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Review on Novel Approach to Food Shelf Life Extension: Fruit Peel Polyphenols as Eco-Friendly Photosensitizers

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Abstract

Polyphenols, a group of phytochemicals, have a vast spectrum of biological activities, including activities against microbes and photosensitizing properties. Their antimicrobial activity is attributed to mechanisms, including the disruption of the membrane, enzyme binding and disruption of microbial signaling pathways. Photosensitizers of polyphenols plays significant role in photodynamic therapy in generating reactive species after light activation, showing a marked ability to target microorganism and cancer cells. Because of the bio functional character of polyphenols, they are, in principle, effective players as medicines, food and environmental purposes. This review highlights the chemical diversity of polyphenols, their interactions with microbial systems, and their photodynamic properties, providing insights into their potential applications in combating antibiotic resistance and improving photodynamic therapies. The presentation also addresses the problems and directions of the future applications of polyphenols in these new functions.

Keywords: Photosensitizer, Photodynamic Therapy, Food Preservation.

1. Introduction

Fruit peels have been demonstrated to possess antibacterial, antioxidant and anti-inflammatory activities. Citrus fruits, such as peels, are also valuable for their nutritional content and bioactive properties. They are rich in sugar, organic acid, lipid, polysaccharide, vitamins, mineral, flavonoids, carotenoids, and volatile compound. Studies on mango peels have shown their potential as a natural source of antioxidants, starch, flour, and feed. They also show anti-inflammatory, anti-fungal and antiproliferative, anti-atherogenic and and anti-thrombotic effects. Polyphenols, a class of phytochemicals found in plants, are essential for human health due to their numerous potential health benefits. Flavonoids, a group of polyphenolic compounds, are widely distributed in the plant kingdom and possess anti-inflammatory, anti-hepatotoxic, and anti-ulcer characteristics. The antioxidant activity is found in fruit peels (grape peel, mango peel and pomegranate peel). Specifically the blackthorn fruits can be employed as natural antioxidants, by virtue of their ability to remove free radicals and protect antioxidant levels during processing and storage. Fruit peels are rich in a variety of phenolic compounds such as gallic acid, quinic acid, protocatechuic acid, catechin, chlorogenic acid, caffeic acid, ferulic acid, and rutin, largely

attributed to antioxidant activities. These molecules are used in both classic and therapeutic ways, for example, protect cells from free radicals or prevent cancer. Banana peels contain more phenolics, and phenolics are known to be beneficial to human health in preventing cancer, diabetes, obesity, and cardiovascular disease. They can also be used as functional additives for food. This research investigates application of natural pigments from fruit peels, which can be utilized for converting them into dye-sensitized solar cells (DSSCs), which is a sustainable energy source that can convert sunlight into electrical energy. Dragon fruit dye is an active ingredient in DSSCs that mediates photoelectron transfer and photon uptake from sunlight's photons. Polyphenols from fruit peels have antimicrobial properties against foodborne infections, working against bacteria by deactivating enzymes or preventing the production of bacterial biofilms. They are natural preservatives that can be used in place of synthetic ones that can cause cancer, allergies, asthma, and skin irritation. Flavonoids, tannins, alkaloids, glycosides, and terpenoids, from fruit peels with pharmacological and medicinal effects. Fruit peel-based polyphenols are in demand today for use in protective food treatments because of their antioxidant and antibacterial activities. These extracts can retain nutritive value and shelf life without the use of artificial chemicals. Pomegranate peel extracts possess strong antibacterial activity, inhibiting the growth of microorganism and delaying the oxidation. Citrus peel polyphenols can also extend the shelf life of meat and seafood items by preventing lipid oxidation and preserving the meat's flavor, color, and nutritional value. Fruit peel polyphenols are also used in functional foods and dietary supplements due to their potential health benefits. Waste valorization of fruit peels constitutes an opportunity to convert them into valuable bioactive products for a number of applications.

