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Potential utilization of citrus waste for maximizing therapeutic benefits through resourceful reuse: A review

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Abstract

Citrus is one among the important fruit crops, pervasively cultivated across the world and hold a prominent status in both human nutrition and global agriculture. For centuries, citrus are being used for medicinal and therapeutic purposes attributed to their rich array of bioactive compounds. The widespread availability and diverse range of phytochemicals in citrus fruits make a valuable component of balanced diet, contributing overall wellness and health. The fruits possess rich nutritional value, making them potentially important demandable crop both in the fresh fruit industries and food processing sectors. However, generation of industrial waste, primarily in the form of peels, pomace, seeds and wastewater, presents a serious problem since it contaminates the environment and possess health hazards. Indeed, managing waste from citrus harbors, numerous health benefits and holds potential for generating designer foods due to its elevated bioactive content, there remains enormous deficit regarding its commercial utilization. A complete understanding about all this information could pave a way for the improved usage of citrus waste as multifunctional fruit, thereby promote the growth of value chain. Therefore, this review will explore the diverse applications of citrus across various industries, *viz.,* culinary, cosmetics, pharmaceuticals, textile and cattle feed.

1. Introduction

India possess extensive genetic diversity in citrus, with a considerable portion comprising of both tropical and subtropical varieties. The Food and Agriculture Organization and World Health Organization, advocates the consumption of adequate quantity of nutritious fruits, which is necessary for overall health benefits. Additionally, a nutritious diet improves the health and humans wellness (Chellammal, 2022). These suggestions highlight the need of including fresh fruits in regular diets in order to enhance nutrition and overall health (Di Vita *et al*., 2020). India stands as a global leader in citrus fruit production and fruits are widely incorporated into the daily diets of Indians in the form of syrups, squashes and as fresh fruits (Pol *et al*., 2023).These fruits are not only valued for their refreshing taste but also for their nutritional benefits, as they are rich in vitamin C and other essential nutrients. In India, citrus is grown in north east, north west, central and southern regions (Biswas *et al*., 2010), covering an area of 252 million hectares with the production of 2,546 million tonnes of fruits (Maheswari *et al*., 2023). It is estimated that domestication of citrus species began approximately thousand years ago (Wang *et al*., 2024). Numerous wild and cultivated citrus species in India exhibit the genetic diversity of the fruit, which has enormous potential to advance the citrus industry and can be utilized for dietary and therapeutic applications (Richa *et al*., 2023). There are numerous citrus species rich in bioactive compounds and therapeutic characteristics whereas, certain fruits are not familiar to the general public but are consumed by the local community resulting in underutilization (Atreya and Shrestha, 2020; Peduruhewa *et al*., 2021). A considerable number of these fruits can thrive under harsh conditions and are renowned for their medicinal and nutritional worth, which can satisfy the demands of health conscious consumers (Kumar *et al*., 2022). The commercially grown citrus fruits in India includes sweet orange (*Citrus sinensis*), pummelo (*Citrus grandis*), grapefruit (*Citrus paradise*), limes (*Citrus aurantifolia*), lemon (*Citrus limon*) and mandarin (*Citrus reticulata*) (Hynniewta *et al*., 2014). The mandarin fruits contain significantly more carotenoids than grapefruit or oranges. β-cryptoxanthin is the main carotenoid found in mandarins, which contributes the orange color of juice and also acts as a precursor of vitamin A. The pink colour of grapefruit is characterized by its high β-carotene content, whereas lycopene is mostly responsible for the red colour of red navel oranges (Marti *et al*., 2009). The byproduct of citrus family includes high levels of naturally occurring flavonoids, including polymethoxylated flavones that are uncommon in other plants (Gunwantrao *et al*., 2016).

Nutrient dense fruit has gained popularity throughout the world in recent years, especially fascinating in light of COVID-19 pandemic situations because it enhances the public's nutritional status and improves their immune and metabolic systems (Meena *et al*., 2022). Since the huge rise in nutrition related health issues occurs worldwide, it is vital to prioritize formal nutrition education aimed at boosting knowledge and promoting regular fruit consumption which could provide significant consideration in balanced diet (Vajargah *et al*., 2022). Numerous investigations revealed that the citrus fruit contains the bioactive compounds and secondary metabolites which could be employed either as supplements or used as a chemotherapeutics

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besides its use as safe bactericides and fungicides, particularly those of botanical origin, or becoming popular among the public. Citrus crops contains phytochemicals which possess various antibacterial and antifungal activity (Zahr *et al*., 2023). Currently, citrus fruit production greatly exceeds consumption, resulting in significant surplus of citrus byproduct waste, approximately 50% of the fruits, including the peel, seed and pomace which are discarded even though they may produce valuable products (Suri *et al.,* 2022) (Figure 1). Because of the severe negative impact on the environment and the economy, waste management is essential. However, utilizing waste is equally important for advancing sustainable economic concepts that lacks awareness. This review will assist to recover useful materials from citrus wastes, thereby minimizing the residual garbage, which also contributes to the clean environment.

