Journal Pre-proofs

Review

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PII: S0963-9969(22)00435-5
DOI: https://doi.org/10.1016/j.foodres.2022.111378
Reference: FRIN 111378

To appear in: *Food Research International*

Received Date: 22 March 2022
Revised Date: 30 April 2022
Accepted Date: 11 May 2022

Please cite this article as: Kumar, N., Daniloski, D., Pratibha, Neeraj, D'Cunha, N.M., Naumovski, N., Trajkovska Petkoska, A., Pomegranate peel extract - a natural bioactive addition to novel active edible packaging, *Food Research International* (2022), doi: https://doi.org/10.1016/j.foodres.2022.111378

Pomegranate peel extract - a natural bioactive addition to novel active edible packaging

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Abstract

The pomegranate (*Punica granatum* L.) fruit peel has been renowned for containing high amounts of bioactive phenolic and flavonoid compounds; however, it has been commonly deemed as an agricultural waste product. The present study comprehensively reviews the impact of pomegranate peel extract as an active addition to different edible packaging materials. This review provides an overview of the recent trends and advances in active edible packaging materials enriched with pomegranate peel and their technological properties. Recently, significant advances have been made to extend the shelf life of perishable food and control the release and transport of nutraceuticals and bioactive molecules by using pomegranate fruit and its underutilized components. Pomegranate peel extract within the edible matrix provide good compatibility between peel particles and the matrix, and can enhance structural, mechanical, and biochemical properties such as antioxidant and phenolic content as well as antimicrobial activity. The addition of pomegranate peel extract in an edible matrix and applied to food products could also assist in the retardation of natural pigments, lipid oxidation, microbial contamination and influence shelf life by sustaining organoleptic properties of food products. However, more studies are needed to investigate practical implications related to the effects of pomegranate peel extract on the optical, physical and barrier properties of edible films and coatings.

Keywords: Pomegranate peel extract; Edible packaging; Active packaging; Shelf life, Valorization.

1. Introduction

The current industrial food sector and scientific community are focused on the sustainable development of food packaging alternatives as replacements for synthetic-based packaging. This is mainly due to increased awareness of the benefits of active and edible packaging for fruits, vegetables and other food products. Edible packaging are food formulations that are typically very thin (generally less than 0.3 mm) and provide a protective layer of biopolymers used for enrobing food products to enhance their shelf life and organoleptic properties (Kumar & Neeraj, 2019; Petkoska, Daniloski, D'Cunha, Naumovski, & Broach, 2021; Senturk Parreidt, Müller, & Schmid, 2018). Recently, particular interest has been given to the development of antioxidant and antimicrobial enriched active packaging. In this context, “natural” active additives, such as plant extracts, essential oils, and probiotic bacteria, are especially important as nutritive and bioactive additives to ecologically friendly packaging materials that can maintain high quality and safe food for consumers for an extended period of time (Bharti et al., 2020; Daniloski et al., 2021; El-Sayed, El-Sayed, Mabrouk, Nawwar, & Youssef, 2021; Petkoska et al., 2021). A special category in active packaging options is edible packaging in the form of coatings and films. Edible packaging is regarded as a novel and essential trend that addresses minimization of food waste, reduces consumption of foods packed into synthetic packaging materials and prolongs the shelf life of food products through preservation of food from microbial contamination (Guillard et al., 2018; Kumar & Neeraj, 2019; Petkoska et al., 2021; Suhag, Kumar, Petkoska, & Upadhyay, 2020). This type of packaging also provides adequate barrier properties against gases and water transpiration and enhances mechanical properties against physical damage.

Many researchers have investigated different types of edible coatings used on food products to extend their shelf life and improve storage stability (El-Sayed et al., 2021; Kumar, Pratibha, Neeraj, & Sharma, 2020; Venkatesh & Sutariya, 2019). In general, edible packaging is biodegradable, non-toxic in nature, and can be used as either a coating or in the form of film depending on the nature of food products (El-Sayed et al., 2021; Petkoska et al., 2021). Different deposition methods of edible coating can be applied to food products and the most common application methods include dipping, spraying, fluidized bed processing and panning, whereas the film formation methods, such as casting and extrusion, can be used to form wrapping around food products (Raghav, Agarwal, & Saini, 2012; Suhag et al., 2020). In addition, a variety of biopolymers from natural sources (polysaccharides, proteins, lipids, waxes) can be used alone and in composite form for developing edible coatings and films; starch, cellulose, chitosan, chitin, pullulan, alginate, gums, and plant- andanimal-based protein, among others (Kumar, Ojha, & Singh, 2019; Pal, Sarkar, Anis, Wiszumirska, & Jarzębski, 2021; Petkoska et al., 2021; Petkoska, Daniloski, Kumar, & Broach, 2021a, 2021b).

Edible packaging tends to retain or, in some cases, even improve nutritional composition, biological and sensory characteristics due to reducing moisture losses, improving surface shine and minimizing biochemical changes during storage (Cui, Surendhiran, Li, & Lin, 2020; Kumar & Neeraj, 2019; Martău, Mihai, & Vodnar, 2019; Meighani, Ghasemnezhad, & Bakhshi, 2015; Reichert et al., 2020; Ruiz-Martínez et al., 2020). The latest trend of using edible packaging containing fruits processing waste extracts high in bioactive compounds is becoming well recognized in industry and research alike. Their incorporation in edible packaging materials is proposed to enhance antioxidant and antimicrobial characteristics (Bayram, Ozkan, Kostka, Capanoglu, & Esatbeyoglu, 2021; Kharchoufi et al., 2018; Kumar, Pratibha, et al., 2020; Yadav, Kumar, Upadhyay, Pratibha, & Anurag, 2021), and modify the structure of films which improves their functionality for food applications (Munir, Javed, Hu, Liu, & Xiong, 2020; Rangaraj, Rambabu, Banat, & Mittal, 2021). In this context, relatively limited data is available on edible coatings and films enriched with pomegranate peel as a natural antioxidant agent. Therefore, the main objective of this review is to comprehensively evaluate the recent studies on enriched edible coatings and films using pomegranate peel extracts and their effects on food product quality. In addition, this review also provides information regarding the effects of pomegranate peel extract on the physical, mechanical, thermal and functional properties of edible packaging.