1.1 Fruit Peels

Fruit is peels are with nutritional and bioactive compounds that have the ability to prevent chronic disease. Nevertheless, their peels made by industrial production have adverse environmental consequences. These peel solutions have a higher concentrations of bioactive compounds in order to protect from insect and microbial damage to the flesh, which offers a potential industry in food and pharmaceuticals [40]. Fruit peels, which are generated as agricultural waste, have antibacterial, antioxidant and anti-inflammatory properties. These compounds have been extracted by researchers, and presented a sustainable alternative to antibiotic problems through prevention of agricultural waste disposal-induced pollution [33]. Citrus fruit peels and seeds can be processed into useful products, such as fish feed, activated carbon, and paper, which help to decrease pollution and processing issues [12]. Citrus fruits contain a high content of sugar, organic acid, lipids, polysaccharides, vitamins, minerals, flavonoids, carotenoids, and volatile substances, with particular differences depending on the species, variety, and cultivation method for flavonoids and vitamin C [12]. Studies on Ataulfo type mango peels are scarce, but the same have been used as the sources for studying antioxidants, starch, flour, and animal feed. They also have a potential use in biogas synthesis and pectin synthesis. Extracts of mango peels contain compounds with anti-inflammatory, anti-fungal, antiproliferative, anti-atherogenic and anti-thrombotic activity [22]. Banana peels have the second-rank highest content of phenolic constituents and are consumed worldwide. They are also claimed to cure a broad range of ailments, such as diabetes, in traditional folkloric medicine and Ayurveda. They also contain micronutrients and antioxidants [9].

1.2 Polyphenols

Polyphenols, secondary metabolites of plants, are flavonoid or non-flavonoid molecules with aromatic rings and hydroxyl groups. They are abundant in natural plant organs and have gained attention for potential health benefits [46]. Plants contain naturally occurring antioxidants, including phenolic and polyphenolic chemicals. Phenolic antioxidants promote health, while flavonoids have anti-inflammatory, anti-hepatotoxic, and anti-ulcer properties. Plant parts like bark, stalks, leaves, fruits, roots, flowers, pods, seeds, stems, latex, and hull contain antioxidant elements. Fruit peels and seeds may also possess antioxidant qualities [15]. Blackthorn fruits are rich in phenolic components, vitamins E, dietary fiber, and carbohydrates, making them valuable in traditional medicine and nutrition. They are also used in pharmaceutical and functional food sectors as natural preservatives, with strong antioxidant properties and antibacterial activity [25].

1.2.1 Phenolic Acid

Many fruit peels' phenolic compounds have now been studied . It is noted that gallic acid, quinic acid, protocatechuic acid, catechin, chlorogenic acid, caffeic acid, ferulic acid, and rutin are their main phenolic compounds, which are mainly associated with their antioxidant [46]. Fruits' preventive qualities are mostly attributed to the presence of phytochemicals or phytonutrients. Numerous polyphenolic chemicals found in citrus peel have both traditional and therapeutic uses. As antioxidants, these substances shield cells from the damaging effects of free radicals and lower the risk of cancer by preventing the growth of tumors (Singh, et al., 2022).

1.2.1.1 Banana Peels

Banana peels, in comparison with others, are considered to be the ones containing the richest amount of phenolic compounds that are beneficial to our health in many ways like cancer risk reduction and lipid oxidation inhibition. They also serve as functional food additives. Bananas' value is boosted and the phenolics juice sector is stabilized through the recovery of these phenolics. Effective recovery and utilization have [42]. The utility of chemical profile and sustainable applications been identified as crucial strategies for the recycling and use of these biological by-products. The banana peels, which are rich sources of oligosaccharides, cellulose, and minerals, are employed as agricultural by-products to reduce the pollution. The peel is also an important resource of phenolic compounds with the total content of phenolics being in the range from 4.95 to 47 mg/g of dry matter. Banana peels show diverse biological and pharmacological impacts [47].

1.2.1.2 Pomegranate Peels

Pomegranate peel, a part of the fruit, contains a polyphenol complex with the powerful anti-inflammatory and antioxidant properties, it also has punicalagin, ellagic acid, and gallic acid [34]. The ingredients of the polyphenols in pomegranate peel enhance the healing of ulcers by the generation of new cells and the repair of the cells that are harmed because of the oxidative stress caused by the free radicals, which makes it a potential future therapy and the new superoxide scavenger [34]. Variety of bioactive compounds such as hydrolyzable tannins (gallic and ellagic acid) and flavonoids (anthocyanins, catechins, and other complexed flavonoids) is found in pomegrant peels [38].

