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Review

A Comprehensive Review: Exploring Bioactive Compounds of Citrus Fruit Peels for Therapeutic and Industrial Applications

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Abstract: Citrus fruit peel has recently been highlighted as one of the major wastes and by-products of the citrus industry, which offers a plethora of health benefits and industrial uses. In addition to the common micronutrients present in the whole fruits (including carbohydrates, fibre, vitamin C, potassium, folate, calcium, thiamin, niacin, vitamin B_6, phosphorus, magnesium, copper, riboflavin, and pantothenic acid), albeit in different proportions, citrus peels contain high amounts of pectin, vitamin C, and phytochemicals. The major phytochemicals present in citrus fruit peel include phenolic acids (caffeic, p-coumaric, ferulic, and sinapic acid), flavanones (naringin and hesperidin), and polymethoxylated flavones (nobiletin and tangeretin), which are important bioactive compounds. The phytochemical and therapeutic efficacies of citrus fruit waste are documented in several early studies; however, detailed information on the industrial uses of these bioactive components is limited. This article aims to highlight recent advancements in the diverse range of applications of citrus fruit peel, including its use as a natural flavouring, an essential oil, and a source of dietary fibre in preventing metabolic and infectious diseases. Moreover, this review discusses the processing methods (drying and extraction) of citrus fruit peel for industrial uses, offering insights that enhance the understanding of the importance of citrus fruit peel not only as a by-product but also as a substance of immense value to human health.

***Keywords*:** bioactive compounds, cirus fruit peel, therapeutics, industrial uses

1. Introduction

Citrus fruits, such as oranges, lemons, and grapefruits, are widely consumed throughout the world for their delicious taste and high nutritional value. These fruits are rich sources of vitamins, minerals, and antioxidants, which are essential for maintaining good health. While the juice of these fruits is typically the primary product, the peel is often discarded as waste by food processing industries. After processing, citrus fruits generate a large number of by-products such as peel, pulp, and seeds, which used to be considered waste. Approximately, 70% of all fresh citrus fruits are consumed by food manufacturing industries, with nearly 50-60% of harvested fruit being converted into fruit wastes such as peel, seed, and cell residues [1].

Present knowledge indicates that citrus fruit-derived nutraceuticals are potential natural sources of anti-carcinogenicity, anti-allergenicity, and anti-aging biochemicals, as well as important constituents in synthetic

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antioxidants [2]. During the COVID pandemic and before any vaccine was developed, a higher intake of citrus fruit nutraceuticals was recommended to boost individual's immunity [3], which increased the industrial uses of citrus fruit pulp and thereby led to an increase of citrus waste [4]. These by-products are rich in bioactive ingredients such as essential oils, dietary fibre, flavonoids, vitamin C, pectin, carotenoids, hesperidin, limonin, and phenolic compounds, which have antimicrobial, antioxidant, anti-inflammatory, antidiabetic, cytotoxic, and anti-obesity properties and are important raw materials in the chemical and pharmaceutical industries. Composition of these ingredients may be similar to fruit pulp but concentration may differ [5-7].

Previously, industries used to discard the waste of citrus peel, but through expert knowledge and hard work that waste has been made useful through proper processing. Earlier studies characterized the chemical composition of bioactive compounds of citrus fruit peel and identification of more such components are underway [8]. That information will be beneficial to formulate healthy food products [9] or useful pharmaceuticals. Apart from nutritional values and health benefits, citrus fruit peels are found to have huge industrial importance such as in the pharmaceutical and cosmetic industries. The uses of Citrus fruit peels are extended to the production of packaging material [10], large-scale natural dyes [11-13], low-cost paper, etc. Given its versatility, abundance, and cost-effectiveness, orange-peel products may significantly contribute to sustainable agriculture waste management practices, and various industries such as food and cosmetics [14].

Articles published in the recent past have provided information about the bioactive compound present in citrus fruit and peels, and their *in vitro* and *in vivo* bioactivities, however, the detailed industrial uses of the peels, challenges in the processing, future uses of these value-added products still need to be discussed. In the present review, the authors have focused on filling these gaps in knowledge and pragmatically reviewed the recent research study findings on the important use of citrus fruit peels. This review may help in further understanding of infinite benefits of citrus fruit peels towards health, environment, and inexpensive and useful industrial products.

2. Origin of citrus fruits

The botanical name and family name of the citrus fruits are mentioned in Table 1 [15]. Citrus fruits have several distinct characteristics that set them apart from other types of fruits. Here are some of the key characteristics of citrus fruits:

(1) Citrus fruits have a thick rind or peel that surrounds the edible fruit. The rind is often rich in essential oils and can be used in various applications such as flavorings, fragrances, and medicine.

(2) The flesh of citrus fruits is typically juicy and acidic, with a sour or tart taste. However, some varieties can be sweet, depending on the balance of sugars and acids.

(3) Citrus fruits are high in vitamins and minerals, particularly vitamin C, which is an important antioxidant that helps to boost the immune system and protect against various diseases.

The peel of citrus fruits is considered an important raw material from the food processing industry [16]. It has abundant nutrients, essential oils, and phenolic acids, representing a valuable resource. Rather than being discarded as waste during fruit processing, these residues can be repurposed as a potential nutraceutical source, offering environmental benefits [17]. Peel represents about 30% of the total fresh fruit weight [18]. The citrus peel has two layers i.e., flavedo (the outer orange layer) and albedo, the inner layer. Of these two layers, the flavedo consists of small oil glands from which the oil is extracted and used by the pharmaceutical industry in the manufacturing of perfumes, cosmetics, and the like.

Table 1. Characteristics of citrus fruits [19, 20]

Fruit	Colour, shape and texture	Bioactive compound	Other characteristics	Therapeutic activity	Industrial uses and market scenario	Reference
Mandarin (*Citrus reticulata*)	Orange to reddish-orange. Small to large, circular to flattened. Smooth surface but sometimes it has pebbled, orange-coloured surface.	Organic acids, sugars, and amino acids, carotenoids, polyphenols, flavonoids, phenolic acids, and limonoids.	Mild and strong flavor, seedless to seed (3-7 seeds), small and plump.	Stomach upset, cough, skin inflammation, muscle pain, and ringworm infections, as well as for lowering blood pressure. Now at present, it is used widely in medicinal activities like anticancer, anti-inflammation, wound healing activity, modulation of bone density, anti-atherosclerotic agents, neuropharmacological activities and antiaging.	Jams, biscuits, cookies and madeleines.	[21-23]
Navel orange (*Citrus sinensis*)	Yellow-orange. Obovate or ellipsoid. Moderately pitted and pebbled.	Flavanone glycosides (FGs) and polymethoxyflavones.	Navel-like structure, at the stylar end, or apex.	Type 2 diabetes. Essential oil suppresses triple negative breast cancer.	Biscuits.	[23-25]
Sweet orange (*Citrus Sinensis*)	Yellow to yellow-orange. Globose but oval to ellipsoid. Finely pitted but smooth, thin to medium-thick, and firm and leathery.	Essential oils, flavonoids, carotenoids, steroids, terpenoids, alkane groups, and ethyl esters.	The presence of a green or yellowish-green calyx and a button at the stem end of the orange indicates the freshness of the fruit.	Antimicrobial and antioxidant.	Produce animal feed, confectionary, bakery products, beverages, biofuels, biodegradable polymers and remediation of contaminated soils.	[26, 27]
Lemon (*Citrus limon*)	Green to bright yellow. Varies in size and shape. Rind is thick to smooth in texture.	Flavonoids (e.g., diosmin, hesperidin, limocitrin) and phenolic acids (e.g., ferulic, synapic, p-hydroxybenzoic acids). The essential oil (D-limonene, β-pinene, γ-terpinene).	Seedless to seedy. The nipple is prominent and large in some varieties, while some have small.	Antioxidant, antimicrobial, antidiabetic, anti-obesogenic, lipid-lowering, anti-colitic, anti-arthritic, antiurolithic, anti-fatigue, ameliorating disuse muscle atrophy, skin protection and prebiotic properties.	Food ingredient with nutritional, antioxidant, and antibacterial properties. Film matrixes or active constituents for food packaging or edible coatings. Application into bioremediation as removers of heavy metals and dyes and into aquaculture as beneficial constituents of fish diet is also promising.	[28]
Pomelo (*Citrus grandis*)	Green to yellow-colored surface when mature. Large to very large, round to oval in shape, and born singly. Rind is thick to very thin and smooth.	Polyphenols, flavonoids, phenolic acids, carotenoids, triterpenoids, phytosterols, carbohydrates, coumarins.	The flesh is firm and crisp, juice vesicles are separable, and the core is open and hollow. Pink fleshed, seeded to seedless, and the flavor is mild to strong.	Prevents obesity.	Sugar pickled pomelo peels, honey pomelo tea, jam and wholemeal of pomelo peels.	[29]
Grapefruit (*Citrus paradise*)	Yellow to pink blushed. Medium to large in size and oblate to spherical in shape. Slightly depressed from the stylar end, and flat on the stem end. Medium thick and smooth.	Vitamins C, E, A, phenolic compounds (flavonoids, phenolic acids and coumarins), carotenoids, limonoids.	The flesh is white and tender/melting with a central core that is usually open, born in clusters, and seeded to seedless, the flavor is strong, and the pink to red color flesh.	No such therapeutic use is available yet.	Mosquito repellent.	[30]