2. Pomegranate peel as a valuable source of bioactive components

The use of antioxidant and antimicrobial agents from plant extracts are an emerging tool in the food industry and are widely used as an active ingredients in the development of edible coatings and films (Bayram et al., 2021; Kumar, Neeraj, Pratibha, & Singla, 2020; Kumar, Pratibha, et al., 2020; Lourenço, Moldão-Martins, & Alves, 2019; Quinto et al., 2019; Santos-Sánchez, Salas-Coronado, Valadez-Blanco, Hernández-Carlos, & Guadarrama-Mendoza, 2017). Several studies have revealed the effects of edible packaging enriched with antioxidant agents on improving the quality and safety of food products, including fruits, vegetables and other food products (Barzegar, Behbahani, & Mehrnia, 2020; López-Palestina et al., 2018; Murmu & Mishra, 2018).

Pomegranate *(Punica granatum* L.*)* peel is typically produced after processing pomegranate fruits and discarded as waste which accounts for approximately 40 - 50% of the total fruit weight (Gullón, Astray, Gullón, Tomasevic, & Lorenzo, 2020; Kumar, Pratibha, et al., 2020). However, it has an excellent valorization potential as it is a rich source of polyphenols and other bioactive compounds (Kaderides, Kyriakoudi, Mourtzinos, & Goula, 2021; Kandylis & Kokkinomagoulos, 2020; Singh, Singh, Kaur, & Singh, 2019). Pomegranate peel contains around 27 different bioactive compounds, including ellagic acid, gallic acid and punicalagin A and B (Drinić et al., 2020; Suhag et al., 2022; Wu & Tian, 2017). These bioactive compounds are primarily responsible for its antioxidant, antimicrobial, antifungal, antiviral, anti-diabetic properties (Andrade et al., 2019; George et al., 2019; Kaderides et al., 2021; Kumar & Neeraj, 2018; Li et al., 2015; Pirzadeh et al., 2021; Singh, Singh, Kaur, & Singh, 2018; Singh et al., 2019). Furthermore, pomegranate peel extracts have the potential to be used as a prebiotic due to its ability to enhance the proliferation of *Bifidobacterium spp.* and *Lactobacillus spp.* (Kandylis & Kokkinomagoulos, 2020; Li et al., 2015). Previous studies have utilized pomegranate peel extract as a part of edible packaging to extend the shelf life of fresh-cut fruits and vegetables, meat and meat products, seafood, dairy and bakery food products (Kharchoufi et al., 2018; Khojah, 2020; Mushtaq, Gani, Gani, Punoo, & Masoodi, 2018; Pirsa, Karimi Sani, Pirouzifard, & Erfani, 2020; Venkatesh & Sutariya, 2019). In this context, the pomegranate peel extract has exhibited antioxidant and antimicrobial properties by reducing lipid oxidation, preventing moisture loss, controlling gas exchange, and reducing the rate of microbial decay during storage (Kumar, Pratibha, et al., 2020). Moreover, a study by Kanatt, Rao, Chawla, and Sharma (2012) indicated that adding pomegranate peel extract as an edible coating has antioxidant and antimicrobial properties. The authors demonstrated potential for the development of active packaging solutions for meat products, including temperature-dependent release of phenolics and antibacterial properties against Gram-positive food pathogens. Previous studies by Nair, Saxena, and Kaur (2018a) and Nair, Saxena, and Kaur (2018b) have also investigated edible packaging enriched with pomegranate peel extract on capsicum and guava fruit during a storage period of 20 and 25 days at 10 °C. The findings indicated extended shelf life and improvements in overall sensory and postharvest quality of the food products. Pomegranate peel enriched edible packaging has also been used on several different food products (Table 1), extending their shelf life by maintaining postharvest characteristics during the storage time. Specific applications include dairy products (cheese, cream cheese), meat (beef, chicken breasts), seafood (fish, shrimps) and fruits and vegetables (strawberry, guava, capsicum). In most cases, pomegranate peel extract in edible packaging exhibits various functionalities: mechanical (permeability, tensile properties, water loss, oxygen permeability); shelf life and safety-related effects (antimicrobial properties, oxidation, lipolysis); maintenance and improvement of sensory attributes; and retention of nutrient content (Abbas & Abdul-Rahman, 2020; Cui et al., 2020; Mehdizadeh, Tajik, Langroodi, Molaei, & Mahmoudian, 2020; Nair et al., 2018a, 2018b; Rongai et al., 2018; Valdés et al., 2020; Venkatesh & Sutariya, 2019).

The addition of pomegranate peel extract as a natural reinforcing agent has also been demonstrated to increase free radical scavenging activity of the polymeric matrix, improving its potential as bio-based food packaging (Kandylis & Kokkinomagoulos, 2020). The phenolic groups from pomegranate peel extract interact with polymers (chitosan/gelatine) and can change the rheological characteristics, structural, and antioxidant properties of materials. For example, a study investigating its rheological properties showed that viscosity and activation energy of materials are highly dependent on temperature, while antioxidant properties of the food products can be enhanced after applying pomegranate peel extracts (Bertolo, Martins, Horn, Brenelli, & Plepis, 2020). The interaction between water and gas barrier properties are usually decreased due to the compatibility between the matrix and filler (Ali et al., 2019; Cui et al., 2020; Kandylis & Kokkinomagoulos, 2020; Kumar & Neeraj, 2019; Munir et al., 2020). Therefore, recent research indicates a potential for pomegranate waste to be used successfully by the food industry and to potentially replace the synthetic antioxidants currently used in packaging materials.

3. Properties of edible packaging enriched with pomegranate peel extract

3.1. 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 films, which could potentially increase their thickness by disrupting their structure (Hosseini, Razavi, & Mousavi, 2009; Moghadam, Salami, Mohammadian, Khodadadi, & Emam-Djomeh, 2020). In a study by Emam-Djomeh, Moghaddam, and Yasini Ardakani (2015), it was reported that the incorporation of active substances affects the thickness, transparency and moisture content of edible packaging as a result of the formation of hydrophobic bonds between the matrix and active substance. This might be due to the addition of 'natural' antimicrobial agents and the presence of soluble and insoluble fibres consequently leading to the formation of sponge-like structures in edible films (Elsabee & Abdou, 2013).

