt, Morocco, and several regions of the Near and Far East. Global production has increased substantially over the last few decades, with India currently recognized as the leading producer. Numerous commercial cultivars are cultivated worldwide, including Bhagwa, Ganesh, Mridula, Maskit, Red Jodhpur, Jalore Seedless, and Red Ruby[3,4].

The growing scientific interest in pomegranate is largely attributed to its rich phytochemical profile and diverse pharmacological activities. Various studies have demonstrated potent antioxidant, anti-inflammatory, antimicrobial, antidiabetic, cardioprotective, and anticancer properties associated with different parts of the fruit. These biological effects are primarily linked to the presence of polyphenolic compounds, particularly tannins, flavonoids, anthocyanins, and phenolic acids. Among these constituents, tannins represent one of the most important groups due to their abundance and broad spectrum of biological activities. Tannins are naturally occurring polyphenolic compounds capable of forming complexes with proteins and polysaccharides, thereby contributing to plant defence against pathogens and herbivores[5,6].

Based on their chemical structures, tannins are generally classified into condensed tannins, gallotannins, ellagitannins, and complex tannins. Among these groups, ellagitannins have attracted considerable attention because of their unique structural features and significant therapeutic potential. These compounds are formed through oxidative coupling reactions involving galloyl groups, resulting in the formation of hexahydroxydiphenic acid (HHDP) moieties. Upon hydrolysis, HHDP spontaneously undergoes lactonization to produce ellagic acid, a bioactive metabolite associated with numerous health-promoting effects[7,8].

Ellagitannins are widely distributed in fruits, nuts, and seeds, including pomegranate, berries, walnuts, and almonds. In pomegranate peel, punicalagin is the predominant ellagitannin and constitutes a major fraction of the total polyphenolic content. Punicalagin can undergo hydrolysis to form punicalin and subsequently ellagic acid, both of which contribute significantly to the biological activities of pomegranate-derived products[7,8].

In addition to fresh consumption, pomegranate is extensively processed into value-added products such as juices, concentrates, jams, jellies, syrups, and alcoholic beverages. The expansion of pomegranate-processing industries has generated substantial quantities of by-products, particularly peels and seeds. These residues, often considered agro-industrial waste, represent an underutilized source of valuable bioactive compounds with considerable commercial and therapeutic potential[9,10].

The accumulation of pomegranate processing waste poses environmental challenges and highlights the need for sustainable valorisation strategies. Recent research has increasingly focused on recovering and utilising bioactive constituents from pomegranate by-products for applications in the food, pharmaceutical, nutraceutical, and cosmetic industries. The high concentration of phenolic compounds, flavonoids, tannins, and bioactive lipids present in these by-products has significantly enhanced their economic value and industrial relevance[9,10].

Among the various fruit components, pomegranate peel deserves particular attention because it accounts for nearly half of the total fruit weight and is generally discarded during industrial processing. Despite being considered waste, the peel contains exceptionally high levels of polyphenols and exhibits remarkable biological activities. Consequently, it represents a promising raw material for the development of novel functional foods, nutraceuticals, pharmaceutical formulations, and cosmetic products[11,12].

Therefore, this review provides a comprehensive overview of the phytochemical composition, biological properties, and industrial applications of different pomegranate components, with special emphasis on the peel, seeds, and arils. Furthermore, recent advances in extraction technologies, valorisation approaches, and potential applications in food, pharmaceutical, and cosmetic sectors are critically discussed to highlight the significance of pomegranate as a sustainable source of high-value bioactive compounds[11,12].