3. Traditional uses of orange peels

Peels from bitter oranges are utilized as neuroprotective and antidepressant medications in traditional Persian medicine [31]. It is consumed orally as an aphrodisiac, hepatoprotective medicinal food, and appetizer. It is also used to treat polymenorrhea, dyspepsia, diarrhea, and bloating. Peels are gastronomic and helpful for gastrointestinal problems as well. In Japanese herbal medicine, bitter orange peel teas have been shown to have digestive and muscle-relaxing properties [32]. The desiccated peels derived from *Citrus reticulata*, often referred to as "chen-pi", boast a rich historical tradition of being employed in traditional remedies to address and alleviate symptoms associated with digestive disorders linked to both acute and chronic inflammation [33].

Extracted from orange peel, orange peel extract (OPE) is abundant in a diverse array of flavonoids. These include polymethoxylated flavones (PMF), c- or o-glycosylated flavones, o-glycosylated flavanones, flavonols, and various phenolic acids, along with their derivatives [34]. The spectrum of bioactivities exhibited by citrus flavonoids encompasses antioxidant, anti-inflammatory, anti-carcinogenic, and anti-atherosclerosis properties. In essence, these compounds contribute to a range of health benefits [35, 36].

4. Composition of orange peels

There has been a lot of focus on the phytochemicals contained in peels and seeds. The citrus peel is divided into two layers: flavedo (the outer orange layer) and albedo (the inner layer). The flavedo layer is made up of small oil glands from which oil is extracted and used by the pharmaceutical industry to make perfumes, cosmetics, and other products. A large amount of citrus peel is produced during citrus processing, accounting for approximately 25-30% of the total weight of citrus fruit [18].

4.1 *Flavonoids*

Flavonoids are an important active compound in citrus peels. Anthocyanidins, flavones, flavanones, flavonols, and isoflavones are examples of flavonoid compounds present in citrus fruit peel [37]. The citrus peel contains a variety of functional compounds, such as flavone glycosides (neohesperidin, naringin, hesperidin, narirutin); triterpene (limonene, citrol); polyethoxylated flavones (tangerine and nobiletin); flavonoids (citacridone, citbrasine, and noradrenaline), etc. Citrus peels contain more of these chemicals and flavonoid content than the fruit's edible portions, which has been expanded to include immature citrus fruits [38]. It has been reported that the ethanolic extract of citrus peels contained higher amounts of flavonoids compared to pulp extract (243-397 mg/g and 81-101 mg/g for peel and pulp extracts, respectively) [39].

Citrus fruit peels possess the highest amounts of polymethoxylated flavones (PMF) compared to other edible parts of the fruits. Flavanone glycosides vary in composition in fruit seeds, peels, and juice because flavonoids vary in composition across various fruit tissues. Naringin, for instance, is present in lemon peels and seeds but not in juice. Citrus seeds and peels, on the other hand, contain a diverse mix of flavanone molecules, while lemon skins are high in neoeriocitrin, naringin, and neohesperidin, lemon seeds are mostly high in neo eriocitrin and hesperidin [40].

Antioxidant activity of flavonoid compounds present in citrus fruit pulp and peels helps in fighting different diseases. The role of flavonoids as anti-inflammatory and anti-oxidant is shown to be through scavenging the free oxygen radicals produced by the reactive oxygen species (ROS) system in the body. Because of their special chemical structure, the molecules are able to react with the free oxygen radicals and prevent abnormal biochemical events. Flavonoids are also thought to prevent increased levels of nitric oxide production. Flavonoid's role in prevention of neurodegenerative and cardiovascular diseases is also believed to be due to its antioxidant activity and reduction of oxidative stress [41]. Citrus fruit peel's major bioactive compounds flavonoids also have anti-cancer activity. Not known much, but it is hypothesized that flavonoids interfere with the altered signaling pathways that lead to unusual apoptosis and cancer. Little is known about flavonoids compound's role in preventing diabetes. It is believed that these compounds increase insulin production and its activity via an unknown mechanism.

4.2 *Carotenoids*

Orange peel is a source of natural pigments such as carotenoids [42]. The waste of orange (var. *Valencia*) peels is rich in apo-carotenoids representing more than 60% of the total carotenoids. β-chryptoxanthin and, dihydroxycarotenoids (zeaxanthin and its epoxides) are also present in minor quantities [43]. β-cryptoxanthin, which exhibits provitamin A activity, was the main compound in the navel variety extract. β-carotene as well as some dihydroxy derivatives were also present [44]. The number of apo-carotenoids in this variety is very low. There are differences in carotenoid composition depending on the orange variety. *Valencia* variety was richer in short-chain apocarotenoids while navel variety was in nonpolar carotenoids [43]. β-citraurin epoxide, a new carotenoid from *Valencia* orange peel [45].

Carotenoids are also known as strong antioxidants. The structure of many carotenoids is derived already and is now well characterized. These molecules are also good scavenger of free radicals generated by the ROS system and are able to reduce oxidative stress. Carotenoids thus act as anti-inflammatory, anti-neurodegenerative and anti-cardiovascular molecules. Among the carotenoids. Lycopene is well studied and shown to modulate the pathways of interferons, Carotenoids can modulate oxidative stress or cause an upregulation of antioxidant and cytoprotective phase II enzymes via nuclear factor erythroid 2-related factor 2 (Nrf2) and peroxisome proliferator-activated receptor (PPAR).

4.3 *Pectin*

Citrus peels and pomace are rich in pectin, known for their ability to lower blood sugar and cholesterol levels [46]. Approximately 85% of the world's commercial pectin is made from citrus peel residues [47]. The raw materials for producing pectin can be fresh peels of citrus fruits viz, lemon, grapefruit, and orange or washed plus dried peels. Fresh citrus peels contain 1.5 to 3% pectin, and dried peels contain 9 to 18% pectin [48]. Citrus fruit peels have an excess of pectin, which appears in the form of protection, in their yellow skin and white skin. The pectin content and quality of citrus peels are listed in decreasing order: lime > lemon > grapefruit > orange > citrus with loose skin [49]. The pectin content of citrus peel is typically 20-30% of the dry weight [37]. Utilizing ultra-high pressure (UHP), pectin extraction was conducted from navel orange peel. The conditions for UHP extraction are as follows: a pressure of 500 MPa, a temperature of 55 °C, and a pressure-holding time of 10 min. Under these optimized conditions, the pectin yield reached 20.44% ± 0.64 [50]. This yield demonstrated a significant increase compared to pectin obtained through traditional heating (15.47% ± 0.26) and microwave-assisted extraction (18.13% ± 0.23) [51, 52] extracted the pectin from Assam lemon (*Citrus limon Burm* f.) peels using conventional, microwave-assisted, and ultrasound-assisted extraction.

5. Processing of citrus peels

The high sugar and pectin content of orange by-products, together with their high moisture content (> 50%), make them ideal growth substrates for microorganisms [53]. To ensure stability and provide a long storage life, drying is also required. Citrus fruit peel is highly used in powder form [15] and also could be used for the extraction of essential oil. Oil extraction could be conducted in several ways like steam distillation [54-55]; solvent-free microwave extraction (SFME) process [56]. The procedure for obtaining powder form of citrus peel is mostly by using drying technology. The various kinds of drying techniques are mentioned below in Figures 1 and 2.