Studies by Mushtaq et al. (2018) and Munir, Hu, Liu, and Xiong (2019) have proposed that the solubility and water vapour permeability (WVP) of zein and surimi films are reduced by increasing the concentration of pomegranate peel extract. However, the thickness and tensile strength of these edible films improve with increasing concentrations of pomegranate peel extract. In addition, the solubility of the edible films decrease by 39.14%, 36.25% and 33.60% with the addition of 2%, 4% and 6% of pomegranate peel extract, respectively. The WVP was reported as 2.06 ± 0.06 with addition of 6% pomegranate peel extract, which is lower compared to addition of 2% (WVP = $2.21 \cdot 10^{-12}$ g/m · S · Pa) and 4% (WVP = $2.09 \cdot 10^{-12}$ g/m · S · Pa) pomegranate peel extract in the investigated edible films (Munir et al., 2019). The mechanical strength and physical properties of the edible film were also increased with increasing concentration of pomegranate peel extract. For example, the thickness and mechanical strength with 6% pomegranate peel extract were reported as 96 µm and 6.00 MPa, respectively, which are higher compared to the addition of 2% and 4% pomegranate peel extract. Furthermore, these findings were also supported in studies by Emam-Djomeh et al. (2015), Oliveira et al. (2016) and Ali et al. (2019), who reported that the incorporation of pomegranate peel extract in edible films increases tensile strength and stiffness. This could also be due to the retention of semi-crystalline structure of the biobased packaging by pomegranate peel extract (Chen et al., 2020). The increased tensile strength and elongation at break in zein protein films have also been observed by Mushtaq et al. (2018); the study indicated that increased tensile strength of the edible films enriched with pomegranate peel extract is due to the formation of hydrogen bonds between the antioxidant agent and the matrix. The higher concentration of pomegranate peel extract decreases the impact strength of starch edible films because of the agglomeration of pomegranate peel extract particles within the matrix (Ali et al., 2019). In general, the elongation at break indicates the elasticity of edible films, and it can also be defined as the deformation of edible films under pressure (Jantrawut, Chaiwarit, Jantanasakulwong, Brachais, & Chambin, 2017). This property decreases with higher concentrations of pomegranate peel extract within the edible coating due to the molecular interaction between the matrix and additives, distribution of particles of pomegranate peel extract and presence of soluble fibres (Hanani, Yee, & Nor-Khaizura, 2019). Similarly, another study conducted by Kanatt et al. (2012) confirmed the physical and mechanical properties of edible materials which incorporated pomegranate peel extract. Hence, the interaction between the matrix and the active extract led to the formation of more cohesive and flexible films (Moghadam et al., 2020).

3.2. Barrier properties

The results of WVP and gas permeability testing are important tools used for the evaluation of mass transfer mechanisms as well as the solute-polymer interactions in edible films. According to the thermodynamics of irreversible processes, water chemical potential difference is the driving force of the water transfer through the film (Anoua, Ramirez-Martinez, Cherblanc, & Benet, 2014). The resistance of barrier against water and gas transmission is one of the most important properties for packaging material, which affects the packed food products' overall quality and nutritional value (Ščetar, Daniloski, Tinjić, Kurek, & Galić, 2022). Therefore, the low barrier property of edible packaging can be considered suitable for food applications to enhance the quality and shelf life of food products (Kanatt et al., 2012; Kurt & Kahyaoglu, 2014). Namely, edible packaging with lower permeability can reduce water and gas transportation in preserved food products (Rambabu, Bharath, Banat, Show, & Cocoletzi, 2019). The barrier properties (WVP and gas permeability) of edible packaging are also related to the shape, size and polarity of the penetrating molecules of the permeant, crystallinity of the materials, degree of crosslinking and chain segmental of polymers with suitable additives (Siracusa, 2012). Several researchers have reported on the influence of pomegranate peel extract on the barrier behaviour of edible films. A study by Emam-Djomeh et al. (2015) evaluated the incorporation of pomegranate peel extract and its effects on the increase of WVP of sodium caseinate film, as did Hanani et al. (2019) for gelatine based films, and He et al. (2019) showed that incorporating pomegranate peel extract in polyvinyl alcohol (PVA) films increases the WVP compared to pure PVA based film. In contrast, Yuan et al. (2016a) reported a decreased WVP of chitosan film by incorporating pomegranate peel extract, as also observed in zein based films by Mushtaq et al. (2018).

3.3. Thermal properties

The thermal stability of edible films varies due to the melting temperature and degradation of the materials (Kumar & Neeraj, 2019). The Thermo-Gravimetry (TG) and Differential Scanning Calorimetry (DSC) are common techniques to evaluate the thermal stability and crystalline nature of the films. The incorporation of pomegranate peel particles within the starch matrix improves the thermal stability of edible films due to the rigidity of the particles (Ali et al., 2019). Other studies done by Kanatt et al. (2012) and Qin et al. (2015) have also demonstrated the increased thermal stability of chitosan and chitosan-PVA films after the incorporation of pomegranate peel extract, which was due to the intermolecular interaction and compatibility between the matrix and the extract.