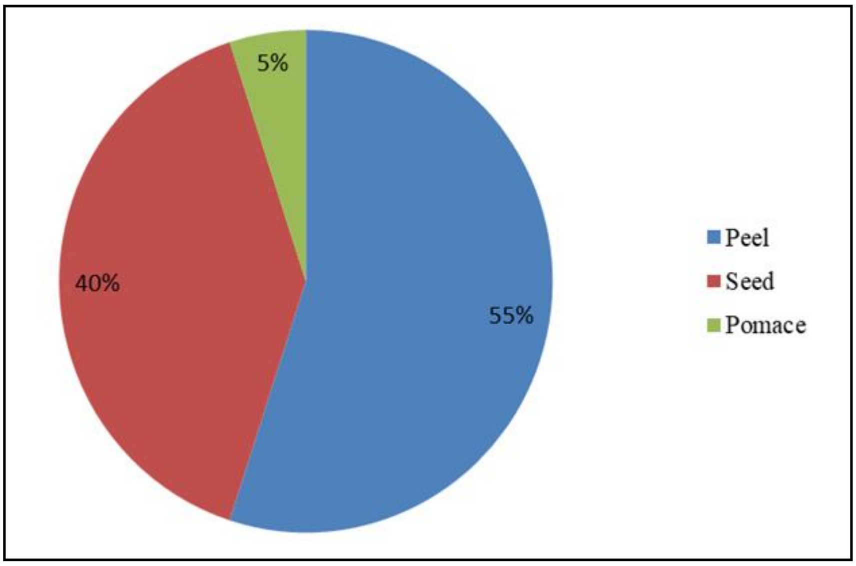

Figure 1: **Relative percentage of citrus waste.**

2. Nutritive values of citrus fruits

Citrus is being grown in 140 countries throughout the world, with major production hubs in China, India, Brazil and United States. Citrus, a member of the Rutaceae family produces fruits with various shapes and sizes, ranging from round to oblong with great nourishing value (Rao *et al*., 2021). The fruits are primarily composed of carbohydrates, such as sucrose, glucose, fructose with little protein as well as fat content (Liu *et al*., 2012). Phytochemicals found in citrus fruits possess a variety of biological properties which includes anti-inflammatory, antimutagenic and anticarcinogenic properties (Borghi and Pavanelli, 2023) even the antioxidant properties of bioactive components in these products may contribute numerous beneficial effects (Chaudhari *et al*., 2016). The chemical profile of citrus fruit includes organic acids, sugars, naringin, flavonoids, hesperidin, narirutin, carotenoids and limonoids which changes substantially between the varieties (Visvanathan and Williamson, 2022). Such variations have an impact on taste, colour and health advantages, which includes antioxidant properties and general quality parameters (Kim *et al*., 2021). In addition it contains coumarins, terpenoids and other mineral components than sugars and vitamins (Uthman and Garba, 2023) illustrated in Table 1.

Table 1: Major nutrient components present in 100 g of various citrus species

Nutrient components	*C. sinensis*	*C. reticulate*	*C. aurantiifolia*	*C. limon*	*C. aurantium*	*C. paradisi*
Protein (g)	0.8	0.9	1.5	1.0	0.7	1.0
Fat (g)	0.3	0.3	1.0	1.0	0.2	0.1
Moisture (g)	88.3	87.8	84.6	85.0	87.6	88.6
Carbohydrates (g)	9.3	10.6	10.9	11.1	10.9	10.0
Calcium (mg)	40	50	90	70	26	30
Iron (mg)	0.7	0.1	5.0	2.3	2.0	0.2
Phosphorous (mg)	30	20	0.1	10	0.3	30

Secondary metabolite confers health benefits by modulating the metabolism, scavenging free radicals and exhibiting antibacterial and anticancer properties (Lin *et al*., 2023). Citrus fruit limits free radical production and lowers homocysteine levels (Azman *et al*., 2019). Kaffir lime (*Citrus hystrix*) exhibits enhanced anti-inflammatory capabilities due to the presence of monogalactosyldiacylglycerol (Prabhu *et al*., 2024). Extensive research have consistently shown that the certain citrus metabolites possess antioxidative properties, promotes digestion and preventive effects against the cardiovascular diseases, diabetes, inflammation and neurological disorders (Abobatta, 2019 and Kim *et al*., 2021) and other mineral nutrient illustrated in (Table 2).

Table 2: Nutrient consortium of citrus species and its role in human health

Nutrient consortium of citrus species	Health promotion function
Vitamin C	Antioxidants
Zinc	Body metabolism
Magnesium	Contraction of muscles
Copper	Essential in health
Folic acid	Nucleic acid and metabolism balance
Thiamin	Brain, heart, nervous system and muscular functions
Niacin	System metabolism
Riboflavin	Reduction reactions

2.1 Citrus seeds

The seeds are the byproduct of industrial processing and fruit consumption, with little value as a commodity (Reazai *et al.*, 2014) approximately 20-25% seeds, which are often left unused after processing and dumped as waste since they are considered useless. Consequently, they are typically thrown away, which causes financial losses for the food industry as well as environmental issues including the production of greenhouse gases. Apart from this, the seeds contains a compound psyllium, which improves digestion and aids in removal of cholesterol (Ono *et al.*, 2011). Citrus seeds contains a large amount of limonin, a secondary metabolite which is also referred to as citrolimonin and evodin that are limonoid derivatives (Fan *et al.*, 2019) used for treatment to human peripheral blood mononuclear cells (PBMCs) (Battinelli *et al.*, 2023). Proteins and essential oils are abundant in citrus seeds (Purewal *et al.*, 2022). Dried citrus seed contains 52-53 % fat, 28% carbohydrates, 3.1% crude protein, 5.5% crude fiber along with 2.5% of phytochemical substances**,** ash and other fatty acids (Reazai *et al.*, 2014) (Figure 2).