The major bioactive compounds of citrus essential oil are terpenes and limonoids. The major terpenes are monoterpene hydrocarbons, oxygenated monoterpenes, terpene alcohol, sesquiterpenes, aldehyde and ester, while limonoids are limonene and nomilin [57]. For example, sweet orange peel is an excellent source of orange essential oil as well as pectin and has long been regarded as an important raw material in the food processing industry [16]. Essential oils, a blend of phytochemicals like monoterpenes, sesquiterpenes, and phenylpropanoids, demonstrate pharmaceutical, antioxidant, and antimicrobial prowess. Preserving stored grains is challenging due to pest infestations, prompting the need for alternative strategies. Chemical insecticides, although widely used, are facing resistance, which reduces their effectiveness. Citrus fruit essential oils emerge as a potent solution, offering impressive repellent, contact, and fumigant activities against stored-product pests [58-61].

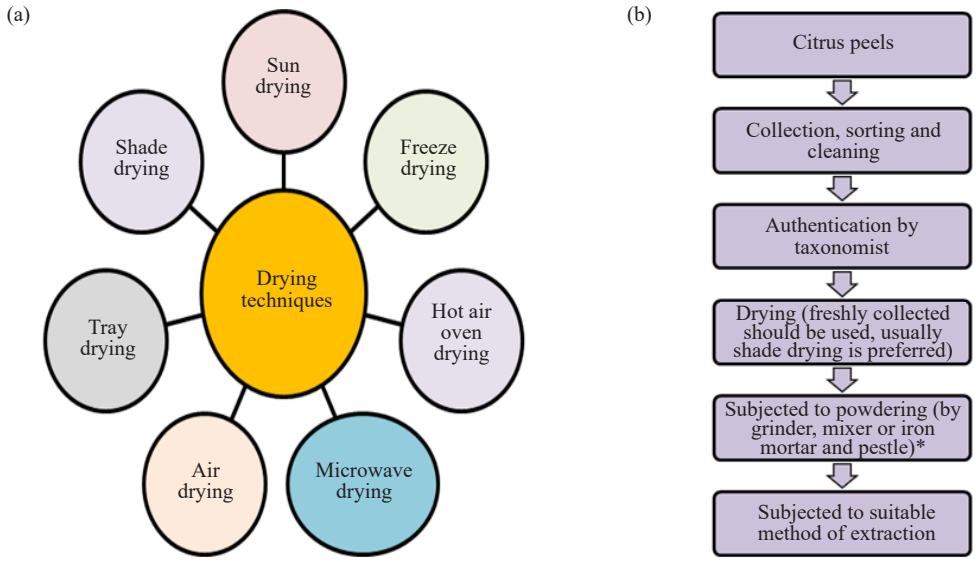

Figure 1. (a) Different drying techniques used to process citrus fruit peels. (b) Representation of the drying process of citrus fruit peel

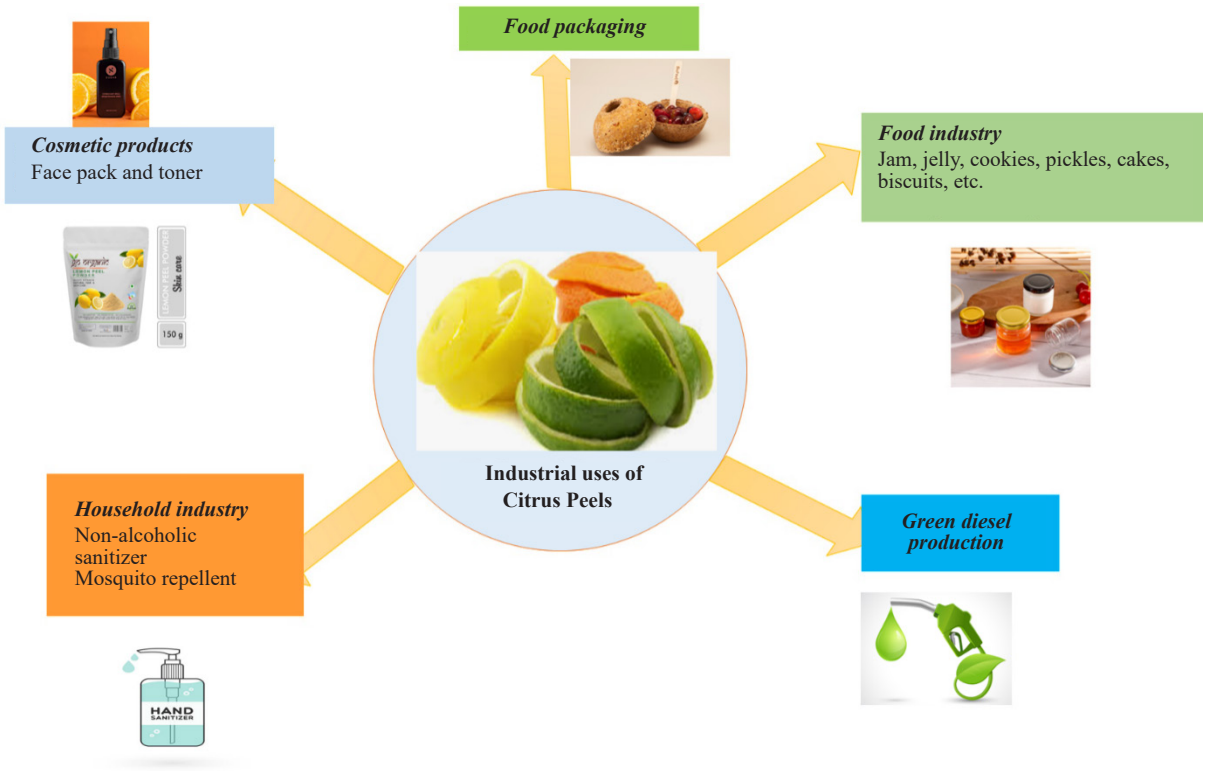

Figure 2. Industrial uses of citrus peel waste

6. Therapeutic uses of citrus fruit peels

6.1 *Antidiabetic properties*

Blood sugar levels are significantly impacted by orange peel extract, suggesting the anti-diabetic benefits of

the same. It can reduce blood sugar levels by up to 19.30% [62]. The antioxidants hesperidin and naringin, which are contained in orange peel, reduce the effects of glucose-6-phosphate and phosphoenolpyruvate. The production of glucose from carbohydrate is aided by the inhibition of α-amylase inhibitory activity, which is implicated in the stimulation of insulin secretion, repair of pancreatic beta cell abnormalities, and stimulation of insulin secretion [63].

The antioxidant, glucosidase inhibition, and antiglycation properties of orange peel (*var. navel*) extracts and individual flavonoids were evaluated to explore the antidiabetic potential of the extract [64]. They have studied seventeen flavonoid compounds in the peel extract, where sinensetin (5-hydroxy-6,7,3′,4′-tetramethoxyflavone) was found to be the best for its antidiabetic activity. Glucosidase inhibitor, and glycation inhibitor flavonoids were tested for anti-diabetic activity [64]. Tangerine peel is being tested as a potential anti-diabetic drug for the complication of diabetic nephropathy. Tangerines and orange peel are high in the natural flavonoid tangeretin. It can significantly slow the development of diabetic nephropathy [65].

6.2 *Alzheimer's disease*

The neuroprotective activity of orange peel extract indicates that it may reduce brain oxidative stress, thereby preventing the progression of Alzheimer's disease [66]. Nobiletin and tangeretin, key citrus flavonoids from *Citrus* L. genus, demonstrate neuroprotective effects in both *in vitro* and *in vivo* studies [67].

6.3 *Antioxidant and anti-inflammatory properties*

Orange peel has anticancer property. Orange peel extract has a high concentration of flavonoids, which increases its antioxidant action in the body. Polymethoxyflavones, one of the bioactive components found in orange peel extract, have anti-inflammatory properties [68]. With the help of efficient bioactive substances from orange peel extract, diseases associated with inflammation can be managed and treated [69].

6.4 *Antimicrobial properties*

The antibacterial activity of orange essential oil inhibits the growth of common food spoilage bacteria such as *Staphylococcus* and *Pseudomonas* [70]. Furthermore, it has potent activity against *Listeria monocytogenes*, a major cause of food-borne illness [71]. The fungus *Aspergillus niger* is inhibited by the component D-limonene in orange peel essential oil. Orange essential oil was used in cupcakes [72]. It is used to make oil phase emulsions, which are then wrapped in tea bags to make a drinkable tea. It is used in the pharmaceutical, fragrance and cosmetic industry. It also plays a vital role in preservation, antimicrobial packaging and pest control [73].