3.4. Antimicrobial properties

The pomegranate peel is a rich source of phenolic compounds and hydrolyzable tannins that have been associated with the promotion of antimicrobial activity (Afaq, Saleem, Krueger, Reed, & Mukhtar, 2005; Chen et al., 2020; Licciardello, Kharchoufi, Muratore, & Restuccia, 2018). Several studies have reported that the incorporation of pomegranate peel extract inhibits the growth of gram-positive and gram-negative microbes (*Escherichia coli, Pseudomonas, Salmonella spp., Staphylococcus aureus, Bacillus cereus, Listeria monocytogenes*), antiviral (Human Norovirus, Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2)) as well as fungal strains (*Candida Albican, Colletotrichum gloeosporioides,* *Botrytis cinerea, Penicillium digitatum, and Penicillium expansum*) (Abbas & Abdul-Rahman, 2020; Emam-Djomeh et al., 2015; Hanani et al., 2019; He et al., 2019; Kanatt, Chander, & Sharma, 2010; Kanatt et al., 2012; Mabrouk, Shaltout, Amin, Ezz, & Zeitoun, 2019; Moghadam et al., 2020; Nair et al., 2018a; Nicosia et al., 2016; Tito et al., 2021; Yuan, Lv, Yang, Chen, & Sun, 2015; Živković et al., 2021). A study by Ali et al. (2019) showed that incorporating pomegranate peel extract in starch edible films increases resistance to microbial growth against *S. aureus* and *Salmonella spp.* A study by Hanani et al. (2019) reported that the antibacterial activity of pomegranate peel extract (5%) in fish gelatine edible films is also effective against *Listeria monocytogenes, Escherichia coli* and *Staphylococcus aureus* by increasing the antimicrobial activity of the gelatine film due to the presence of phenolic and bioactive compounds in pomegranate peel. Namely, the film's antimicrobial activities increased significantly after the pomegranate peel incorporation. Abbas and Abdul-Rahman (2020) have investigated pomegranate peel extract in chitosan isolate films; reporting that the antimicrobial pomegranate peel is effective against Gram-negative bacteria (*Escherichia coli, Salmonella spp, Pseudomonas aeruginosa*), Gram-positive bacteria (*Staphylococcus Aureus, Bacillus spp*) and yeast (*Candida Albican*). A study of Moghadam et al. (2020) showed that incorporation of pomegranate peel extract in mung bean protein films produced strong antibacterial activity against *Escherichia coli* O157:H7 and *Listeria monocytogenes* compared to mung bean protein film which did not show any antibacterial activity against the tested strains. The antibacterial activity of pomegranate peel is attributed to the presence of tannins (punicalagins) and polyphenols (ellagic acid) which can act as antibacterial agents through different mechanisms such as microbial enzyme inhibition, reduction of membrane fluidity or by membrane perforation. In addition, *in vitro* findings by Tito et al. (2021) discovered that pomegranate peel extract is an inhibitor of SARS-CoV-2 spike binding to human ACE2 receptors. Although the reported findings are only preliminary and *in vitro*, there is strong potential for developing novel types of packaging for a variety of food items with the potential of reducing the spread of the virus.

3.5. Antioxidant activity

The incorporation of antioxidants into edible packaging improves the bioactive properties of the packaging material and can assist in preserving the nutritional value, shelf life and quality of the food products by retarding or suppressing oxidative stress (Chen et al., 2020; Kumar & Neeraj, 2019; Silva-Weiss, Ihl, Sobral, Gómez-Guillén, & Bifani, 2013). Various assays, such as 2.2 - diphenyl-1-picrylhydrazyl (DPPH), 2,2'-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid (ABTS) and ferric reducing antioxidant power (FRAP) are commonly used to evaluate the antioxidant activity of edible films. Furthermore, it is recommended that at least two different types of antioxidant assays be used when evaluating any food product's antioxidant activity (Munialo, Naumovski, Sergi, Stewart, & Mellor, 2019). The degree of antioxidant activity is generally proportional to the added amount of antioxidant agent (Gómez-Estaca, Giménez, Montero, & Gómez-Guillén, 2009; Moradi et al., 2012); however, this is not without limitations as antioxidant saturation levels are reached based on the additives profile (Munialo et al., 2019). Studies by Yuan, Lv, Zhang, Sun, and Chen (2016a) and Yuan, Lv, Tang, Zhang, and Sun (2016b) found that the addition of pomegranate peel extract significantly enhanced the antioxidant activity of chitosan-based films. Several other studies have also observed antioxidant effects following incorporation of pomegranate peel in different zein, fish gelatin, chitosan, pullulan and mung bean edible films, due to its higher phenolic content and tannin content (Hanani et al., 2019; Kumar et al., 2019; Moghadam et al., 2020; Mushtaq et al., 2018). Pomegranate peel improved the antioxidant properties of the fish/gelatine films in radical-scavenging activity tests in the study by Hanani et al. (2019), while Moghadam et al. (2020) showed that mung protein films enriched with pomegranate peel have high total phenolic content (TPC) and antioxidant activity (measured by ABTS and DPPH). Namely, TPC increased from 3.48 mg gallic acid equivalents (GAE)/g film (for the film without the extract) to 13.88 mg GAE/g for the film with 25% of pomegranate peel due to the peel being a rich source of phenolic compounds (catechins, punicalin, pedunculagin, punicalagin, gallic acid, and ellagic acid). These results indicate that the anti-radical activity and reducing power of the mung bean protein film increases with the addition of thepomegranate peel (Hanani et al., 2019; Magangana, Makunga, Fawole, & Opara, 2020). Therefore, this might be of potential benefit for commercial utilization in the packaging of food products that have a high susceptibility to oxidation.

4. 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, flavor, and other sensory attributes of packed items (Bodbodak, Shahabi, Mohammadi, Ghorbani, & Pezeshki, 2021; Giannelli et al., 2021; Ko, Dadmohammadi, & Abbaspourrad, 2021; Kumar, Neeraj, et al., 2020). Wambura, Yang, and Mwakatage (2010) have applied a coating on roasted peanuts to investigate their oxidative stability and antioxidant property when stored at 35 ^{o}C for 12-weeks. The coating was prepared using the carboxymethyl cellulose (CMC) enhanced with jujube, pomegranate peel extract and tocopherols. The incorporation of pomegranate extract was the most effective addition to edible material as it improved the storage stability and protected the browning of roasted peanuts (Wambura et al., 2010). Zarei, Ramezani, Ein-Tavasoly, and Chadorbaf (2015) studied the effect of pomegranate peel extract (1%) and orange peel extract (1%) with chitosan nanoparticles on quality of refrigerated stored silver carp fillet. The authors found that the developed nano-chitosan-based coating with incorporated orange and pomegranate peel extracts helped to minimize lipid oxidation and improve the sensory and physiochemical quality of refrigerated fish fillets. Furthermore, Yuan et al. (2016b) observed the effect of chitosan coatings combined with pomegranate peel extract and sodium metabisulphite on refrigerated pacific white shrimps. The coating helped maintain the white shrimp's quality and reduced the total value of volatile based nitrogen compounds, pH, and microbial counts. Chitosan coating with pomegranate peel extract was more effective than chitosan coating or pomegranate peel extract alone in the retard of melanosis in shrimp, suggesting that there is a synergistic effect between chitosan coating and pomegranate peel extract. The pH of the fresh shrimp was 7.24 (initially), but during storage, there is a rise in pH of shrimp due to the accumulation of basic compounds because of the activity of bacteria or enzymatic actions (Yuan et al., 2016b). However, the rise in pH was highest in the control shrimp for all the sampling days, while it was significantly inhibited by chitosan coating and pomegranate peel extract or chitosan coating alone. The bioactive compounds in pomegranate peel possess antioxidant and antimicrobial properties that contribute to positive effects in storing meat, seafood and other food products (Yuan et al., 2016b).