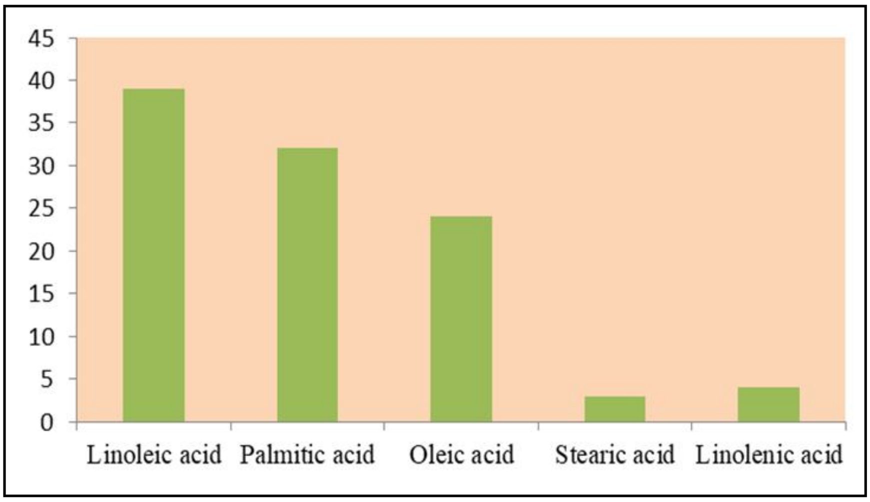

Figure 2: Fatty acids composition (%) of citrus seed oil.

Lemon seed has medicinal properties such as, antifertility action, antioxidant activity and hepatoprotective activity. Also citrus seed oil has its application in skin creams along with shower gel (Rahman *et al.*, 2022). The *C. limon* seed contains a variety of phytochemicals, including phenolic acid, phenolic esters, thiamine and triterpenoids (Sakthivel *et al.*, 2022) and other phytochemical constituents which are illustrated in Table 3. Kinnow seeds could be employed in the creation of pharmaceutical related supplements, low cost antioxidants and cosmetics. The beneficial flavonoids found in citrus seeds can be made into dietary supplements or anticancer medications (Banjerdpongchai *et al.*, 2016). Sweet orange seeds are excellent choices for food fortification agents because of high fat, carotenoid, fibre, polyphenols and protein contents (Hussain *et al.,* 2023). The aqueous extract of syrian citrus seeds contains bioactive chemical that can help to prevent oxidative stress including cancer, ageing, atherosclerosis, cardiovascular disease and neurological diseases (Alghabra *et al.*, 2022). Grapefruit seed oil are also used as lubricant and preservative for textile fibers like rayon, wool and silk, simultaneously used for making soaps and paints (Adeyeye and Adesina, 2015).The average dried seed to pulp percentage is 4.8 and it is used as the supplement of protein for livestocks (Maqbool *et al.*, 2023) besides for the production of biodiesel (Ezekoye *et al.,* 2019). Consuming citrus seeds assists in eliminating parasites such as threadworms (Rahman *et al.*, 2019). The peel and seed, are abundant in bioactive components and it is possible to extract the essential oils, aromatic compounds and low methoxyl pectin (Mahawar *et al.*, 2020). Also, it is used both for food and industrial applications satisfying the growing demands for edible and also for oleochemical products (Anwar *et al.*, 2008).

Bakery products despite their widespread consumption around the world, cookies and biscuits are made using refined white flour, these foods lack significant nutritional value. Supplementing these foods with orange seed powder significantly increased the vitamins A, D, E, K, and B complexes, with the exception of B_1 and B_2 vitamins. The five percentage substitution of orange seed powder resulted in high-quality biscuits with adequate colour, good taste, texture, excellent flavour and overall acceptance (Hussain *et al.,* 2023). The seeds also contains useful chemicals such as carotenoids and flavonoids, which are antioxidants that block the activity of free radicals and could result in significant impacts on health (Reazai, *et al.,* 2014 and Rahman *et al*., 2022).

Table 3: Phytochemical constituents present in *C. limon* seed extracts

Phytochemicals	Intensity of the phytochemical
Alkaloids	Highly detected
Steroids	Highly detected
Tannins	Less detected
Gums	Less detected
Flavonoids	Less detected
Cardiac glycosides	Less detected

2.2 Citrus peel

During citrus processing, substantial amount of peel is generated as byproduct, which holds the potential to emerge as an excellent source of phenolic and dietary fibre. Fruit peel extracts show potential in the food business as sources of bioactive chemicals, approximately 30-34% of citrus peel is produced as waste during the juice extraction process (Rafiq *et al*., 2018). The peel contains a variety of phytochemicals and the bioactive constituents, including polyphenols, flavonoids (naringin, hesperidin, nobiletin, and tangeretin), essential oils (D-limonene), pigments (carotenoids), carbohydrates (pectin, cellulose, hemicellulose and dietary fibre), flavouring compound and pigments (Suri *et al*., 2022). The pectin extracted exhibited antioxidative and anticancer properties (Wang *et al*., 2014). Peel contains pectin, a commonly used dietary fiber which varies according to the varieties (Rafiq *et al*., 2016) (Figure 3). The main use of pectin is as a thickening agent, stabilizer and emulsifier (Singhal *et al*., 2022). As a result, it is used to make jams, jellies, marmalade, fruit juice, confectionery and bread filling (Suri *et al*., 2022) and also employed for the stabilization of acidic milk beverages (Maqbool *et al*., 2023). Citrus peel extracts can serve as natural antioxidants and functional ingredients in probiotic yogurt (Sharma *et al*., 2023). In contrast, citrus peel can be utilized as a biodegradable polymer for producing innovative food packaging. Additionally, the recovered bioactive components can be directly or indirectly applied to foods to extend the shelf-life (Andrade *et al*., 2022). Orange peel and red orange pigment contains β-carotene, a naturally occurring antioxidant with a high phenolic content that prevents diseases, which also adds qualitative features including bitterness, flavor, colour and antioxidants (El-ghfar *et al*., 2016). The fresh, sliced, grated, crushed or dried orange peel is popular ingredient in flavouring food by European and Asian cuisine and also used to prepare herbal tea (Rangnekar *et al*., 2024). The peel of *C. limon* is more efficient against Gram-positive bacteria than Gram-negative bacteria due to the lipopolysaccharide coating because citrus species have antibacterial activity. Additionally, *Citrus unshiu* peel extract inhibits the bacteria, *viz., Listeria monocytogenes, Staphylococcus aureus and Bacillus cereus* (Zaki and Naeen, 2021).