Bioactive chemicals from orange peels are extracted and tested for antimicrobial activity against a number of pathogenic plant fungi. The extracts of five different citrus peels (key lime, orange, pomelo, lemon, and mandarin orange) were evaluated on seven fungi species (*Alternaria solani*, *Alternaria alternate*, *Rhizoctonia solani*, *Macrophomina phaseolina*, *Trichothecium roseum*, *Fusarium solani*, and *Fusarium equiseti*). It was observed that the pomelo peel extract is the most effective anti-fungal, followed by orange peel extract, lemon peel extract, mandarin orange and key lime peel extracts [74].

Flavonoid compounds are known as effective antiviral molecules. They inhibit viruses at multiple stages of the virus life cycle including virus internalization, genome replication and assembly [75]. Previous studies have shown Hepatitis C Virus (HCV), Human Immunodeficiency Virus (HIV), Influenza dengue and Respiratory Syncytial Virus (RSV) are inhibited by different flavonoids [76]. Effective antiviral activity of vitamin C was reported from earlier studies. Citrus fruit peels are rich in vitamin C. Vitamin C acts as a strong antioxidant and thus plays a role as anti apoptotic molecule.

Orange peel extracts which contain vitamin C and other antioxidants help to enhance immunity and to prevent respiratory viral and bacterial diseases. The world recently experienced the historically worst pandemic due to COVID-19 which killed several million people. Before vaccines were developed against COVID-19, eating citrus fruit was recommended, which helped reduce the activity against the virus and save many people's lives [3, 77]. Citrus fruit also helps in reducing the chances of severe diseases caused by influenza, and dengue. There is a need for alcohol-free hand sanitizers which has fewer health hazards compared to alcohol-based products. The peel extracts based sanitizer

proved to contain considerable antimicrobial activity against the pathogenic bacteria, and effective against pathogenic viruses such as COVID-19 [78].

6.5 *Anti-obesity significance*

Orange peel powder protects against diseases caused by oxidative stress and inflammation, which are associated with obesity. As fat deposits build, the pro-inflammatory response rises. Consuming citrus aids in managing aberrant lipid profiles and endothelial dysfunction. Orange peels are rich in antioxidants, vitamin C, pectin, and flavonoids, all of which have been demonstrated to be highly beneficial in lowering inflammation and endothelial dysfunction brought on by obesity [79].

6.6 *Other health effects: anticancer effects*

Citrus peel essential oil has a sedative effect on the human central nervous system, which can alleviate stress and fatigue. Furthermore, despite its trace levels in essential oil, coumarin has a clear anticancer effect; it most likely works by decomposing the toxic functional groups in carcinogenic substances and inhibiting cancer cell metabolism [80]. It has been demonstrated that citrus peel essential oil acts as an expectorant, cough suppressant, gastrointestinal motility promoter, and digestive juice secretion enhancer. It also helps to ease pain, dissolve gallstones, and reduce inflammation [81, 82] suggested that citrus peels offer potential as a dietary supplement which could be used as a functional food additive.

Bioactive compounds derived from citrus fruits are abundant in therapeutic qualities, functioning as antioxidants, anticancer, antitumor, and anti-inflammatory agents. Additionally, they are recognized for their antiviral, antiplatelet aggregation, and anti-inflammatory properties [19, 83]. Certain bioactive compounds have been documented for their ability to induce protective enzymes in the liver and inhibit the damage to genetic materials within cells [84]. Hesperidin plays an essential role in blood vessel osmotic pressure maintenance, vascular fragility reduction, capillary toughness increase, and bleeding time reduction. It has the ability to lower low-density lipoproteins (LDL) levels in the body. It can be used as an adjuvant therapy for cardiovascular diseases [37]. Pectin contains dietary fiber, which is essential for keeping a healthy body. It helps to improve gastric motility and nutrient absorption. Furthermore, it has the potential to prevent and treat high blood pressure, cancer, diabetes, obesity, and other diseases. Pectin can be used as a weight loss agent due to its satiating impact. Naringin is used in the pharmaceutical industry to make drugs for the prevention of cardiovascular disease and anti-inflammatories [85].

7. Biopolymers, ethanol production and activated carbon

The creation of bioactive scaffolds that promote bone repair is important for hard tissue regenerative medicine initiatives. Because of their excellent capacity to imitate the bone extracellular matrix, biopolymers containing synthetic polymers offer a new option for this application. Orange (*Citrus sinensis*) rind pectin and bovine tendon collagen were used to make scaffolds [86]. Orange-peel can do ethanol production by using hydrolysis for 15 min, and further processing it at 121 °C and 15 psi pressure [87]. Citrus seeds have a strong biodiesel potential due to their 30% oil content (by weight). By trans-esterifying citrus seed oil with methanol under the catalysis of sodium methoxide, it generated methyl esters that met both the ASTM D6751 and EN 14214 biodiesel criteria [1]. Activated carbon was created by using orange peels and it was also used to remove acetic acid from an aqueous medium [88]. Iron-impregnated activated carbons derived from waste *Citrus limetta* peels (referred to as AC-CLPs) for the novel purpose of fluoride ion removal from water. The adsorbents were meticulously crafted by subjecting the chosen biomass to activation through $FeCl_3$, followed by carbonization at two distinct temperatures, namely 250 and 500 °C [89]. The resulting carbon materials were denoted as AC-CLP250 and AC-CLP500, respectively [90].

8. Value added products with citrus fruit peels

Citrus peel cellulose is commonly used in cakes, biscuits, bread, and other food products. It can also be used in dishes as an anti-stickiness agent. They have advantageous properties such as the ability to bind water and create gels. It can be used to replace fat in ice cream without significantly changing the flavor, color, or aroma. The change results in a 70% fat replacement, making the ice cream low in calories and beneficial for gut health and disease prevention [9]. Table 2 describes the various value-added food products.

Table 2. Nutraceutical foods with citrus food wastes

Food products	Details of the products	References
Herbal cookies	When the orange peel is added to herbal cookies, their nutritional value, bioactive components, textural as well as organoleptic were improved.	[91]
Tri color pasta	Orange pomace is used to make tricolour pasta. The prepared pasta has more nutritional value and viscoelasticity.	[92]
Biscuits	Mandarin and orange peels were used to make biscuits (marie). The addition of peels had resulted in no negative side effects. They boosted the antioxidant activity, shelf life, crude fibre, ash, and ether extract content of biscuits. The usage of peels also reduced serum total cholesterol, liver lipid and cholesterol, and blood glucose levels.	[23]
Frozen sausages	Orange peel extract was used to increase the storage duration of frozen sausages. It improves microbiological security and sensory quality. It increases the lipid oxidation and also has no effects on color.	[93]
Beef processing	Orange peel extract was added to minced beef. It had effects on the physical, chemical, biological, and microbiological properties of minced beef. To decrease the amounts of free fatty acids, peroxide, and thiobarbituric acid in the minced beef, orange peel extract was added.	[94]
Encapsulated beads	Alginate, Aloe vera, and orange peel extract were encapsulated in bio-polymeric foamy beads. These natural remedies are workable for delaying cell aging, and boosting healthy cell growth, resulting in a natural treatment.	[95]
Jam	The pectin extracted from citrus fruit peels has been added to jam which stabilises the jam during transportation and also improves the flavour and reduces syneresis therapy, resulting in an unrivalled taste.	[37]
Fruit juices	Pectin has acid resistance properties when added to fruit juice and syrup, as it can stabilise and suspend oily lactic acid, resulting in juice with a fresh flavour.	[37]
Seasoning for white and red meat and snack	They used a dehydration process in low temperatures for the subproduct creation, and it was possible to minimize the intensity of limonene contained in the fruit's peel to reduce its bitter flavor without losing its beneficial properties.	[96]
Chocolates	No changes in the polyphenol content.	[97]

9. Packaging material

The citrus peel waste is used in the synthesis of biodegradable packaging material. Also, edible packaging film was developed by using lemon peel pectin. The prepared edible film was also used for coating the edible cheese by wrapping it, which eventually improved the physicochemical, textural, and microbial stability of the cheese (ricotta) wrapped in edible film [10]. Orange peels, often discarded as challenging food waste, present an opportunity for bioplastic production due to their high starch content. Additionally, the peels contain pectin, a key factor enhancing the strength of bioplastics. Comprising hemicelluloses, starch, cellulose, lignin, soluble sugars, fat, ash, protein, and flavonoids, orange peels possess diverse components. Their substantial cellulosic content, when disposed of in landfills, leads to the production of methane gas, contributing to global warming. To address this, a study employed pulverization using a pestle and mortar as part of a mechanical disruption method to extract polymeric materials from orange peels. The resulting paste underwent further processing, including treatment with HCl and glycerol. Uniformly mixed and shaped,

the paste was cast into molds and left at room temperature for 48 h, resulting in a developed film with a thickness of 0.2 mm. This process represents a vital step in transforming orange peels from waste into a valuable and environmentally beneficial product [98].