A study by Alsaggaf, Moussa, and Tayel (2017) developed an edible chitosan coating incorporated with pomegranate peel extract to enhance the physicochemical properties of refrigerated *Nile tilapia* fish fillets, stored at 4 °C for 30 days. The pomegranate peel extract contributed to preserving and maintaining biological, sensorial quality, including texture, colour, odour, shelf-life, and antimicrobial activity of refrigerated fish fillet (Alsaggaf et al., 2017). Mohebi and Shahbazi (2017) developed a film and wrapping material to study the effect on fresh shrimp during refrigeration. For this purpose, chitosan and gelatine were used alone and combined with incorporation with pomegranate peel extract, cellulose nanoparticles and *Ziziphora clinopodioides* Lam. essential oil. All treated shrimp samples showed less bacterial contamination compared to the control. The chitosan-based film combined with pomegranate peel extract (1%), cellulose nanoparticles (1%) and *Ziziphora clinopodioides* Lam. essential oil (1%) demonstrated the highest antibacterial activity and organoleptic score after 11 days of storage (Mohebi & Shahbazi, 2017). Tayel, Moussa, Salem, Mazrou, and El-Tras (2016) investigated a novel bioactive edible coating formulated with chitosan and various plant extracts (pomegranate peel, cress seeds, olive leaves and senna pods) to control citrus fruits mould over a storage time of 2 weeks. The study revealed that incorporating each plant extract in chitosan coating individually, demonstrated potential to combat fungal growth on citrus fruit. Most citrus damage is caused by *Penicillium spp.* such as green (P. *digitatum*) and blue mould (*P. italicum*). The most effective extracts for the treatment of green and blue mould were cress and pomegranate peel extracts which significantly prevented citrus fruits from decay after 14 days of treatment (Tayel et al., 2016), meaning that natural derivatives could be used as powerful antifungal alternatives to protect citrus fruits. A study by Kharchoufi et al. (2018) investigated chitosan and locust bean gum-based antifungal edible coating incorporating pomegranate peel extract and biocontrol agents to reduce the physiological and postharvest decay of orange fruits. The results revealed that incorporating the extract in coating materials reduced postharvest disease incidence, disease severity and lesion diameter in the oranges with excellent antifungal activity against *Penicillium digitatum*. In addition, Licciardello et al. (2018) studied the effect of chitosan and locust bean gum edible coatings with incorporation of pomegranate peel extract on white shrimps during refrigerated storage. The addition of the extract helped to maintain products physical properties and antimicrobial activity against *Pseudomonas* spp. The combination of chitosan film with pomegranate peel extract (10g /L) could be used to control the spoilage of seafood products due to their antimicrobial properties (Yuan et al., 2015). Pectin based edible coating incorporated with pomegranate peel extract and anti-browning agents (calcium ascorbate and citric acid) was investigated on fresh-cut 'Rojo Brillante' fruits at 5 °C for 5 days of storage (Taberner, Sanchís, Mateos, Palou, & Pérez-Gago, 2016). The active edible coating maintained the color of the fresh cut fruits due to controlling of enzymatic activity and phenol oxidation. The incorporation of pomegranate peel extract with pectin and calcium ascorbate reduced the firmness of coated fruits compared to control samples, which can improve the marketability of fruits by preserving their flavour and sensory characteristics (Taberner et al., 2016). Other studies have evaluated the antifungal properties of coated capsicum and guava at 10 °C for 20 days of storage (Nair et al., 2018a, 2018b). For this purpose, the edible polysaccharide coatings were developed using chitosan and alginate enriched with pomegranate peel extract. The studies showed that the extract was compatible and enhanced the quality of capsicum and guava fruits in terms of prolonged shelf life, retardation of the respiration rate, increased phenolic and antioxidant activities, and good antifungal properties against *Colletotrichum gloeosporioides* (Nair et al., 2018a, 2018b). Two studies extensively investigated the shelf life of litchi and bell pepper and proposed a way to maintain the postharvest quality of certain groups of fruits and vegetables by using chitosan-pullulan composite edible coating enriched with pomegranate peel extract, due to improved barrier properties of materials against gas and water transpiration (Kumar, Neeraj, et al., 2020; Kumar, Ojha, Upadhyay, Singh, & Kumar, 2021a). The authors also found improved quality, sensory and antimicrobial properties (Kumar, Neeraj, et al., 2020; Kumar et al., 2021a). For example, the extension of shelf life of litchi and bell pepper was prolonged for 3 and 6 days, respectively. The sensory evaluation score on 18 days of cold storage in treated bell pepper was 7.2 (freshness), 7.7 (colour), 7.3 (texture), 7.4 (taste) with 7.4 of overall acceptability which was higher compared to control bell peppers i.e. 5.1 (freshness), 6.1 (colour), 6.8 (texture), 6.4 (taste) and 6.1 (overall acceptability). The bell peppers stored at room temperature were significantly higher in overall acceptability in treated (6.53) compared to untreated samples (4.27) on 12th day of storage. In the case of litchi fruits, higher overall acceptability was recorded with treated fruits (5.35 and 7.56) compared to control fruits (4.11 and 6.65) at room and cold storage condition (out of 9 scale), respectively, on 12th day of storage (Kumar, Neeraj, et al., 2020; Kumar et al., 2021a).

5. Health benefits of pomegranate peel extract

Pomegranate fruits, peels, leaves, and seeds have been used for a long time as traditional herbal medicine in many countries. Due to many bioactive compounds found in pomegranate peels and pomegranate fruits in general, several health benefits are ascribed to the consumption of this fruit. Namely, consumption of pomegranate was reported to have cardio-protective, anti-inflammatory, anti-allergic, support immune function, cholesterol-lowering, and may protect against cancer and type 2 diabetes (Banihani, Swedan, & Alguraan, 2013; Laurindo et al., 2022; Magangana et al., 2020; Saroj, Kushwaha, Puranik, & Kaur, 2020).