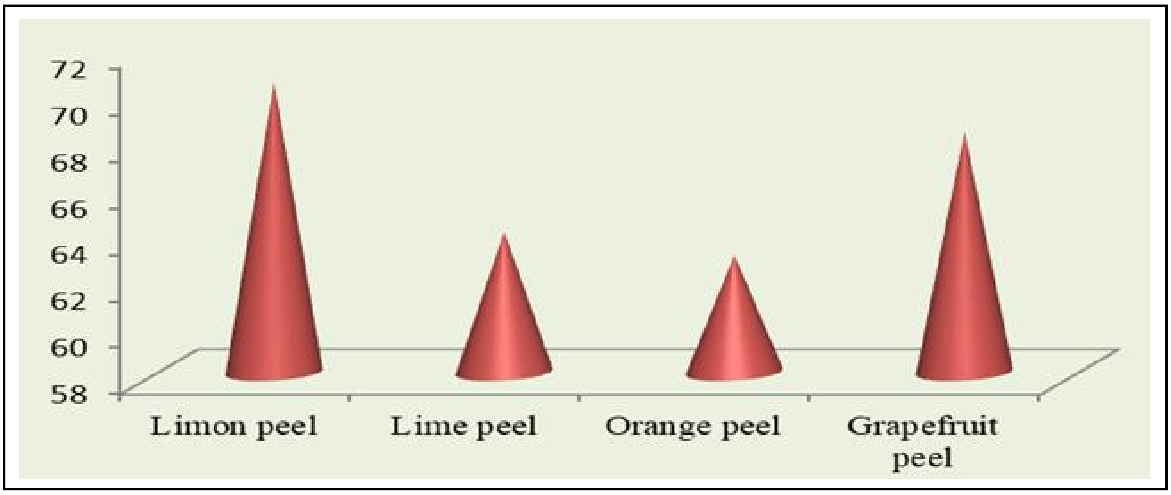

Figure 3: Total dietary fiber (%) in different citrus species.

The peel of *C. sinensis* extracts showed antityphoid action against *Salmonella paratyphi* A, B and *Salmonella typhi* (Al-Snafi, 2016). The analysis of the citrus peel essential oils revealed that the *C. sinensis* has a significant amount of limonene followed by *C. paradisii* and *C. reticulata*. Monoterpene hydrocarbons were found predominantly in these oils (Kamal *et al*., 2011). Orange peels have been shown to be effective in the creation of food grade plastics along with food preserving qualities (Cardoso *et al*., 2022).

Additionally, citrus peel have been used for culinary purpose (Ademosun *et al.,* 2018). An edible film with high tensile strength, antioxidant and antibacterial characteristics was created by combining orange peel pectin 50% along with 50% fish gelatin, additionally edible coating is also used in cheese and fresh strawberries (Monika and Choudhury, 2022). The sensory and physicochemical properties of chocolate ice cream made with orange peel fibre as a fat alternative were assessed with 78% acceptability (Comas *et al*., 2013). A wine is a complicated matrix chemically, thus depending on the kind of wine that needs to be clarified the bioadsorbents derived from orange and lemon peel, particularly the lemon bioadsorbent which have strong clearing capabilities (Raurich *et al*., 2019).

2.2.1 Mineral composition

Citrus peel are rich in essential minerals, particularly potassium, calcium and magnesium illustrated in Table 4. A glass of orange juice provides nearly 10% of the daily recommended intake (DRI) of potassium, compared to 6% from one orange fruit (Baghurst *et al.,* 2003). Citrus peel generally contain higher levels of potassium and calcium than the pulp. Magnesium is also more abundant in the peel of oranges, pommelo, lemon and grapefruit. Iron is a key micronutrient found in both the pulp and peel, while zinc levels are more prevalent in the peel of oranges, grapefruit and lemons varieties (Gorinstein *et al.,* 2001).These findings highlighted the nutritional benefits of consuming citrus peel, which contains major bioactive compounds (Figure 4).