1.2.1.3 Citrus Peels

Citrus peel, a by-product of juice extraction or processing, presents a major pollution problem because it spoils quickly. On the other hand, it can also be employed in the production of value-added food

products [23]. The exploration of the phytochemistry of citrus peel by researchers seeks to uncover applications in the field of functional foods, as well as dietary supplements and nutraceutical products. The natural antibiotics of the product create a preservative that is harmless to health and thus cuts the number of synthetic substitutes necessary to use [23].

1.2.2 Flavonoids

1.2.2.1 Citrus Peels

Recent technological developments have dramatically allowed for the extraction and purification of citrus waste, a phenomenon that liberates beneficial flavonoids. In citrus fruit peels that are rich in this particular nutraceuticals the flavonoids can be used as starting materials, zein suggests [45]. Citrus is a popular fruit crop worldwide represented by different choices such as oranges, lemons, and tangerines. These fruits are endowed with secondary metabolites, vitamins, minerals, and fibers. Among them, flavonoids and phenolic acids are the main type of phenolic compounds, and the ultimate ingredient is the skin containing natural antioxidants. Shell, the "skin" that makes from 50% to 65% of the fruit's weight, contains bioactive flavonoids with pharmacological effects including anti-inflammatory, anti-cancer, antibacterial, anti-aging and cardiovascular [1]. Citrus peel's flavonoids are undoubtedly the leading bioactive compounds, particularly when it comes to its anticancer, degenerative and infectious disease prevention among others. Detecting bioactive components that have potent anticancer effect would be desired, but there are increasing evidences that these chemical compounds work together in the citrus peel extract (Nooshin Koolaji, et al., 2020).

1.2.2.2 Apple Peels

Apple peel contains three to six times more flavonoids than flesh, including special flavonoids like quercetin glycosides, and it has a strong antioxidant effect in its extract (Khalid, et al., 2021). Flavonoids, which are a group of secondary metabolites of polyphenolic plants, are strong antioxidants that are helpful in the maintenance of a healthy lipidic system and the prevention of vascular diseases, such as diabetes, cancer and hyperglycemia (Zhang, et al., 2020). Apple intake comprised of phenols and flavonoids is associated with lower cancer incidence, prevention of chronic diseases, and heart disease in women [13]. The year due to its widespread consumption. Apples, a fruit that is popular and a good source of powerful phytochemicals, are connected with the lowest risk of diabetes, heart disease, asthma, and cancer, respectively, since they are antioxidants [8].

1.2.3 Non-Flavonoids

Grape phenolic compounds fall into two major families: flavenoids (flavonols, dihydroflavonols, flavan-3-ols, and anthocyanins) and non-flavonoids (hydroxybenzoic acids, hydroxycinnamic acids, and stilbenes) which are classified on the basis of the basic structure of these molecules the movement of hydoxyl groups and their replacement methods [26]. Non-flavonoid phenolics, e.g. hydroxycinnamates, stilbenes, and benzoic acids, play a major role in wine. Benzoic acids are found in both grape and wood, while hydroxycinnamates and stilbenes are found in grapes. Hydroxycinnamates are phenolic acids which have a phenolic ring with a conjugated double bond occurring between the carboxylate group and the phenolic ring. There are three fundamental acids in grapes: coumaric, caffeic, and ferulic acids. Despite the fact that gallic acid is not originally derived from grapes, wine is capable of synthesizing it

through the hydrolysis of the gallates. The main sstilbene present in the grapes, resveratrol, is formed through the glycosylation of vines [4].

1.3 Photosensitizer Dye

The research involved the examination of the natural pigments that are found in the peel of the *Ananas Comosus*, *Mangifera indica*, *Punica granatum*, and *Musa paradisiaca* fruit, the production of the latter by means of dye-sensitized solar cells, and their physical properties [2]. The extract of prickly pear fruit is used as a photosensitizer to form Dye-sensitized Solar Cells (DSSC), which is one of the most cost-effective, environmentally friendly, and simple means of producing the energy [27]. The research applied a variety of spectrometers to investigate the optical and electrical properties of a sensitizer DSSC, the natural dye that transfers photoelectron and absorbs photons from the light rays of the sun. The dye components were characterized using Fourier Transforms Infra-Red, and the absorption spectra of the extracted dragon fruit dye were acquired using UV-Vis spectrophotometers (Sari, et al., 2023).