Citrus peel finds application in producing food-grade kraft paper, biodegradable polymers, and packaging materials. Citrus residue serves as a source of bio-oil, biogas, ethanol, and activated carbon, offering potential in enzyme production, cellulose, nano cellulose, dietary fibers, and more [99, 100].

10. Natural dyes

Orange peel is a good source of natural colors and is high in carotenoids. Orange peel dye has antioxidant, antibacterial, and ultraviolet (UV)-protective qualities, and has been applied to wool, cotton, and tencel fabric [11]. Lemon peel waste from juice processing companies, constituting about 50% of the weight, is an excellent resource. It serves as a raw material for producing valuable pectin, lemon oil, and a stable yellow natural colorant known as limocitrol glycoside. This water-soluble dye, a flavonoid, offers an industrial alternative to both synthetic and natural yellow colorants like curcumin, crocin, norbixin, or riboflavin (vitamin B2) [12]. Recent study evaluates *Citrus limonum* (lemon) peel's adsorption potential for removing anionic dyes (methyl orange and Congo red) from aqueous solutions [13].

11. Raw material for paper making

Cellulose separated from orange peel waste is mainly used as an additive in paper-making industries [101].

12. Future scope and considerations

Supplements containing the glycosides found in orange peel extract may be beneficial when the body is under significant oxidative stress and the supplements are taken consistently over a lengthy period of time. Identification and recommendation of correct and efficient dosage is required. The value of citrus peel extract in a multitargeted pharmaceutical strategy must be determined, for example, whether it is used to treat or prevent cancer [102].

In a recent report, Pal et al. [103] elaborated that pomegranate and sweet lemon peels have carbon contents of 56.43 and 55.89%, respectively, which in turn suggested their utilization in different industries. Rafiq et al. [104] indicated that more research is needed to determine the bioavailability and genuine benefits of citrus peel extracts for the environment and farmers. Addi et al. [105] have suggested that methidathion and chlorpyriphos ethyl are the most detected pesticides in citrus fruits, which could have harmful side effects if they remain in more than the permissible limit.

12.1 *Probiotics*

The effectiveness of probiotic starter cultures, namely L. *acidophilus*, S. *thermophilus*, and *Bifidobacterial* sp., was improved when citrus peels were added to synbiotic yogurt and stored in cold conditions. Their findings indicate that incorporating citrus peels, particularly those from sweet orange and sour orange, holds promise as a versatile additive for creating probiotic and synbiotic yogurts. This enhancement results in improved antioxidant and antibacterial properties, along with increased viability of probiotics during storage. These outcomes suggest the potential for utilizing citrus peels in the development of functional dairy products [106].

12.2 *Animal feed*

Ahmad et al. [107] concluded from the study that methanolic extract of citrus supplementation of quails (0.5 to 1.5 mL/kg of feed) can improve feed intake, weight gain, dressing percentage, relative weight of lymphoid organs, and digestibility coefficient. The same supplementation at a dose of 1.5 mL/kg of feed has provided positive impacts on

antibody titers against various viral diseases.

One of the most widely cultivated fruit trees in the world is the citrus fruit, which is a member of the *Rutaceae* family. Since ancient times, citrus fruit peels have been a source of nutrition and medicine. Citrus peel is thus a prospective source of foods with beneficial properties. Many bioactive substances, such as polyphenols, pectins, proteins, pigments, dietary fibers, and essential oils, can be found in citrus peel, which is a valuable natural source.

Overall, citrus fruit peels exhibited many biotherapeutic properties such as antioxidant, antibacterial, anticancer, anti-inflammatory, and antidiabetic. Additionally, it could be used as a thickening, flavoring, and food coloring agent in the food industry. Citrus peel, a waste product of the citrus processing industry, thus demonstrates potential economic benefits by returning to the food processing chain as an additive and offering sustainable and creative approaches to the exploitation of food waste. To get the most benefits from citrus peel extract, further research is currently being done on it.

13. Challenges in using the citrus peel wastes

Citrus fruit peels have various uses in the pharmaceuticals, nutraceutical and cosmetics industries, owing to their therapeutic and health benefits. However, there are many challenges that need to be addressed to make better use of citrus fruit peels. There are abundant sources of these peels, but the collection, and processing of these materials face major challenges. Environmental instability, poor water solubility, and low bioavailability limit faster processing and wide application. Flavonoids of citrus fruits exhibit poor bioavailability and increased sensitivity to different environmental conditions, such as pH, heat, and oxidation. Changes in these conditions promote the degradation of flavonoids, which lowers the total flavonoid content. Preservation of key bioactive compounds in citrus fruit peels has been now partially resolved by using nanotechnology, where the extracted bioactive compounds may be encapsulated (nano liposomes, nano particles, etc.) in various types of nanoparticles and make the components thermostable. In a developing country like India with a vast population, collection and short-term storage of fruit peels is a huge challenge. People need to be aware of the use of these citrus fruit peels through recycling. There is a need to set up a policy for the collection and storage of the citrus waste and more focus should be given to the micro-process industries for low-cost effective utilization and marketing of these value-added products to the local as well as to the international market.

14. Conclusions

This review demonstrated the presence of many important bioactive compounds in citrus fruit peels. This article highlighted the present knowledge about the various uses of citrus-peel extracts as nutraceuticals, pharmaceuticals, and in other industries. Key bioactive compounds present in citrus fruit peels include essential oils, flavonoids, carotenoids, steroids, terpenoids, alkane groups, ethyl esters, vitamins C, E, and A, and phenolic compounds, which provide a wide range of benefits, including antioxidant activity and antimicrobial activity, as well as applications in the production of natural dyes, value-added products, packaging materials, and low-cost paper. Because of the limitless uses of citrus peels, harvesting and processing of this material have now become a growing industry. However, there are several challenges in large-scale processing and preparation of bioactive compounds from citrus fruit peels in countries like India. Effective policies, government-industry collaboration, and large funding opportunities would help in overcoming these challenges. Successful implementation of such policies would also help in achieving the aims of the Sustainable Development Goals (SDGs) set by the United Nations.

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Conflict of interest

Authors declare that there is no conflict of interest.

References

[1] Maqbool Z, Khalid W, Atiq HT, Koraqi H, Javaid Z, Alhag SK, et al. Citrus waste as source of bioactive compounds: Extraction and utilization in the health and food industry. *Molecules*. 2023; 28(4): 1636.

[2] Mahato N, Sharma K, Sinha M, Cho MH. Citrus waste derived nutra-pharmaceuticals for health benefits: Current trends and future perspectives. *Journal of Functional Foods*. 2018; 40: 307-316.

[3] Richa R, Kohli D, Vishwakarma D, Mishra A, Kabdal B, Kothakota A, et al. Citrus fruit: Classification, value addition, nutritional and medicinal values, and relation with pandemic and hidden hunger. *Journal of Agriculture and Food Research*. 2023; 14: 100718.

[4] Satari B, Karimi K. Citrus processing wastes: Environmental impacts, recent advances, and future perspectives in total valorization. *Resources, Conservation and Recycling*. 2018; 129: 153-167.

[5] Geraci A, Di Stefano V, Di Martino E, Schillaci D, Schicchi R. Essential oil components of orange peels and antimicrobial activity. *Natural Product Research*. 2017; 31(6): 653-659.

[6] Li ZH, Cai M, Liu YS, Sun PL, Luo SL. Antibacterial activity and mechanisms of essential oil from *Citrus medica L. var. sarcodactylis*. *Molecules*. 2019; 24(8): 1577.

[7] Khule GD, Khupase SP, Giram KK. Development and quality evaluation of orange pomace fortified biscuits. *Journal of Pharmacognosy and Phytochemistry*. 2019; 8(3): 3695-3701.