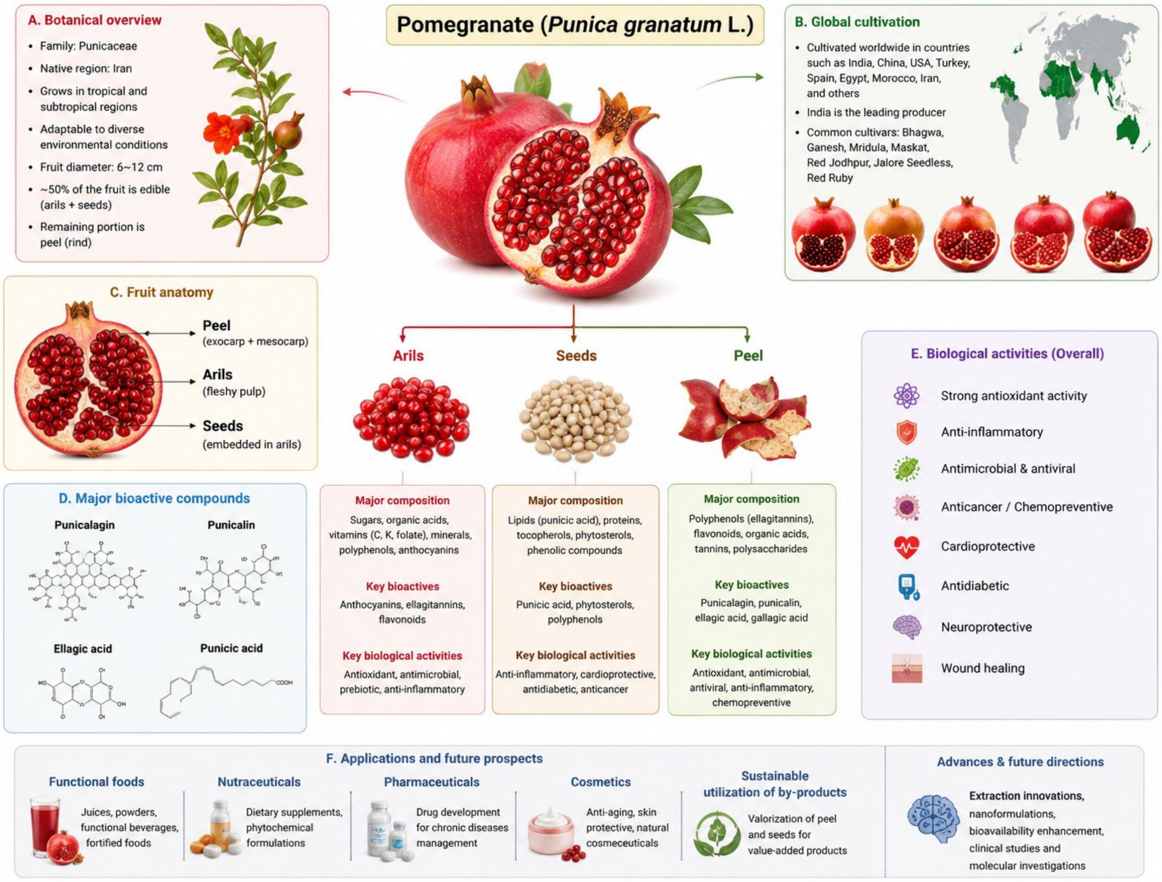


Figure 1. Structural components of pomegranate and their associated bioactive compounds, biological functions, and commercial applications.

Table 1. Bioactive Constituents of Different Parts of Pomegranate

Fruit Part	Major Bioactive Compounds	Chemical Class	Biological Activities
Aril	Anthocyanins, Ellagic acid, Gallic acid	Polyphenols	Antioxidant, antimicrobial, cardioprotective
Seed	Punicic acid, Linoleic acid, Tocopherols	Fatty acids, Vitamins	Anti-inflammatory, antidiabetic, anticancer
Peel	Punicalagin, Penicillin, Ellagic acid, Flavonoids	Ellagitannins, Polyphenols	Antioxidant, antimicrobial, antiviral, anticancer
Juice	Anthocyanins, Tannins, Phenolic acids	Polyphenols	Cardioprotective, antiatherogenic
Flower	Gallic acid, Ursolic acid	Phenolics	Antidiabetic, anti-inflammatory

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 colour. Important quality parameters for industrial applications include acidity, total soluble solids, and aril colour. 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 colour. 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[13,14].

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 tumour development, modulate inflammatory pathways, and inhibit oxidative damage at the cellular level[14,15].

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[14,15].

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[14,15].

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[14,15].

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 key ingredients in several traditional food preparations[16,17].

Recent research highlights the growing potential of pomegranate-based food products, particularly because of 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[16,17].

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[16,17].

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[16,17].

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 glycaemic parameters and may reduce atherogenesis through its antioxidant properties[16,17].

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 tegmen, 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].