1.4 Photodynamic Properties

The study of fruit peels rich in polyphenols as natural photosensitizers in the photodynamic treatment, to develop an understanding of their potential for this application, has been explored. When these substances are illuminated by light, the photosensitizers' reaction with the oxygen produces the reactive oxygen species, which has antibacterial properties. Such natural antioxidants have been reported to give biosecurity by polyphenols like hypericin and epigallocatechin gallate as they are used in antimicrobial photodynamic treatment for in vitro and ex vivo studies. A study on blackthorn fruit peel extracts has indicated that the growth of *Listeria monocytogenes* was found to be blocked by those extracts, and the activities of the polyphenolic content, the most concerning part of flavonols, including laserotherapy and vitamin D side effects, were linked to the antibacterial effects. These results propose blackthorn fruit peel to be a green source of photosensitizers to be applied in food hygiene and control [25]. Polyphenol-containing natural agents are penetrated as promising the photosensitizers of the progressive antimicrobial photodynamic treatment, which is being proponed as unwritten antibiotics due to their inherent photodynamic characteristics [43]. The former studies directed the attention to the polyphenolic content found in fruit peel as an alternative electron donor, besides that it also could be used for antibacterial purposes, offering the potential of a natural and effective treatment of microbiota.

2. Polyphenols Against Food Borne Pathogens

Foodborne infections caused by pathogens like *Salmonella* and *Escherichia coli* will continue to be a main public health concern considering the enormous economic impacts. These agents may form toxins and spoil food, therefore, putting our health at a high risk level. The World Health Organization has, in one of its 2010 reports, listed 351,000 mortalities apart from 582 million cases of 22 foodborne infections; the viruses that caused the infections, among them, were the culprit (Zhang, et al., 2021).The polyphenols gives a solution to encounter against the pathogens by their properties to this problem.

2.1 Antibacterial, Antifungal, Antibiofilm, Antioxidant Properties

Fruit peels contain antimicrobial substances that help fight contamination and control food-borne pathogens. These substances destroy enzymes, preventing bacterial biofilm formation and are used in prescribed drugs. However, natural preservatives can cause cancer, allergies, asthma, and skin irritation.

Polyphenols and plant compounds are beneficial for the human gut microbiota, and are used in food packaging systems. Peel-derived metabolites are secondary compounds that defend plants from pests and have anti-inflammatory properties [6]. Peels can be composed of bioactive components, among them, are the flavonoids, tannins, alkaloids, glycosides, and terpenoids. According to reports, this bioactive substance has therapeutic and medicinal effects, including especially antibacterial, hypoglycemic, anti-inflammatory, and antioxidant [40]. The bio disc method was used to determine the antibacterial potential of the peels from the mango trees in question (Saleem, et al., 2019). It has been confirmed that mango peels contain a high amount of gallotannins, benzophenone, and flavonol O- and xanthone C-glycosides as the main ingredients in the sample. These elements are also antigens, and hence they exert anti-inflammatory, anti-fungal, antiproliferative, anti-atherogenic, and anti-thrombotic actions[22]. The overall antioxidant activities of the 4 extracts were determined by 2 different test models of radical scavenging. The methods used are plotted through four different studies done to appraise the overall antioxidant activity; the former of which are two distinct free radical scavenging tests named ABTS+ and DPPH (Rojas, et al., 2018). It is widely acknowledged that phenolic chemicals are more effective against Gram-positive bacteria than Gram-negative ones [11]. Assays for biofilm formation were conducted using 96-well microtiter plates [40]. Propolis, an external topical treatment for fungal skin disruptions, has been proven effective against *Trichophyton rubrum*, *Trichophyton mentagrophytes*, and *Microsporum gypseum*. Its main active ingredients are flavonols like galangin, izalpinin, and rhamnocitrin, along with chalcones and flavanones. Other active propolis polyphenols include 2,4-dihydroxychalcone and 2,4-dihydroxy-3-methoxychalcone [10]. Red seaweed Jania rubens inhibits various bacteria, fungi, and viruses, while myricetin, rutin, morin, and quercetin inhibit fungal cell proliferation. Galangin and kaempferol inhibit *Aspergillus tamarii*, *Aspergillus flavus*, *Cladosporium sphaerospermum*, *Penicillium digitatum*, and *Penicillium italicum*. Naringenin treatments increase antioxidant levels and decrease lipid peroxidation in rats. Eriodictyol and hesperidin show antifungal activities, with eriodictyol exhibiting the strongest. Glycitein, daidzein, and genistein impact *Candida albicans* and *Candida rubrum*, while curcumin has distinct antifungal action against 20 *Candida species* [10].