Pomegranate is known for its biological effects, exerted through the free radical scavenging capabilities of its phenolic compounds. Phenolic compounds such as anthocyanins, ellagic acid glycosides, free ellagic acid, ellagitannins, punicalagin, punicalin and gallotannins are also found in the peel (Karimi, Sadeghi, & Kokini, 2017). Most of the antioxidant compounds are concentrated in pomegranate peel and juice, which accounts for 92% of the antioxidant activity of the fruit (Ismail, Sestili, & Akhtar, 2012). For example, punicalagin is an ellagitannin found in the peel of pomegranate; it is a polyphenol with antioxidant, hepatoprotective, anti-diabetic, anti-atherosclerotic and chemopreventive and antiproliferative activity against tumor cells (Venusova, Kolesarova, Horky, & Slama, 2021). However, to warrant wide utilization, all bioactives from pomegranate peels should be investigated more rigorously in clinical studies for their potential effects, long-term safety, and to better understand its chemical profile to establish toxicological toxicity limits (Karimi et al., 2017).

In general, pomegranate peel is a relatively low-cost by-product of the food industry with great potential to improve the physicochemical and sensory properties of food products when incorporated into polysaccharides, proteins, lipids or composite films. Future research should also focus on incorporating pomegranate peel extract in functional food and beverages because it can be considered as a prebiotic and probiotic agent that can improve human gut microflora and potentially, overall human health (Ibrahim, Awad, & El-Sayed, 2020).

6. Conclusion and future perspectives

The beneficial effects of active edible packaging containing pomegranate peel extract as a carrier for naturally-derived food components on perishable foods has been proposed by several studies in this review. The pomegranate peel is considered as a valuable source for phenolic and flavonoid compounds, such as ellagic acid, gallic acid, punicalagin A, punicalagin B, quercetin, and several other bioactive compounds that contribute to its antioxidant, antimicrobial and antifungal properties. The increased concentration of pomegranate peel extract within the edible film matrix can improve the mechanical (stiffness, modulus, tensile and drop impact strength), antioxidant, antimicrobial, and thermal properties of food products. Pomegranate peel extract is also associated with reducing the barrier properties against water and gas exchanges of the films and can assist in the retardation of lipid oxidation and microbial contamination. Considering all of the proposed beneficial effects of adding pomegranate peel extract into functional packaging material, the benefits of applying these films may enhance the shelf life and improve the sensory aspects of packed food products.

A limitation of wide use of pomegranate peel extract is its bitter taste. To mask this, appropriate encapsulation methods could be considered, and a variety of biopolymers/edible matrices are often used for this purpose. Encapuslated forms of pomegranate peel extracts are designed with customized wall thicknesses that enable proper masking of the bitter taste of the extract and can determine the release effect of the extract over certain period of time.

Pomegranate peel extract from biowaste is a low or no cost example which can contribute to the mission of sustainable natural solutions for incorporating antioxidant and ntimicrobial compounds in active packaging. Furthermore, by decreasing the amount of biowaste materials in supply chains, there will be less need to landfill in line with several Sustainable Development Goals promoted by the United Nations (2015), as well as being with aligned with the principles of circular economy. In order to utilize pomegranate peel and its potential benefits for novel trends in active edible packaging and sustainable food processing technology, future research should be orientated towards identifying the optimum levels /ratios of pomegranate peel extract and its potential interaction with different edible matrices. The valorization of by-products of pomegranate fruit in edible packaging should also be considered in industrial scale food coating applications or for other food processing needs such as increasing the health promoting effects of functional foods.

Acknowledgement

The author sincerely acknowledges the contributions of the co-authors and their institutions and delegates their selfless efforts. The graphical abstract is created with BioRender.com

Author Contributions

N.K. conceived the study and research question, and all authors designed the review. N.K. and A.T.P. wrote the original draft, conceptualized, reviewed and edited the manuscript. D.D., N.N. and N.D.C. provided critical feedback and analysis. A.T.P. provided critical feedback and analysis, supervised, reviewed and edited the manuscript. All authors have contributed to the manuscript and reviewed the final version.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The authors declare no conflict of interest. N.N. has previously received funding from National Health and Medical Research Council, Australian Capital Territory government, Dementia Research Foundation, Arthritis ACT, Australian Association of Gerontology; university grants from University of Newcastle, Australian National University, University of Canberra; industry funding from Assistive Technology Australia (P/L), Chiron Health Products (P/L), Capitol Chilled Foods Australia (P/L); received travel funding from Nutrition Society of Australia and Australian Atherosclerosis Society.

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Figures and tables

Table 1. Application and functions of pomegranate peel extract in edible packaging and their effect on food products.

Table 1. Application and functions of pomegranate peel extract in edible packaging and their effect on food products.

Biopolymers	**Plasticizer / additives**	**Pomegranate peel**	**Edible film/ coating**	**Application**	**Effects**	**References**
Chitosan and polyvinyl alcohol	0.1% (v/v) glycerol	0.15% (ml) pomegranate peel extract	Film	-	Incorporation of pomegranate peel extract showed protection against UV light, improved tensile strength, antioxidant activity and antimicrobial properties against *B. cereus* and *S. aureus*	Kanatt et al. (2012)
Casein	30% glycerol	Methanol : acetone : water (20 : 40 : 40) extract	Film	Ground beef	Showed antimicrobial activity against *E. coli and S. aureus,* extended shelf life of beef, increasing concentration of extract affect mechanical & barrier property of the film, increased phenolic activity	Emam-Djomeh et al. (2015)
Chitosan	0.5% (w/w) glycerol/ 10 g/L carvacrol	10g/L aqueous extract of pomegranate peel	Film	-	Pomegranate peel enriched film exhibited higher phenolic and antioxidant activity, antibacterial activity against E.*coli* and S. *aureus*	Yuan et al. (2015)