[8] Singh B, Singh JP, Kaur A, Singh N. Phenolic composition, antioxidant potential and health benefits of citrus peel. *Food Research International*. 2020; 132: 109114.

[9] de Moraes Crizel T, Jablonski A, de Oliveira Rios A, Rech R, Flôres SH. Dietary fiber from orange byproducts as a potential fat replacer. *LWT-Food Science and Technology*. 2013; 53(1): 9-14.

[10] Suri S, Singh A, Nema PK. Current applications of citrus fruit processing waste: A scientific outlook. *Applied Food Research*. 2022; 2(1): 100050.

[11] Naveed T, Babar AA, Rashdi SY, Rehman F, Naeem MA, Wang W, et al. Dyeing and colorfastness properties of tencel fabric treated with natural dye extracted from orange peel. *Surface Review and Letters*. 2021; 28(3): 2050055.

[12] Ciriminna R, Forest B, Meneguzzo F, Pagliaro M, Hamann MT. Technical and economic feasibility of a stable yellow natural colorant production from waste lemon peel. *Applied Sciences*. 2020; 10(19): 6812.

[13] Bhatnagar A, Kumar E, Minocha AK, Jeon BH, Song H, Seo YC. Removal of anionic dyes from water using *Citrus limonum* (lemon) peel: equilibrium studies and kinetic modeling. *Separation Science and Technology*. 2009; 44(2): 316-334.

[14] Rafiq S, Kaul R, Sofi SA, Bashir N, Nazir F, Nayik GA. Citrus peel as a source of functional ingredient: A review. *Journal of the Saudi Society of Agricultural Sciences*. 2018; 17(4): 351-358.

[15] Agrawal SS, Paridhavi M. *Herbal Drug Technology*. India: Universities Press; 2012.

[16] Pandharipande S, Makode H. Separation of oil and pectin from orange peel and study of effect of pH of extracting medium on the yield of pectin. *Journal of Engineering Research and Studies*. 2012; 3(2): 6-9.

[17] Zareiyan F, Khajehsharifi H. Analyzing bioactive compounds in essential oil of Citrus maxima and *Citrus sinensis* peel. *Journal of Essential Oil Bearing Plants*. 2021; 24(4): 677-682.

[18] Kammoun Bejar A, Ghanem N, Mihoubi D, Kechaou N, Boudhrioua Mihoubi N. Effect of infrared drying on drying kinetics, color, total phenols and water and oil holding capacities of orange (*Citrus sinensis*) peel and leaves. *International Journal of Food Engineering*. 2011; 7(5): 5.

[19] Addi M, Elbouzidi A, Abid M, Tungmunnithum D, Elamrani A, Hano C. An overview of bioactive flavonoids from citrus fruits. *Applied Sciences*. 2021; 12(1): 29.

[20] Suthar P, Kehinde BA, Rafiq S, Ansari N, Singh B, Kumar H. Orange wastes and by-products: Chemistry, processing, and utilization. In: Muzaffar K, Sofi SA, Mir SA. (eds.) *Handbook of Fruit Wastes and By-Products*. Boca Raton: CRC Press; 2022. p.87-98.

[21] Shorbagi M, Fayek NM, Shao P, Farag MA. *Citrus reticulata* Blanco (the common mandarin) fruit: An updated review of its bioactive, extraction types, food quality, therapeutic merits, and bio-waste valorization practices to maximize its economic value. *Food Bioscience*. 2022; 47: 101699.

[22] Goldenberg L, Yaniv Y, Porat R, Carmi N. Mandarin fruit quality: a review. *Journal of the Science of Food and Agriculture*. 2018; 98(1): 18-26.
[23] Magda RA, Awad AM, Selim KA. Evaluation of mandarin and navel orange peels as natural sources of antioxidant in biscuits. *Alexandria Journal of Food Science and Technology.* 2008; 75: 75-82.
[24] Du C, Zuo F, Cao Y, Zang Y. Anti-diabetic effects of natural and modified 'Ganzhou' navel orange peel pectin on type 2 diabetic mice via gut microbiota. *Food & Function*. 2023; 14(24): 10977-10990.
[25] Yang C, Zhang W, Xiang S, Chen L, Chun J, Chen H. Navel orange peel essential oil inhibits the growth and progression of triple negative breast cancer. *BMC Complementary Medicine and Therapies*. 2024; 24(1): 233.
[26] Tahir Z, Khan MI, Ashraf U, Adan IR, Mubarik U. Industrial application of orange peel waste; a review. *International Journal of Agriculture and Biosciences*. 2023; 12(2): 71-76.
[27] Yousof SM, Atta R, Khalil IA, Zayed MA, Seddek A. *Citrus sinensis* (Sweet oranges) wastes: The orange wealth. In: *Mediterranean Fruits Bio-wastes: Chemistry, Functionality and Technological Applications*. Cham: Springer International Publishing; 2022.
[28] Jiang H, Zhang W, Xu Y, Chen L, Cao J, Jiang W. An advance on nutritional profile, phytochemical profile, nutraceutical properties, and potential industrial applications of lemon peels: A comprehensive review. *Trends in Food Science & Technology*. 2022; 124: 219-236.
[29] Xiao L, Ye F, Zhou Y, Zhao G. Utilization of pomelo peels to manufacture value-added products: A review. *Food Chemistry*. 2021; 351: 129247.
[30] Dessai P, Pangam H. Formulation and evaluation of herbal mosquito repellants in roll-on forms. *Research Journal of Pharmacy and Technology*. 2023; 16(6): 2941-2944.
[31] Pasdaran A, Hamedi A, Shiehzadeh S, Hamedi A. A review of citrus plants as functional foods and dietary supplements for human health, with an emphasis on meta-analyses, clinical trials, and their chemical composition. *Clinical Nutrition ESPEN*. 2023; 54: 311-336.
[32] Memariani Z, Gorji N, Moeini R, Farzaei MH. Traditional uses. In: *Phytonutrients in Food*. Woodhead Publishing; 2020.
[33] Shi M, Guo Q, Xiao Z, Sarengaowa, Xiao Y, Feng K. Recent advances in the health benefits and application of tangerine peel (citri reticulatae pericarpium): A review. *Foods*. 2024; 13(13): 1978.
[34] Zahr S, Zahr R, El Hajj R, Khalil M. Phytochemistry and biological activities of *Citrus sinensis* and *Citrus limon*: An update. *Journal of Herbal Medicine*. 2023; 15: 100737.
[35] Chen XM, Tait AR, Kitts DD. Flavonoid composition of orange peel and its association with antioxidant and anti-inflammatory activities. *Food Chemistry*. 2017; 218: 15-21.
[36] Wang T, Tao Y, Lai C, Huang C, Ling Z, Yong Q. Influence of extraction methods on navel orange peel pectin: Structural characteristics, antioxidant activity and cytoprotective capacity. *International Journal of Food Science & Technology*. 2023; 58(3): 1382-1393.
[37] Shan Y. *Comprehensive Utilization of Citrus By-Products*. Academic Press; 2016.
[38] Ye X. *Phytochemicals in Citrus: Applications in Functional Foods*. CRC Press; 2017.
[39] Chauhan N, Sharma D, Rana K, Neelam, Thakur A, Verma R, et al. Citrus. In: *Nutraceuticals from Fruit and Vegetable Waste*. Wiley; 2024. p.223-246.
[40] Khan MK, Dangles O. A comprehensive review on flavanones, the major citrus polyphenols. *Journal of Food Composition and Analysis*. 2014; 33(1): 85-104.
[41] Al-Khayri JM, Sahana GR, Nagella P, Joseph BV, Alessa FM, Al-Mssallem MQ. Flavonoids as potential anti-inflammatory molecules: A review. *Molecules*. 2022; 27: 2901.
[42] Murador DC, Salafia F, Zoccali M, Martins PL, Ferreira AG, Dugo P, et al. Green extraction approaches for carotenoids and esters: Characterization of native composition from orange peel. *Antioxidants*. 2019; 8(12): 613.
[43] Chedea VS, Kefalas P, Socaciu C. Patterns of carotenoid pigments extracted from two orange peel wastes (*Valencia* and *Navel* var.). *Journal of Food Biochemistry*. 2010; 34(1): 101-110.
[44] Zhang Y, Jin J, Zhu S, Sun Q, Zhang Y, Xie Z, et al. Citrus *β*-carotene hydroxylase 2 (BCH2) participates in xanthophyll synthesis by catalyzing the hydroxylation of *β*-carotene and compensates for BCH1 in citrus carotenoid metabolism. *Horticulture Research*. 2023; 10(3): 1-12.
[45] Molnár P, Szabolcs J. β-Citraurin epoxide, a new carotenoid from *Valencia* orange peel. *Phytochemistry*. 1980; 19(4): 633-637.
[46] Bishnoi S, Yadav S, Sharma D, Pathera AK. Effect of orange peel and moringa leaves extracts on quality of chicken sausages under frozen storage. *Nutrition & Food Science*. 2022; 52(7): 1181-1193.
[47] Pasarin D, Ghizdareanu AI, Teodorescu F, Rovinaru C, Banu A. Characterization of pectin oligosaccharides