2.2 Microorganism Involved

- **Gram-positive bacteria**: These bacteria have a thick peptidoglycan layer and include pathogens like *Staphylococcus aureus*, *Listeria monocytogenes*, and *Bacillus cereus*, which can be controlled using polyphenols from fruit peels.
- **Gram-negative bacteria**: These bacteria have a thin peptidoglycan layer and include pathogens like *Escherichia coli*, *Salmonella enterica*, and *Pseudomonas aeruginosa*, which polyphenols from sources such as pomegranate and grape peels can help inhibit.
- **Fungi**: Includes molds and yeasts like *Candida albicans*, *Penicillium spp.*, and *Aspergillus flavus*, which polyphenols from citrus and pomegranate peels have been shown to inhibit.
- **Function of Polyphenols**: Polyphenols possess antibacterial, antifungal, and antioxidant properties.They help disrupt biofilm formation, reduce virulence factors, and inhibit pathogen adhesion to surfaces (such as oral cavities or wound sites).

Table 1: Bacteria Involved and Polyphenols Source to Control the Bacterial Growth.

Microorganism	Gram Staining	Application	Polyphenol Source	Polyphenol Function	Reference
Escherichia coli	Gram-negative	Foodborne pathogen control	Pomegranate peel	Inhibits growth, reduces virulence, controls pathogenicity	Saad et al., 2021
Salmonella enteric	Gram-negative	Foodborne pathogen in food products	Orange peel	Antibacterial activity, inhibits bacterial growth	Serra et al., 2020
Listeria monocytogenes	Gram-positive	Foodborne pathogen in ready-to-eat foods	Apple peel	Inhibits growth and biofilm formation, improves food safety	Moradi et al.,2020
Staphylococcus aureus	Gram-positive	Skin infections (medical)	Apple peel	Antibacterial properties, prevents infection spread	Moradi et al., 2020
Bacillus cereus	Gram-positive	Foodborne pathogen in food products	Banana peel	Antibacterial activity, inhibits growth	Hossain et al., 2021
Clostridium botulinum	Gram-positive	Botulism in canned foods	Orange peel	Inhibition of toxin production and bacterial growth	Serra et al., 2020
Pseudomonas aeruginosa	Gram-negative	Wound infections, medical devices	Grape peel	Antibacterial properties, disrupts biofilm formation	Sánchez-González et al., 2020
Streptococcus mutans	Gram-positive	Dental plaque formation	Pomegranate peel	Inhibits bacterial adhesion and biofilm formation in the oral cavity	Saad et al., 2021
Enterococcus faecalis	Gram-positive	Nosocomial infections	Orange peel	Inhibits growth, reduces antibiotic resistance	Serra et al., 2020
Vibrio cholerae	Gram-negative	Cholera (intestinal infections)	Apple peel	Antibacterial activity, prevents pathogen adhesion	Moradi et al., 2020
Mycobacterium tuberculosis	Gram-positive	Tuberculosis (medical)	Grape peel	Inhibits growth, reduces infectivity	Sánchez-González et al., 2020

Helicobacter pylori	Gram-negative	Gastric infection	Banana peel	Antibacterial effect, inhibits growth of H. pylori	Hossain et al., 2021

Table 2: Fungi Involved and Polyphenols Source to Control the Fungal Growth.