Table 4: Major and minor nutrient concentrations in citrus peel

Nutrients	Concentration	Reference
P	0.12 ± 0.02	Tiencheu *et al.*, 2021
K	0.23 ± 0.08	
Ca	0.21 ± 0.05	
Mg	0.07 ± 0.01	
Na	0.08 ± 0.03	
Fe	0.06 ± 0.01	
Zn	0.06 ± 0.003	Rehman *et al.*, 2019
Mn	0.05 ± 0.002	

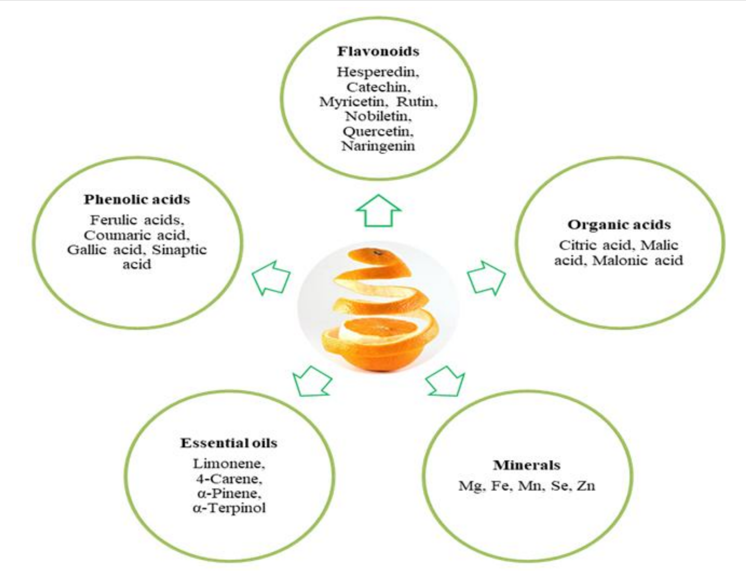

Figure 4: Bioactive compounds in citrus peel.

2.3 Citrus leaves

A significant source of bioactive ingredients in citrus leaves are phenolic compounds, ascorbic acid and flavonoid, which have acquired considerable significance (Zhang *et al*., 2020) (Table 5).

The *C. limon* leaves are used in India and other tropical countries to make tea and to cook meat and seafood dishes. Eastern nations Kebabs are flavoured with limon leaves and it is also used for garnishing puddings and cakes in Western countries (Walc *et al.,* 2021). Citron (*Citrus medica*) leaves were utilized in an aromatic maceration process in a recipe for rose wine made without roses (Brigand and Nahon, 2016). The leaves of kaffir lime which is rich in nutrients are used in meals in addition to ginger and lemon grass (Carla *et al*., 2018).

The leaves of citrus are chosen for nutritional qualities as well as for local applications in traditional medicines for the treatment of several ailments (Bachra *et al*., 2017). The leaves of *Citrus limetta* have the potential to be an effective natural antiviral and antioxidant (Chitra, 2020). In a study, it was found that an extract from the leaves of *C. aurantifolia* had antiplatelet properties (Zibaee *et al.,* 2020). The healthy leaves of mandarin contains the metabolites like vanillic acid, beta citronellol, quinic acid, n-hexadecanoic and diethylene glycol (Konda *et al.*, 2022) and different essential oils (Walc *et al.*, 2021) (Figure 5).

Table 5: Secondary metabolites content in *C. limon* leaves

Amino acids	Proline, threonine, valine, tryptophan, methionine, glutamine, isoleucine, glutamic acid, glycine, histidine, leucine, lysine, phenylalanine, aspartic acid, tyrosin, asparagine, glutamic acid
Organic acids	Ascorbic acid, threonic acid, citramalic acid, benzoic acid, citric acid, succinic acid, pyruvic acid, p-coumaricacid, shikimic acid, pipecolic acid, ferulic acid, glucaric acid urocanic acid, fumaric acid, glycolic acid and quinic acid
Sugar and sugar alcohols	Fructose, arabinose, inositol, glucose, lyxose, glycerol, rhamnose, sorbose, maltose, galactose, ribose and sucrose

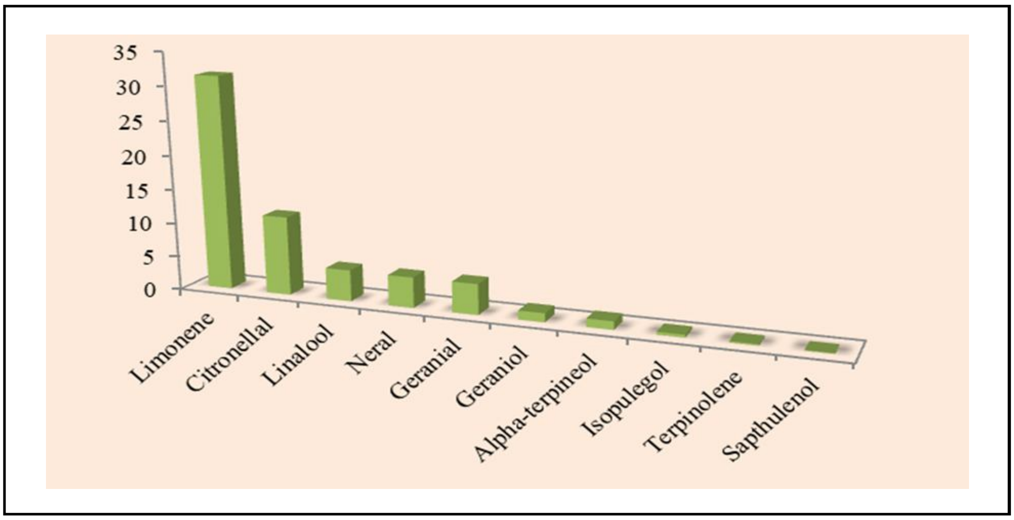

Figure 5: Different essential oil present in *C. limon* leaves.