obtained from citrus peel pectin. *Fermentation*. 2023; 9(3): 312.
[48] Berk Z. Chapter 1-Introduction: History, production, trade, and utilization. In: Berk Z (ed.) *Citrus Fruit Processing*. San Diego, CA, USA: Academic Press; 2016. p.1-8.
[49] Mahajan M, Sadana R. Citrus based food products and their shelf life. In: *Recent Advances in Citrus Fruits*. Cham: Springer International Publishing; 2023. p.367-393.
[50] Bai C, Chen R, Chen Y, Bai H, Sun H, Li D, et al. Plant polysaccharides extracted by high pressure: A review on yields, physicochemical, structure properties, and bioactivities. *International Journal of Biological Macromolecules*. 2024; 263: 129939.
[51] Guo X, Han D, Xi H, Rao L, Liao X, Hu X, et al. Extraction of pectin from navel orange peel assisted by ultra-high pressure, microwave or traditional heating: A comparison. *Carbohydrate Polymers*. 2012; 88(2): 441-448.
[52] Singhal S, Deka SC, Koidis A, Hulle NR. Standardization of extraction of pectin from Assam lemon (*Citrus limon* Burm f.) peels using novel technologies and quality characterization. *Biomass Conversion and Biorefinery*. 2024; 1-2.
[53] Mohsin A, Hussain MH, Zaman WQ, Mohsin MZ, Zhang J, Liu Z, et al. Advances in sustainable approaches utilizing orange peel waste to produce highly value-added bioproducts. *Critical Reviews in Biotechnology*. 2022; 42(8): 1284-1303.
[54] Sikdar DC, Menon R, Duseja K, Kumar P, Swami P. Extraction of citrus oil from orange (*Citrus sinensis*) peels by steam distillation and its characterizations. *International Journal of Technical Research and Applications*. 2016; 4(3): 341-346.
[55] Cholke PB, Bhor AK, Shete AM, Sonawane RK, Pravin C. Extraction and GC-MS analysis of orange (*Citrus sinensis*) peel oil. *Research Journal of Life Sciences, Bioinformatics, Pharmaceutical and Chemical Sciences*. 2017; 2(5): 41-51.
[56] Ciriminna R, Fidalgo A, Delisi R, Carnaroglio D, Grillo G, Cravotto G, et al. High-quality essential oils extracted by an eco-friendly process from different citrus fruits and fruit regions. *ACS Sustainable Chemistry & Engineering*. 2017; 5(6): 5578-5587.
[57] Li S, Lambros T, Wang Z, Goodnow R, Ho CT. Efficient and scalable method in isolation of polymethoxyflavones from orange peel extract by supercritical fluid chromatography. *Journal of Chromatography B*. 2007; 846(1-2): 291-297.
[58] Geraci A, Di Stefano V, Di Martino E, Schillaci D, Schicchi R. Essential oil components of orange peels and antimicrobial activity. *Natural Product Research*. 2017; 31(6): 653-659.
[59] Ikeda NY, Ambrosio CM, Soares MI, Alencar SM, Gloria EM. Antibacterial, antioxidant activity and volatile composition of essential oils extracted from crude organic propolis and its residues from propolis extract production. *Natural Volatile & Essential Oils-NVEO*. 2019; 6: 1-311.
[60] Ikeda NY, Ambrosio CM, Miano AC, Rosalen PL, Gloria EM, Alencar SM. Essential oils extracted from organic propolis residues: An exploratory analysis of their antibacterial and antioxidant properties and volatile profile. *Molecules*. 2021; 26(15): 4694.
[61] Visakh NU, Pathrose B, Chellappan M, Ranjith MT, Sindhu PV, Mathew D. Chemical characterisation, insecticidal and antioxidant activities of essential oils from four *Citrus* spp. fruit peel waste. *Food Bioscience*. 2022; 50: 102163.
[62] Nazir A, Itrat N, Shahid A, Mushtaq Z, Abdulrahman SA, Egbuna C, et al. Orange peel as source of nutraceuticals. In: *Food and Agricultural Byproducts as Important Source of Valuable Nutraceuticals*. Cham: Springer International Publishing; 2022. p.97-106.
[63] Sundaram R, Nandhakumar E, Haseena Banu H. Hesperidin, a citrus flavonoid ameliorates hyperglycemia by regulating key enzymes of carbohydrate metabolism in streptozotocin-induced diabetic rats. *Toxicology Mechanisms and Methods*. 2019; 29(9): 644-653.
[64] Zhang J, Zhang L, Lai C, Liang Y, Gao L, Kaliaperumal K, et al. Nutraceutical potential of navel orange peel in diabetes management: The chemical profile, antioxidant, α-glucosidase inhibitory and antiglycation effects of its flavonoids. *Food Bioscience*. 2022; 49: 101943.
[65] Sun P, Huang R, Qin Z, Liu F. Influence of tangeretin on the exponential regression of inflammation and oxidative stress in streptozotocin-induced diabetic nephropathy. *Applied Biochemistry and Biotechnology*. 2022; 194(9): 3914-3929.
[66] El-Aziz A, Mohammad N, Shehata MG, Alsulami T, Badr AN, Elbakatoshy MR, et al. Characterization of orange peel extract and its potential protective effect against aluminum chloride-induced Alzheimer's disease. *Pharmaceuticals (Basel)*. 2023; 16(1): 12.