Microorganism	LPCB Staining	Application	Polyphenol Source	Polyphenol Function	Reference
Aspergillus flavus	Fungi	Mycotoxin production in food storage	Orange peel	Prevents fungal growth and mycotoxin formation	Serra et al., 2020
Candida albicans	Fungi	Fungal infection (medical)	Grape peel	Antifungal properties, disrupts cell membrane integrity	Sánchez-González et al., 2020
Penicillium spp.	Fungi	Mold contamination in food storage	Apple peel	Antifungal effects, delays mold growth	Moradi et al., 2020
Rhizopus stolonifer	Fungi	Food spoilage and fermentation control	Pomegranate peel	Inhibition of fungal growth, prevents spoilage in food	Saad et al., 2021
Trichophyton mentagrophytes	Fungi	Athlete's foot, skin infections	Banana peel	Antifungal effects, reduces fungal hyphal growth	Hossain et al., 2021
Fusarium spp.	Fungi	Mycotoxin contamination in food and feed	Grape peel	Antifungal properties, inhibits fungal growth	Sánchez-González et al., 2020
Botrytis cinerea	Fungi	Post-harvest rot in fruits and vegetables	Pomegranate peel	Inhibits fungal growth and reduces spoilage in stored produce	Saad et al., 2021
Saccharomyces cerevisiae	Yeast (Fungi)	Fermentation in baking and brewing	Apple peel	Modulates fermentation, enhances flavor, and bioactive properties	Moradi et al., 2020

3. Applications

Fruits contain polyphenols, which are anti-inflammatory, antioxidant, and potentially health-promoting chemicals. Fruit peels, often discarded, are a significant source of these polyphenols. Recent studies show their use in functional meals, health supplements, and food preservation.

3.1 Antioxidant and Anti-inflammatory Effects

The phenomenon of food peels is a perfect example of food polyphenols which are known for their ability to combat inflammation and as antioxidants. For example, the polyphenols quercetin and catechins have been found to be the free radicals neutralizers; therefore, they allow to relax the oxidative stress, and reduce the inflammation, which is usually the source of a chronic illness. A report from a group of researchers points out that the stated polyphenols from apple peels are supposed to be the possible cancers and cardiovascular problems preventers (Pellegrini, et al., 2013). The polyphenols contained in the skin of the fruit also have potent antioxidant activities that are effective in scavenging the body's harmful free radicals and thus can prevent the body from the effects of oxidative stress which is a key factor in getting ill like cancer, diabetes, and cardiovascular diseases. The polyphenol effectiveness of the apple, grape, and citrus peel-derived free radicals scavenging compounds was confirmed in a research done by [49]. Those peel polyphenols which have been shown to decrease inflammation markers and anti-inflammatory pathways produce the characteristic necessary to treat diseases such as inflammatory bowel disease or arthritis [20]. Fruit peel polyphenols, especially in citrus and apple peels, have a high level of antioxidative power that contributes to the removal of XR and hence the therapy of troubles like arthritis (Shahidi & Naczk, 2004). Apart from their powerful antioxidant effects, the polyphenols present in fruit peels can reverse inflammation and, thus, find a place as a therapeutic to treat diseases such as arthritis [18]. Because the use of polyphenols can change the way an inflammatory pathway works, they can be used to treat diseases involving inflammation such as arthritis [18]. It is of great importance that the citrus peel polyphenols be mentioned here as they comprise the largest part of the polyphenols found in the skins of citrus fruits, such as lemons, oranges, and grapefruits, and possess the properties of potent antioxidants. These are the compounds that protect the body from the sources of oxidative medicine such as free radicals and oxidative stress aging and chronic illnesses [44].

3.2 Anticancer Potential

It has been demonstrated that the polyphenols in fruit peels, like those in pomegranates, can stop the growth of cancer cells and cause apoptosis in a variety of cancer types [5]. Apple peel extracts, rich in polyphenols, have been found to inhibit cancer cell growth, particularly in breast and colon cancer. Polyphenols found in pomegranate skin, including caffeic acid, ellagic acid, punicalagin, and punicalin, have been shown to have antineoplastic effects in cervical cancer models, suggesting that these polyphenols could be potential substitutes for cervical cancer prevention and treatment [41]. Citrus peels contain flavonoids with potential cancer-fighting properties, modulating cellular processes like proliferation, apoptosis, and metastasis, with further research exploring their chemo preventative potential [17]. Apple peels, particularly those from Red Delicious and Granny Smith, are rich in polyphenols, which have antioxidant and anti-inflammatory benefits, potentially reducing heart disease and certain cancer risks (jillian kubala, 2024).