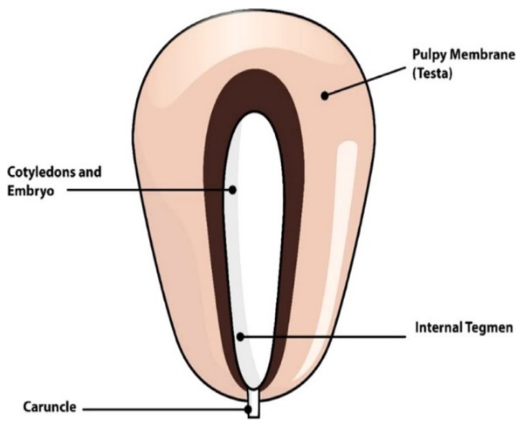


Fig. 2 The pulpy membrane, called the teste, that surrounds the embryo and cotyledons is visible

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[20, 21].

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, gallocatechol), coumarins, nucleosides, and essential amino acids further enhance the functional properties of the seeds[20, 21].

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 such as solvent extraction and cold pressing, as well as advanced methods such as ultrasound-assisted extraction and supercritical fluid extraction, influence both the yield and quality of the oil[20,21].

able 3. Extraction Techniques for Pomegranate Peel Bioactives

Method	Solvent	Advantages	Limitations
Maceration	Ethanol/Water	Simple, low cost	Long extraction time
Soxhlet	Organic solvents	High yield	Solvent intensive
Ultrasound-Assisted Extraction (UAE)	Ethanol-Water	Fast, eco-friendly	Equipment cost
Microwave-Assisted Extraction (MAE)	Ethanol-Water	High efficiency	Thermal degradation ris
Supercritical CO_2 Extraction	CO_2	Solvent-free	Expensive
Solid-State Fermentation	Biological process	Produces ellagic acid	Process optimization required

3.1 Biological Properties of Pomegranate Seeds

Pomegranate seeds possess a diverse range of biological activities that are primarily attributed to their rich content of punicic acid, polyphenols, phytosterols, tocopherols, and other bioactive constituents. These compounds have attracted considerable attention because of their potential therapeutic applications in the prevention and management of various chronic diseases[23,24].

Anticancer Activity

Numerous experimental studies have demonstrated that pomegranate seed oil and seed-derived extracts exhibit significant anticancer effects against a variety of malignancies, including breast, prostate, colon, lung, liver, and skin cancers. The underlying mechanisms involve inhibition of cancer cell proliferation, induction of apoptosis, suppression of angiogenesis, and modulation of inflammatory and metastatic signalling pathways. These findings suggest that pomegranate seed bioactives may serve as promising candidates for cancer prevention and adjunctive therapy[23,24].

Antioxidant and Anti-inflammatory Activity

Pomegranate seeds are an abundant source of natural antioxidants that effectively scavenge reactive oxygen species (ROS) and reduce oxidative stress. Their antioxidant potential contributes to cellular protection against oxidative damage, while their anti-inflammatory properties help regulate inflammatory mediators and signalling pathways involved in the pathogenesis of chronic diseases. Consequently, pomegranate seed constituents may play an important role in reducing inflammation-associated disorders[23,24].

Antidiabetic and Metabolic Effects

Pomegranate seed oil has shown considerable potential in improving insulin sensitivity, enhancing glucose utilization, and regulating carbohydrate metabolism. Furthermore, it has been reported to reduce body fat accumulation, improve lipid metabolism, and mitigate obesity-related complications. These beneficial effects highlight its potential application in the prevention and management of metabolic syndrome, type 2 diabetes mellitus, and associated disorders[23,24].

Cardioprotective and Skeletal Benefits

The bioactive compounds present in pomegranate seeds contribute to cardiovascular health through multiple mechanisms, including reduction of serum cholesterol levels, inhibition of lipid peroxidation, and protection against oxidative damage to vascular tissues. In addition, pomegranate seed constituents have been associated with improvements in bone mineral density and calcium homeostasis, suggesting a protective role in maintaining skeletal health and reducing the risk of osteoporosis[23,24].

Neuroprotective Activity

Emerging evidence indicates that pomegranate seed oil exerts neuroprotective effects by reducing oxidative stress and neuroinflammation within the central nervous system. These properties may contribute to the prevention or delay of neurodegenerative disorders and support cognitive function during aging[23,24].