[67] Braidy N, Behzad S, Habtemariam S, Ahmed T, Daglia M, Mohammad Nabavi S, et al. Neuroprotective effects of citrus fruit-derived flavonoids, nobiletin and tangeretin in Alzheimer's and Parkinson's disease. *CNS & Neurological Disorders-Drug Targets*. 2017; 16(4): 387-397.
[68] Zhang M, Jiang H, Ou S, Qian M, Qi H, Chen J, et al. Dietary sinensetin and polymethoxyflavonoids: bioavailability and potential metabolic syndrome-related bioactivity. *Critical Reviews in Food Science and Nutrition*. 2023; 1-7.
[69] Li S, Lambros T, Wang Z, Goodnow R, Ho CT. Efficient and scalable method in isolation of polymethoxyflavones from OPE by supercritical fluid chromatography. *Journal of Chromatography B*. 2007; 846(1-2): 291-297.
[70] Schillaci D, Napoli EM, Cusimano MG, Vitale M, Ruberto G. Origanum vulgare subsp. hirtum essential oil prevented biofilm formation and showed antibacterial activity against planktonic and sessile bacterial cells. *Journal of Food Protection*. 2013; 76(10): 1747-1752.
[71] Cusimano MG, Di Stefano V, La Giglia M, Di Marco Lo Presti V, Schillaci D, Pomilio F, et al. Control of growth and persistence of Listeria monocytogenes and β-lactam-resistant Escherichia coli by thymol in food processing settings. *Molecules*. 2020; 25(2): 383.
[72] Suthar M, Dufossé L, Singh SK. The enigmatic world of fungal melanin: A comprehensive review. *Journal of Fungi*. 2023; 9(9): 891.
[73] Benjamin AC, Akingbala JO, Baccus-Taylor GS. Effect of drying and storage on flavour quality of orange (Citrus cinensis (Linn) Osbeck) peel for cupcakes. *Journal of Food Agriculture and Environment*. 2007; 5(2): 78.
[74] Mshari A, Alrudainy AM, Abu-Mejdad NM. Study the effect of some citrus peel extracts against plant pathogenic fungi. *Asian Journal of Water, Environment and Pollution*. 2022; 19(6): 103-110.
[75] Santhi VP, Sriramavaratharajan V, Murugan R, Masilamani P, Gurav SS, Sarasu VP, et al. Edible fruit extracts and fruit juices as potential source of antiviral agents: a review. *Journal of Food Measurement and Characterization*. 2021; (6): 5181-5190.
[76] Badshah SL, Faisal S, Muhammad A, Poulson BG, Emwas AH, Jaremko M. Antiviral activities of flavonoids. *Biomedicine & Pharmacotherapy*. 2021; 140: 111596.
[77] Shim D, Kim HJ, Lee J, Lee YM, Park JW, Yang S, et al. *Citrus junos* tanaka peel extract ameliorates hdm-induced lung inflammation and immune responses in vivo. *Nutrients*. 2022; 14(23): 5024.
[78] Verma J, Mishra R, Mazumdar A, Singh R, El-Gendy NS. Development and evaluation of an eco-friendly hand sanitizer formulation valorized from fruit peels. *International Journal of Biomaterials*. 2023; 2023(1): 2516233.
[79] Nakajima VM, Macedo GA, Macedo JA. Citrus bioactive phenolics: Role in the obesity treatment. *LWT-Food Science and Technology*. 2014; 59(2): 1205-1212.
[80] Bunse M, Daniels R, Gründemann C, Heilmann J, Kammerer DR, Keusgen M, et al. Essential oils as multicomponent mixtures and their potential for human health and well-being. *Frontiers in Pharmacology*. 2022; 13: 956541.
[81] Agarwal P, Sebghatollahi Z, Kamal M, Dhyani A, Shrivastava A, Singh KK, et al. Citrus essential oils in aromatherapy: Therapeutic effects and mechanisms. *Antioxidants.* 2022; 11(12): 2374.
[82] Oboh G, Olatunde DM, Ademosun AO, Ogunsuyi OB. Effect of citrus peels-supplemented diet on longevity, memory index, redox status, cholinergic and monoaminergic enzymes in Drosophila melanogaster model. *Journal of Food Biochemistry*. 2021; 45(2): e13616.
[83] Abou Baker DH, Ibrahim EA, Salama ZA. Citrus peels as a source of bioactive compounds with industrial and therapeutic applications. In: *Phenolic Compounds-Chemistry, Synthesis, Diversity, Non-Conventional Industrial, Pharmaceutical and Therapeutic Applications*. London: IntechOpen; 2021. p.1-3.
[84] Sharma K, Mahato N, Cho MH, Lee YR. Converting citrus wastes into value-added products: Economic and environmently friendly approaches. *Nutrition.* 2017; 34: 29-46.
[85] Ameer B, Weintraub RA, Johnson JV, Yost RA, Rouseff RL. Flavanone absorption after naringin, hesperidin, and citrus administration. *Clinical Pharmacology & Therapeutics*. 1996; 60(1): 34-40.
[86] Guzmán-Chávez ML, Claudio-Rizo JA, Caldera-Villalobos M, Cabrera-Munguía DA, Becerra-Rodríguez JJ, Rodríguez-Fuentes N. Novel bioactive collagen-polyurethane-pectin scaffolds for potential application in bone regenerative medicine. *Applied Surface Science Advances*. 2022; 11: 100317.
[87] Chandra I, Abha S, Bandyopadhyay KK, Shruti S, Priya P, Prachi J, et al. Bioethanol production by Zymomonasmobilis MTCC No. 2427 using orange peels as low cost substrates. *International Journal of ChemTech Research*. 2013; 5(6): 2787-2792.
[88] Hasdemir İM, Yılmazoğlu E, Güngör S, Hasdemir B. Adsorption of acetic acid onto activated carbons produced from hazelnut shell, orange peel, and melon seeds. *Applied Water Science*. 2022; 12(12): 271.
[89] He M. *Tailored waste-derived biochar for energy recovery and environmental applications*. Dissertations. Hong

Kong Polytechnic University; 2023.
[90] Siddique A, Nayak AK, Singh J. Synthesis of $FeCl_3$-activated carbon derived from waste *Citrus limetta* peels for removal of fluoride: An eco-friendly approach for the treatment of groundwater and bio-waste collectively. *Groundwater for Sustainable Development*. 2020; 10: 100339.
[91] Sowmya RS, Sugriv G, Annapure US. Effect of basil herb on cookies development and its effect on the nutritive, elemental, phytochemical, textural and sensory quality. *Journal of Food Science and Technology*. 2022; 59(9): 3482-3491.
[92] Kaur M, Dhaliwal M, Kaur H, Singh M, Punia Bangar S, Kumar M, et al. Preparation of antioxidant-rich tricolor pasta using microwave processed orange pomace and cucumber peel powder: A study on nutraceutical, textural, color, and sensory attributes. *Journal of Texture Studies*. 2022; 53(6): 834-843.
[93] Bishnoi S, Yadav S, Sharma D, Pathera AK. Effect of orange peel and moringa leaves extracts on quality of chicken sausages under frozen storage. *Nutrition & Food Science*. 2022; 52(7): 1181-1193.
[94] Nupur AH, Mazumder MA, Karmoker P, Alim MA. Effectiveness of orange peel extract on the quality of minced beef during frozen storage. *Journal of Food Processing and Preservation*. 2022; 46(7): e16659.
[95] Dhasmana A, Malik S, Ranjan A, Chauhan A, Tashkandi HM, Haque S, et al. A bioengineered quercetin-loaded 3D bio-polymeric graft for tissue regeneration and repair. *Biomedicines*. 2022; 10(12): 3157.
[96] Espinosa-Garza G, Antonyan N, Loera-Hernández I. Orange peel dehydration and creation of new edible products. *International Journal of Food Engineering*. 2018; 4: 327-331.
[97] Albak F, Tekin AR. Development of functional chocolate with spices and lemon peel powder by using response surface method: Development of functional chocolate. *Akademik Gıda*. 2014; 12(2): 19-25.
[98] Yaradoddi JS, Banapurmath NR, Ganachari SV, Soudagar ME, Sajjan AM, Kamat S, et al. Bio-based material from fruit waste of orange peel for industrial applications. *Journal of Materials Research and Technology*. 2022; 17: 3186-3197.
[99] Kashyap S. Bio-valorization of citrus waste for the production of bioactive molecules for food applications. In: *Microbial Bioprocessing of Agri-food Wastes*. CRC Press; 2023. p.21-44.
[100] Sharma P, Vishvakarma R, Gautam K, Vimal A, Gaur VK, Farooqui A, et al. Valorization of citrus peel waste for the sustainable production of value-added products. *Bioresource Technology*. 2022; 351: 127064.
[101] Buxoo S, Jeetah P. Feasibility of producing biodegradable disposable paper cup from pineapple peels, orange peels and Mauritian hemp leaves with beeswax coating. *SN Applied Sciences*. 2020; 2: 1-5.
[102] Koolaji N, Shammugasamy B, Schindeler A, Dong Q, Dehghani F, Valtchev P. Citrus peel flavonoids as potential cancer prevention agents. *Current Developments in Nutrition*. 2020; 4(5): 1-20.
[103] Pal DB, Kapoor A, Arya AK, Arya RK, Tiwari AK. Characterization and sustainable utilization of *Punica granatum* and *Citrus limetta* peels: Insights for biomass valorization. *Biomass Conversion and Biorefinery*. 2024; 1-9.
[104] Rafiq S, Kaul R, Sofi SA, Bashir N, Nazir F, Nayik GA. Citrus peel as a source of functional ingredient: A review. *Journal of the Saudi Society of Agricultural Sciences*. 2018; 17(4): 351-358.
[105] Addi EH, Addi AA, Achemchem F. Evaluation of four pesticides residues contents in the citrus fruits from Souss-Massa area (Morocco). *Environmental Engineering & Management Journal*. 2014; 13(3): 663-667.
[106] Fathy HM, Abd El-Maksoud AA, Cheng W, Elshaghabee FM. Value-added utilization of citrus peels in improving functional properties and probiotic viability of Acidophilus-bifidus-thermophilus (ABT)-type synbiotic yoghurt during cold storage. *Foods*. 2022; 17: 2677.
[107] Ahmad F, Sultan A, Khan S, Ali M, Ali I, Abdullah H, et al. Effect of citrus peeling (*Citrus sinensis*) on production performance, humoral immunity, nutrients, and energy utilization of broiler quails. *Poultry Science*. 2024; 103(1): 103207.