Chitosan + montmorillonite	0.1% (v/v) glycerol	1 %, 1.5 % and 2% pomegranate rind powder	Film		Incorporation of pomegranate peel extract significantly improved the water vapour barrier property, tensile strength of film affected by incorporation of pomegranate peel extract and contained higher phenolic and antioxidant activity	Qin et al. (2015)
Montmorillonite	0.75 g glycerol	Pomegranate peel pectin	Film	-	Improved mechanical strength and young module of the film but decreased elongation after incorporating pomegranate peel pectin.	Oliveira et al. (2016)
Wheat and corn floor		5% and 10% pomegranate peel extract	Coating	Fresh silver carp	Improved storability and shelf life of fillets, minimized lipid oxidation, showed antioxidant and antimicrobial effects	Tarkhasi (2016)
Chitosan	-	1.5% Pomegranate peel extract	Coating	Pacific white shrimp	Reduced the microbial load on Pacific white shrimp and extended shelf life during 10 days of storage period	Yuan et al. (2016b)
Chitosan	1% glycerol	0.5%, 1.0%, 1.5% and 2.0%	Coating	Nile tilapia (*Oreochromis*	Extend shelf life and maintained chemical,	Alsaggaf et al. (2017)

		pomegranate peel extract		*niloticus*) fillets	microbiological and sensory quality of Nile tilapia fillets	
Gluten	3% glycerol	5% (w/v) peel extract	Film	-	Incorporation of pomegranate peel extract showed good structural stability and molecular interaction between material and plant extract	Kumari, Mahajan, Joshi, and Gupta (2017)
Hydroxypropyl high-amylose starch	20% polyethylene glycol	(0, 2, 4, 6, 8, 10, 12, and 14% w) peel powder based on dry starch content	Film	-	Showed excellent antimicrobial activity against *S. aureus* and *Salmonella* bacteria. Improved mechanical strength and young modulus of film Showed good compatibility between material and peel powder with crystalline nature	Ali et al. (2019)
Polycaprolactone /starch	-	Pomegranate rind (filler)	Film	-	Showed good antimicrobial activity against *S. aureus, and mechanical strength*	Khalid et al. (2018)
Chitosan and locust bean gum	Glycerol	0.072g, 0.180 g, 0.361 g, 0.061g, 0.152g and 0.304g dry water pomegranate peel extract	Edible film/ coating	Oranges	Control the growth of *Penicillium digitatum* and to reduce postharvest decay of oranges	Kharchoufi et al. (2018)

Chitosan and locust bean gum	20% (w/w) glycerol	0.072g, 0.180g and 0.361g dry peel extract/ml	Coating	White shrimps	Addition of pomegranate peel extract was found effective to minimize reduction of microbial load i.e. *Pseudomonas spp*. and p*sycrotrophic* on white shrimps during storage period and also reduced the production of volatile base	Licciardello et al. (2018)
Zein	0.3 ml glycerol	Aqueous extract (0, 25, 50 and 75 mg/g of film forming solution	Film	Cheese (Kalari/kradi)	Minimize lipid oxidation, showed antimicrobial activity against *E. coli, P. perfringens, M. luteus, E. faecalis, S. aureus, P. vulgaris and S. typhii* without affecting sensory properties	Mushtaq et al. (2018)
Chitosan and alginate	0.75% and 10% (w/v) glycerol	1% pomegranate peel extract	Coating	Capsicum	Maintained postharvest and sensorial quality of capsicum during storage and also inhibit the growth of fungal strain (C. *gloeosporioides*)	Nair et al. (2018a)
Chitosan and alginate	0.75% and 10% (w/v) glycerol	1% pomegranate peel extract	Coating	Guava	Maintained postharvest and sensorial quality of guava during storage at low temperature for 20 days with restricting respiration, weight loss and ethylene production.	Nair et al. (2018b)

-	-	Pomegranate peel extracts (0.75%, 1.5% and 3%)	Coating	Strawberries	Higher correlation between spectra and disease severity Inhibit the growth of *Botrytis cinerea* gray mould fungus Extend shelf life of strawberry	Rongai et al. (2018)
Pectin	2.5g/kg oleic acid	15g/kg aqueous Pomegranate peel extract	Coating	Fresh-cut 'Rojo Brillante'	Reduced enzymatic browning, maintained firmness and sensory appearance	Taberner et al. (2016)
Fish gelatin	30% (w/w) glycerol	1% - 5% (w/w) peel powder	Film	-	Improve mechanical strength, antioxidant & antimicrobial activity against *S. aureus, L.monocytogenes, E. coli.* Increased water barrier properties and decreased solubility	Hanani et al. (2019)
Polyvinyl alcohol	5 g Sodium dehydroacetate	Powder	Film	-	Improved mechanical strength, no effect on barrier property, complex interaction between material and extract, antibacterial property against *E. coli and S. aureus*	He et al. (2019)

Chitosan:pullulan	1% (v/v) glycerol	5% (v/v) pomegranate peel extract	Film	-	Improved mechanical, functional, antioxidant and phenolic activity of the film. The interaction of peel extract was shown excellent in 50: 50 blend film of chitosan and pullulan	Kumar et al. (2019)
Mung bean protein	50% (w/w) glycerol	0-, 2.5, 12.5, and 25% w/w (Pomegranate peel powder)	Film	-	Improved mechanical, functional, antioxidant and antimicrobial properties of the edible film	Moghadam et al. (2020)
Silver carp surimi protein	60% (w/w) glycerol/ 0.25% (w/v) Tween 80	0, 2%, 4% and 6% (w/w) peel extract	Film		Incorporation of pomegranate peel extract improved the mechanical, thermal, and barrier properties of film, concentration of pomegranate peel extract have significant effects on the properties of film, good interaction between protein and phenolic content of pomegranate peel	Munir et al. (2019)
Chitosan	100 mg glycerol	0.25%, 0.5% pomegranate peel extract	Film as wrapping material	Cream cheeses	Incorporation of pomegranate peel extract improved the overall properties i.e. antioxidant, antimicrobial, mechanical etc. of the film	Pirsa et al. (2020)