3.3 Anti-Diabetic Effects

Mango peel polyphenols have shown promise in lowering blood sugar, which could aid in the management of diabetes (Kanti, et al., 2018). Apple polyphenols can lower blood glucose levels by inhibiting carbohydrate digestion enzymes and improving insulin sensitivity [19]. Citrus peel extracts,

which are rich in flavonoids, especially hesperidin and naringin, have been shown to lower blood sugar levels by altering important pathways related to glucose metabolism [3]. By enhancing insulin sensitivity and lowering oxidative stress, pomegranate peel extracts have demonstrated strong antidiabetic effects [32].

3.4 Food Preservation and Food Shelf Life

Fruit peel-derived polyphenols are increasingly used in food preservation due to their antioxidant and antibacterial properties. These extracts are increasingly used as natural preservatives to preserve nutritional value and increase shelf life without artificial chemicals. A study found that pomegranate peel extract's polyphenols effectively preserve fresh-cut fruits by preventing microbial development and delaying oxidation [29]. Polyphenols found in fruit peels can prolong the shelf life of fresh produce and minimize post-harvest losses when added to edible coatings. Citrus peel polyphenols, for instance, have the ability to cover fruits and vegetables with a thin layer that prevents moisture loss and microbiological contamination (Varma, et al., 2016). Pomegranate and grape peel polyphenol extracts have been used to extend the shelf life of meat and seafood items. By preventing lipid oxidation, these extracts help preserve the meat's flavor, color, and nutritional value while it is being stored [36]. The creation of formulations rich in polyphenols that can take the place of artificial preservatives in processed foods has also been the subject of research. To stop microbial contamination and spoiling, polyphenols found in grape and apple peels, for example, have been added to food packaging materials and food formulations such as sauces and beverages (Jaganathan, et al., 2021). Polyphenols, found in citrus, pomegranate, apple, and grape peels, act as antioxidants by scavenging free radicals and preventing oxidative damage to food items. This activity maintains product quality by postponing fat and oil deterioration in fried foods, snacks, and oils [30]. Fruit peels, including those from pomegranates, apples, and mangos, contain polyphenols that have been shown to have antibacterial and antifungal qualities. In foods like meat, dairy, and drinks, they prevent the growth of spoilage germs and harmful bacteria including *Salmonella spp*, *Listeria monocytogenes*, and *Escherichia coli* (Toker, et al., 2017). Strawberry, a high-nutrient fruit, can degrade rapidly and have a limited shelf life. Chitosan biopolymer is used to apply antioxidant-rich edible coatings. Apple fruit peel, a natural source of antioxidants and polyphenols, can be used as an antioxidant ingredient in a chitosan-based APP edible coating to increase strawberry postharvest life and reduce food processing wasten (Asad Riaz, et al., 2020).

3.5 Skin Health and Anti-aging

Polyphenols from fruit peels are also used in cosmetics and skincare products due to their anti-aging effects. They help in reducing skin damage from UV radiation, promoting collagen synthesis, and improving skin elasticity. The dermatological benefits of polyphenols, particularly from citrus and pomegranate peels (Gong, et al., 2021). Fruit peel polyphenols have been used in cosmetics because of their capacity to shield skin cells from UV rays, enhance skin hydration, and lessen wrinkle visibility [48]. Because of their anti-aging and skin-protective properties, polyphenolic chemicals found in pomegranate and blueberry peels are frequently employed in cosmetic compositions [7].

3.6 Functional Foods and Nutraceuticals

Fruit peel polyphenol extracts are increasingly used in nutraceuticals and functional meals to offer health benefits beyond basic nutrition, such as reducing cholesterol, boosting metabolic health, and improving

gastrointestinal health. This trend is driven by the potential health benefits of fruit peel polyphenols (Yuan, et al., 2020).