2.4 Citrus pomace

About half of citrus fruit volume is eliminated during the industrial juice making process, leaving behind an immense quantity of pomace. This pomace contains numerous health promoting components such as the fibre, polysaccharides, phenolic compounds, phytochemicals, antioxidants and other essential compounds (Maqbool *et al*., 2023) (Figure 6). The pomace obtained from *C. sinensis* contains the phenolic compound (800 mg of gallic acid equivalent per g), beta carotene (3 mg /g) and vitamin C (60 mg /100 g) (Ningrum *et al*., 2018). Citrus pomace and its biopolymers, including pectin and cellulose were used to create biocomposite membranes for aqueous acidic solutions and films for agricultural mulching can be made from these membranes (Zannini *et al*., 2021).

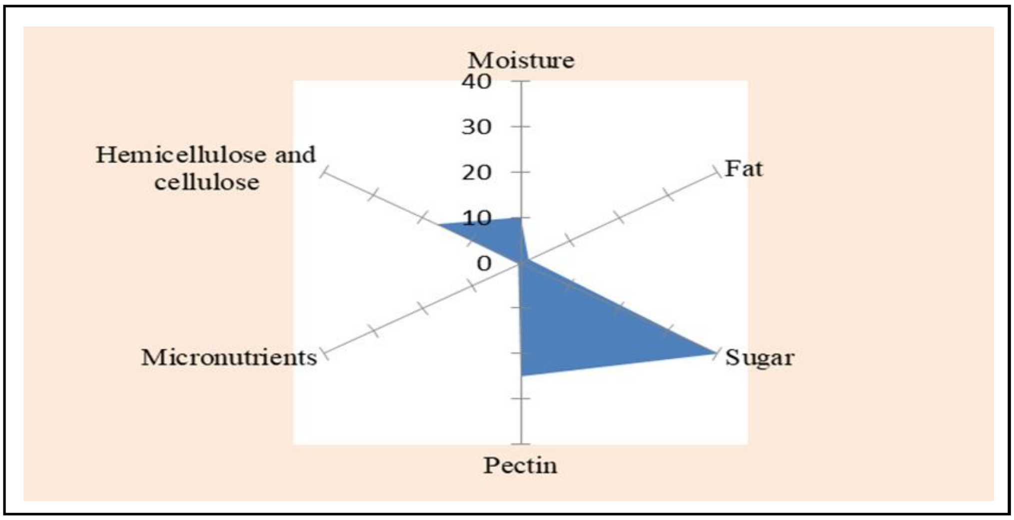

Figure 6: Essential compounds present in dried citrus pomace (%).

The addition of citrus pomace increased fibre content by 1.52 times, calcium levels by 14.33 times and dietary fibre by 2.12 times (Asif*et al*., 2023). Pectin rich byproducts of orange juice offers a great deal of potential as dietary fibre source. Pectin is gaining popularity mainly due to the potential to reduce blood triglyceride, cholesterol levels, also modifies glucose metabolism by lowering the glucose response curves due to unique gelling qualities, mostly used as a food additive (Quiles *et al*., 2016). Citrus pomace is used as feed additives which exhibit potential for utilization in cattle feed due to their high nutritional content and quality attributes (Karunsky *et al*., 2021).

2.5 Essential oil

Essential oil are the fragrant substances that accumulated in the oil sacs or oil glands found in flower, leaf and peel, particularly in the flavedo portion (Brah *et al*., 2023). Essential oil of citrus is a complex blend of around 400 components, aside from their pleasing aroma, citrus essential oil possess calming, uplifting and positive effect. Hence, used in aromatherapy either as diffusion sprays for cars, houses or as massage oils (Agarwal *et al.,* 2022). The active components found in essential oils (CEOs) of citrus include α-/β-pinene, β-d-limonene, α-terpineol myrcene, α-humulene, sabinene and linalool which belongs to the monoterpenes, monoterpene aldehyde/alcohol and sesquiterpene groups, respectively. Aside from their antibacterial, antimicrobial and insecticidal qualities (Salvatore *et al*., 2022; Saini *et al*., 2022), these chemicals have several other health promoting qualities and enormous use in food applications (Bora *et al*., 2020). Citrus essential oil comprises of more than 2000 organic components, with major fractions including monoterpenes, sesquiterpenes and their oxygenated derivatives, along with aliphatic aldehydes, alcohols and esters (Brah *et al*., 2023).

The oil extracted from small green bitter orange fruits was known as petitgrain which was later on used to describe the essential oils that were distilled from young shoots, buds and leaves. The blossom oil extracted from bitter orange (*C. aurantium*) is known as neroli and depending upon the harvest, storage and extraction the quality of the produce varies. The main component of essential oils are linalool and the flower oil of orange and lemon bergamot contained aldehydes, mainly geranial and neral stereoisomers (Palazzolo *et al*., 2013). Incorporating essential oils from mandarin, orange and lemon peel at the concentrations of 0.5%, 0.1% and 0.3% resulted in antibacterial and antifungal characteristics in ice creams without affecting sensory attributes (Tomarand Akarca, 2019). Citrus essential oil holds enormous potential for preserving meat and meat products (Emenike *et al*., 2021). In the food and cosmetics sectors, essential oils (EOs) are widely used to make flavouring of foods, laundry detergents, cologne, shampoos, soaps, lotions and insect repellents (Tundis *et al*., 2023). The essential oil extracted from the leaves of *Citrus macroptera* a semi wild species has antibacterial properties (Aktar and Foyzun, 2017). The essential oil of *C.limon* peel have high antifungal properties against the fungus *Candida albicans*, which causes oral candidiasis and its effectiveness is due to the terpenoids in essential oil of lemon peel. Essential oil of citrus contains monoterpenes, which are the natural antioxidants with radical scavenging properties (Lv *et al*., 2015) and many other therapeutic role (Grover *et al.,* 2023; Tundis *et al.,* 2023) which is illustrated in Table 6.