Other Therapeutic Applications

Beyond the aforementioned benefits, pomegranate seeds have demonstrated protective effects against nephrotoxicity and may contribute to improved reproductive health. Traditional medicinal systems have also utilized pomegranate seeds for the management of liver-related disorders and other health conditions. Collectively, these findings emphasize the substantial therapeutic potential of pomegranate seeds as a valuable source of bioactive compounds for pharmaceutical, nutraceutical, and functional food applications[23,24].

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[25,26].

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[25,26].

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[25,26].

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 fibre, particularly insoluble fibre, and contains high levels of bioactive compounds[27,28].

The peel exhibits a wide range of colours, 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[27,28].

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 because of its high bioactive content and functional properties[27,28].

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 dominantfraction of total tannins. The peel is particularly rich in hydrolysable tannins, especially ellagitannins, which are known for their strong antioxidant capacity demonstrated through various in vitro studies[29–32].

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[29–32].

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[29–32].

In addition to extraction technologies, biotechnological approaches such as fermentation have been explored for the valorisation 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.

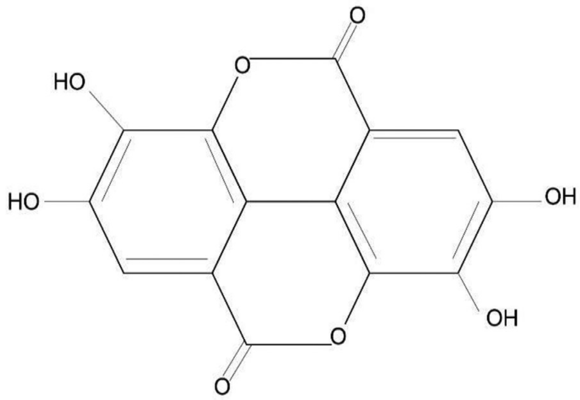
The peel exhibits a wide range of biological activities, including strong antioxidant, antimicrobial, anti-inflammatory, antiproliferative, and anticancer effects. These properties are primarily attributed to its high concentration of polyphenols, flavonoids, and other bioactive compounds. Due to these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

Table 2. Biological Activities of Pomegranate Components

Component	Compound	Target Disease/Condition	Mechanism of Action
Aril	Anthocyanins	Oxidative stress	ROS scavenging
Seed Oil	Punicic acid	Diabetes	Improved insulin sensitivity
Seed Oil	Punicic acid	Cancer	Induction of apoptosis

Peel	Punicalagin	Microbial infections	Cell membrane disruption
Peel	Ellagic acid	Inflammation	NF-dB inhibition
Juice	Polyphenols	Cardiovascular disease	ACE inhibition

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



anion, **Fig 3.** 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. In order 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 fibber, 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 gelatine, 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 nano emulsions, nanoparticles, nanoliposomes, phytotomies, 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].

6.Conclusion

Mexico is one of the major producers of pomegranate (Punica granatum L.), owing to the fruit's remarkable adaptability to diverse climatic and environmental conditions. In recent years, pomegranate has attracted considerable scientific interest because of its rich phytochemical composition and broad spectrum of biological activities. These beneficial effects are primarily attributed to bioactive constituents such as ellagic acid, punicalagin, penicillin, and punicic acid, which are distributed throughout different parts of the fruit.

Numerous in vitro and in vivo studies have demonstrated the therapeutic potential of these compounds in the prevention and management of various pathological conditions, including inflammation, cancer, obesity, diabetes mellitus, bacterial infections, and viral diseases such as influenza. The antioxidant, anti-inflammatory, antimicrobial, and anticancer properties of pomegranate-derived phytochemicals have further increased their relevance in biomedical and pharmaceutical research.

Despite these promising findings, significant knowledge gaps remain regarding the absorption, bioavailability, metabolism, and molecular mechanisms of action of these bioactive compounds in humans. Therefore, further preclinical and clinical investigations are necessary to establish their efficacy, safety profiles, and optimal dosage ranges. Such studies will be essential for facilitating the development and commercialization of pomegranate-derived ingredients and formulations for applications in the food, pharmaceutical, nutraceutical, and cosmetic industries.

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