3.7 Waste Valorization

Peels from fruits are frequently seen as agricultural waste. Nevertheless, the process of extracting polyphenols from these peels presents a chance for waste valorization, transforming them into useful bioactive substances that can be used in cosmetics, food, and medicine (Mandal et al., 2018). Fruit peels high in polyphenols can be used in waste valorization procedures, turning food industry by-products into valuable bioactive extracts, in response to the growing need for sustainable practices (Sharma et al., 2015).

4. Challenges

4.1. Complex Extraction Processes

- The extraction of polyphenols from fruit peels is challenging due to their diverse composition and the need for optimization of extraction methods like solvent extraction, ultrasound-assisted extraction, and supercritical fluid extraction, which often use harmful chemicals.

4.2. Low Yield

- Fruit peels often contain low concentrations of polyphenols, resulting in low extraction yields, and seasonal and geographical variations can affect their recovery.

4.3. Stability Issues

- Polyphenols are sensitive to environmental factors like light, heat, and oxygen, leading to degradation during extraction, storage, or processing, and can easily oxidize, potentially reducing their bioactivity.

4.4. Standardization and Purity

- Polyphenols extracted from plants often contain impurities or bioactive compounds, complicating standardization and limiting their efficacy in therapeutic or industrial applications due to inconsistent quality.

4.5. Regulatory and Safety Challenges

- Polyphenol extracts pose challenges in food or medicine applications due to potential toxicity and potential regulatory standards compliance.

4.6. Application-Specific Limitations

- Polyphenols may have low photostability or suboptimal absorption in photodynamic therapy, and their strong taste or color may not be desirable in certain food applications.

4.7. Strategies to Overcome Challenges:

- The development of green extraction methods, encapsulation or nanoformulation for improved stability and bioavailability, genetic or biotechnological approaches to enhance polyphenol content in fruit peels, and integration of advanced analytical techniques for standardization.

5. Future Directions

The future of polyphenol extraction from fruit peels is promising, with numerous potential advancements aimed at improving efficiency, sustainability, and applicability. Below are key future directions:

5.1. Green and Sustainable Extraction Methods

- The various extraction techniques, including solvent-free methods like supercritical CO_2 or water-based extractions, enzyme-based extractions, microwave- and ultrasound-aided extractions, which aim to minimize environmental impact, improve yield, reduce time, and lower energy consumption.

5.2. Waste Valorization

- Circular Economy Models and Comprehensive Utilization are two strategies for utilizing fruit peels as by-products in the food industry, aiming to reduce waste and create value-added products.

5.3. Enhanced Extraction Technologies

- Hybrid techniques combine existing technologies for better efficiency, while nanotechnology integration uses nanomaterials for selective polyphenol extraction. AI and machine learning optimize extraction conditions using predictive models for maximum yield and quality.

5.4. Improved Polyphenol Stability

- The study explores the use of micro- or nano-encapsulation techniques and natural preservatives in combination with antioxidants to protect polyphenols from degradation and oxidation.

5.5. Standardization and Quality Control

- Advanced analytical tools like mass spectrometry and NMR are used for precise profiling and quantification of polyphenols, while industry-wide standards for extraction and quality assessment ensure consistency across products.

5.6. Biotechnology and Genetic Engineering

- Genetically modified crops and fermentation techniques are being employed to enhance the availability of polyphenols in fruit and biotransform peels into enriched extracts.

5.7. Scale-Up and Industrial Applications

- Pilot-scale facilities are being established to convert lab-scale methods into industrial production, while cost-effective solutions are being designed to make polyphenol extraction economically viable for various industries.

5.8. Advanced Applications

- Polyphenols are being utilized in functional foods and nutraceuticals, pharmaceutical applications, and the cosmetic industry for their antioxidant and anti-aging properties, as well as in disease prevention and therapeutic purposes.

5.9. Interdisciplinary Research

- The study explores the use of polyphenol extracts in biodegradable films and active packaging, as well as their potential as eco-friendly agents for wastewater treatment and pest control.

5.10. Policy and Public Awareness

- Government support for research and sustainable extraction practices, along with consumer education about polyphenol benefits and fruit peel waste products, are crucial for promoting sustainable practices.

6. Reference

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