Table 6: Essential oil and its therapeutic properties

Compounds	Uses
Limonene	Antimicrobial, antidiabetic, antiviral, antioxidant
α-phellandrene	Boost immunity and antifungal properties
α-pinene and β-pinene	Antibacterial, fungicidal and antiviral
β-myrcene	Antioxidant, analgesic, antidiabetic, anti-inflammatory and antifungal
Linalool	Anti-inflammatory effects
1,8-cineole	Inflammatory airway diseases

Table 7: Comparative biochemical analysis of various citrus wines

Parameters	Orange	Mandarin	Kinnow
TSS (^{o}B)	7.80	8.00	7.99
Titratable acidity (% CA)	0.70	0.86	0.86
pH	3.78	3.72	3.74
Ethanol (%)	10.20	11.70	12.20
Free aldehyde (ppm)	48.0	45.0	48.4
Visual colour	Reddish yellow	Light pale yellow	Reddish yellow
Sensory score (out of 20)	14.0	15.0	13.0

2.6 Citrus wines

Citrus wine plays a significant role in advancing the growth of the citrus sector, the varieties with high sugar content lower bitter chemical concentration and less acidity are typically chosen. In comparison to other wines, citrus derived wines typically have a mellower body and a lower alcohol concentration. Furthermore, citrus wine retains much of the original flavor and beneficial components of citrus, including vitamins, polyphenols, pectins, carotenoids and fatty acids. Gamgyul wine made from entire *C. unshiu* fruits has antioxidant and antidiabetic properties which inhibits LDL (low density lipoprotein) oxidation and contains flavanones (Park and Lee, 2017). The biochemical properties of citrus fruits varies depending upon the varieties (Joshi *et al.,* 2012) which are indicated in Table 7.

The bioactive elements offer citrus wine a particular flavour and biological benefits, such as antiaging, health care, sustenance, moistening the lung, nourishing the liver and alleviating stress (Liu *et al*., 2022). Citrus wines have the potential to act as α-glucosidase inhibitors, preventing the digestion of food starches without causing any adverse effects, also as a good antidiabetic and antioxidant (Park and lee, 2017). The yeast mixture increases the content of hesperidin and nobiletin in citrus wine, thereby enhancing its quality (Zou *et al*., 2024).

2.7 Citrus branch, bark and wood

According to research by Okla *et al*. (2019), branch bark and wood of *C. aurantium* are major constitute of phytochemicals, illustrated in (Table 8). The main component of the essential oil that is derived from these sections is D-limonene, which has strong antibacterial properties. This discovery implies that D-limonene has potential uses in the creation of antibacterial drugs, cosmetics and pharmaceuticals. In green branches, most predominant compounds present are D-limonene (71.57%), oleic acid (2.72%), dodecane (4.80%) and trans-palmitoleic acid (2.62%) as indicated in (Table 6). Primary chemicals found in the branch bark included dodecane (5.73%), dimethyl anthranilate (3.13%), γ-terpinene (6.68%) and D-limonene (54.61%). Dodecane (5.31%), β-fenchol (6.83%), dimethyl anthranilate (8.13%) and D-limonene (38.13%) were the primary components found in the branch wood. Against *Agrobacterium tumefaciens*, the essential oil (EO) from branches showed the strongest antibacterial activity at 25 µl concentration, with 17.66 mm of inhibition zone (IZ) value. Against *Dickeya solani* and *Erwinia amylovora*, the EO from leaves and twigs showed significant activity of 17.33 mm, inhibition zone value. These results point to the possibility of *C. aurantium* EO as an effective antibacterial agent.

Table 8: Oil yield from bark of *C. aurantium*

Parts used	Oil yield (ml/100 g material)	Reference
Branches	1.55	Okla *et al.,* 2019
Wood of branches	1.15	
Branch bark	1.10	

2.8 Packaging material

A combination of both primary and secondary synthetic antioxidants is widely used in the plastics industry to improve polymer stability during the melting process and to stop deterioration while storing. Despite being economical and successful, these additives have potential for causing a long-term environmental risks and adverse health effects due to their reaction byproducts. As a result, researchers have turned into organic substances as safer and greener alternatives in comparison to synthetic versions (Rojas-Lema *et al*., 2022). A novel area of research focuses on utilizing leftover citrus peels to develop biodegradable packaging materials. The edible film composed of 50% orange peel pectin and 50% fish gelatin significantly enhanced the microbiological stability, physicochemical and texture of wrapped ricotta cheese (Jridi *et al.,* 2020). Furthermore, *C. limon* and *C.aurantifolia* peels were utilized to create an enticing coating for fresh strawberries, demonstrating the potential of citrus peel-based materials in food preservation (Muñoz-Labrador *et al.,* 2018). The cuticular wax of mandarin fruits acts as a physical barrier and inhibits *Penicillium digitatum* colony expansion, providing antifungal action in fruit preservation (Safranko *et al*., 2023). Active packaging films incorporating with orange peel powder significantly extend the shelf life of the products, primarily due to exceptional oxygen barrier and antioxidant properties (Yun and Liu, 2022).