Pomegranate peel/orange peel	20% glycerol	-	Film as wrapping material	Bread	Pomegranate peel extract particles uniformly distributed in the film matrix and improve color visibility Significantly reduced the weight loss of bread and microbial load during storage	Venkatesh and Sutariya (2019)
Chitosan	1% glycerol	3% pomegranate peel extract	Film	Chicken breasts	Improved storability of chicken breasts and protect against *P.aeruginosa and S. aureus, bacillus, and* yeast *(Candida Albican.* The incorporation of pomegranate peel extract also improved the sensorial properties of the chicken breasts during the storage	Abbas and Abdul-Rahman (2020)
Chitosan/gelatine	-	Peel extract	Film	-	Improved rheological, antioxidant and antimicrobial properties of the film after incorporation of pomegranate peel extract	Bertolo et al. (2020)
Zein	20% glycerol + chitosan nanoparticle	Peel extract	Film	-	Improved thermal properties of zein active film. Inhibited growth of *L. monocytogenes*	Cui et al. (2020)

Fish gelatine and κ-carrageenan		0.5%, 1.0%, 1.5% and 2.0% peel extract	Coating	Fish fillet	Prolonged shelf life of fish fillet with higher sensorial attributes up to 30 days of storage Reduced microbial count during storage. Authors recommended a combination of edible coating of fish gelatin:carrageenan: pomegranate peel extract prolong shelf life of fish fillet during refrigerated storage conditions.	Khojah (2020)
Chitosan-starch	30% (*w*/w) glycerol / tween 80/ 0.2% essential oil	0.5% and 1% peel extract	Films	beef	Incorporation of pomegranate peel extract and essential oil extended shelf life of beef during storage, enhanced antioxidant and antimicrobial activity	Mehdizadeh et al. (2020)
Chitosan / Poly (ethylene oxide)	Polyethylene oxide	Pomegranate peel extract	Coating	Meat	Improved storability & shelf life of beef during storage. Showed excellent physiochemical properties as well as antimicrobial activity against E. *coli*	Surendhiran, Li, Cui, and Lin (2020)

Fish gelatine	-	(0, 10, 30 wt.) % Peel powder	Film	-	Increased stiffness of the edible film, decreased elongation & transparency, no difference in barrier properties, increased film resistance, and high thermal properties with antimicrobial activity against *S. aureus*. Incorporation of pomegranate peel powder maintained the integrity of materials.	Valdés et al. (2020)

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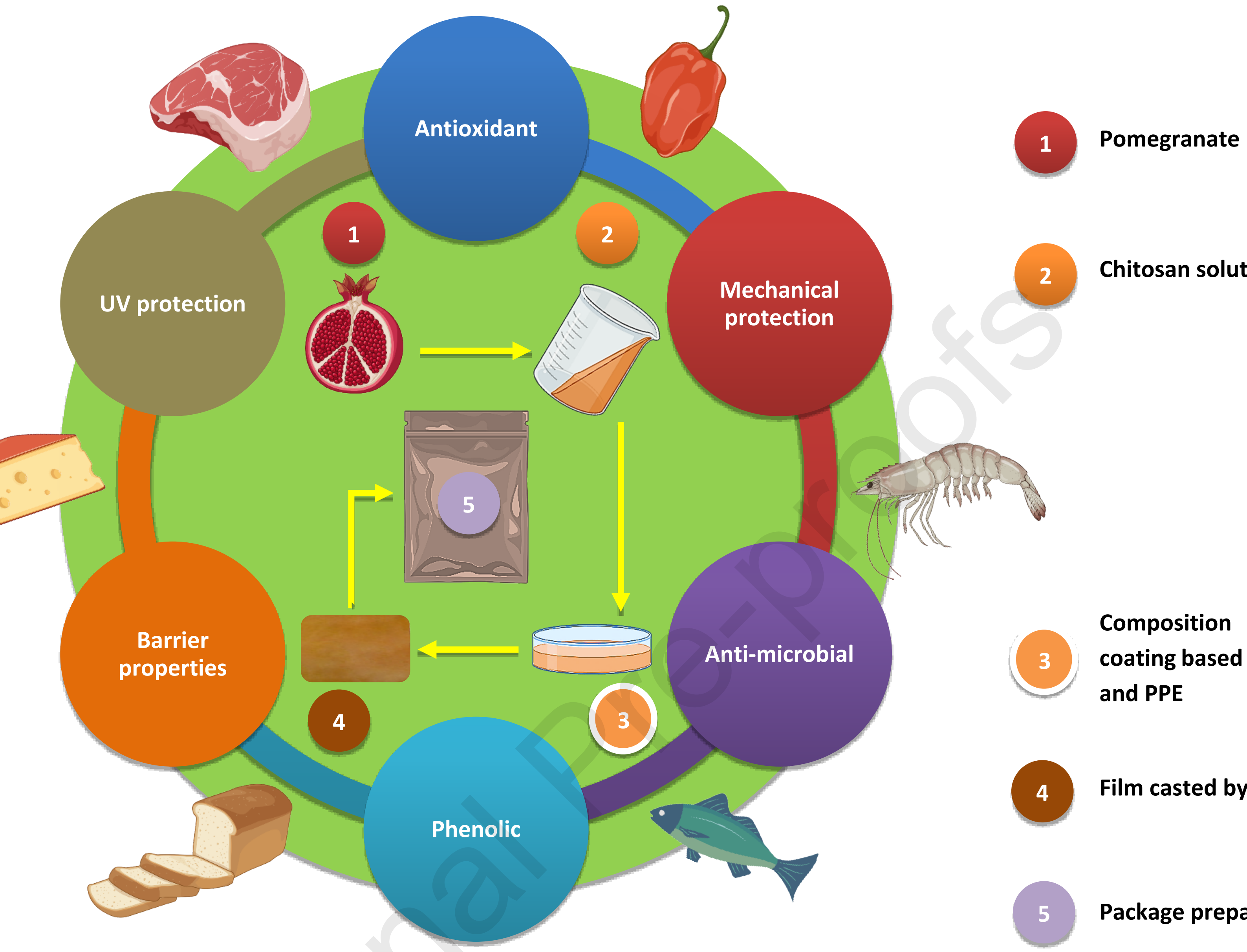
Antioxidant
Mechanical protection
Anti-microbial
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Highlights

- Edible films and coatings with addition of pomegranate peel extracts are reviewed
- Pomegranate peel is a valuable source of bioactive compounds
- Active role of edible packaging is emphasized by addition of pomegranate peel extracts
- Pomegranate peel extracts as a healthy addition to edible packaging formulations.