2.9 Strategies for valorizing unutilized citrus fruits parts

Citrus waste, rich in functional components, is being utilized in various ways to mitigate environmental harm from improper disposal and to meet the growing issue about waste valorization. Researchers provide insight using citrus trash for animal feed, compost and the production of biofuels like bioethanol (Bernal-Vicente *et al.,* 2008; Casquete *et al.,* 2015). Applications for citrus waste span both food and non-food sectors, leveraging this natural resource to create biofuel, bioethanol, biogas, natural acids, enzymes and more. Research is still being done to determine whether citrus peels have further medicinal uses and to evaluate the properties affecting the food products and customer acceptance.

2.10 Pharmaceuticals and drug industry

Citrus fruits are increasingly utilized in the pharmaceutical industry due to their rich bioactive components, making them suitable for medicine production (Table 9). Besides the essential oils, peels of citrus are abundant rich in flavonoids, particularly polymethoxylated flavonoids like nobiletin and tangerine. These compounds have demonstrated various pharmacological actions, including anti-cancer, antioxidant and anti-inflammatory effects (Manthey *et al.,* 2001; Tripoli *et al.,* 2007). Research has shown that peel extract can reduce the gastrointestinal volume and gastric acid output while drastically increasing the gastric pH (Naser *et al.,* 2020). Additionally, citrus peel essential oil has been recommended as a potential antimicrobial agent or preservative in the pharmaceutical industry (Liu *et al.,* 2021). Phytochemicals generated from citrus waste are also used in skin, hair and nail care products, as well as lotions (antibacterial and antifungal), soaps, fragrances and cosmetics (Mahato *et al*., 2018). Citrus pulp effectively removes metals and pollutants from industrial effluents using adsorption techniques. The polymer electrolyte membrane fuel cell, which was created by synthesizing activated carbon from the citrus pulp, is seen as a possible next-generation power source (Chavan *et al*., 2018).

Table 9: Different citrus species and its bioactive compounds for health benefit

Scientific name	Common name	Functional compounds	Health benefits	Reference
C. aurantifolia	Acidlime	Hesperetin, apigenin, nobiletin, kaempferol, rutin and quercetin	antibacterial, antilipidemia, antidiabetic, antiparasitic, antifungal and antihypertensive	Narang *et al.,* 2016
C. aurantium	Bitter orange	Synephrine alkaloids, tyramine, N-methyltyramine, hordenine octopamine, and phenethylamine	Gastrointestinal disorders, antiseptic, sedative, stomachic and tonic for obesity	Jyotsna and Suryawanshi, 2011
C. reticulata	Mandarin	Phenolic compounds, carotenoids and amino acids	Dyspepsia, anticholesterolemic, antiscorbutic, and gastrointestinal distension	Musara *et al.,* 2020
C. sinensis	Sweet orange	Hesperidin, sinensitin, liminoids, polyphenols	Reduce risk of kidney stones, cholesterol levels, and anti-inflammatory effects	Maqbool *et al.,* 2023
C. medica	Citron	Phenolics, flavonones, vitamin C, pectin	Antibacterial and antifungal properties	
C. maxima	Pommelo	Naringin, naringenin, phenols	Antihyperlipidemic properties	
C. limon	Lemon	Eriocitrin, hesperidin, quercetin, hesperetin	Antioxidant action, and reduce cardiovascular complications	
C. latifolia	Lime	Hesperidin, and tangerine	Improve immunity, and promote healthy skin	
C. paradisi	Grapefruit	Quercetin, naringin, narirutin	Antioxidant, antitumor activity, promote bone cell activity	
C. japonica	Kumquat	Polyphenols, vitamin C	Liver protections and anticancer activity, antioxidant	
C. hystrix	Kaffir lime	Glycerolglycolipids, flavonoids tocopherols, tannins, alkaloids and furanocoumarins	Antifungal, antibacterial, anticholinesterase, antioxidant, chemopreventive, anticancer and hepatoprotective effects	Abirami *et al.,* 2014
C. glauca	Desert lime	Aldehydes and citral	Skin cleansers	Mabberley, 2004
C. jambhiri	Kachai lemon	Phenolic compounds	Antioxidant potential	Kumar *et al.,* 2019
C. sunki	Jingyul	dl-limonene, carvone, β-myrcene, and dl-limonene	Human skin health applications, antimicrobial activities and anti-inflammatory	Yang *et al.,* 2010
Fortunella japonica	*Margarita*			
C. *australasica*	Finger lime	Saponins, hytosteroids, triter-penoids, alkaloids, cardiac glycosides, anthraquinones	Antibacterial activity	Mpala *et al.,* 2022
C. macroptera	Wild orange	Ribalinine, bergamottin edulinine, psoralen, severine, geipavarine marmin, , β-pinene, α-pinene, ρ-cimene, γ-terpinene	Antidiabetic, cardioprotective, hepatoprotective and antidepressant	Lala, 2019

3. Conclusion

The underutilised parts of citrus fruit present a promising frontier that could improve human health. Exploring the applications in citrus based medicines, nutraceuticals, functional foods and cosmetics can result in innovative products that advance health and sustainability. By turning waste into valuable resources, the value chain for citrus fruits is enhanced and reduces negative environmental effects. Furthering this work, citrus fruits can be used to the maximum potential and contribute to a healthier and more eco-friendly future.

Future work of research

Citrus byproducts are often discarded despite their rich nutritional content and bioactive compounds. Moreover, the medicinal properties of these by-products could lead to new pharmaceutical applications as well as health supplements as functional foods. The cosmetic industry also stands to benefit, as citrus by-products can be utilized in developing natural skincare and beauty products. The continuous recycling of waste products in the production cycle will contribute in the creation of a more sustainable system. In general, this strategy encourages a circular, responsible and efficient economy.

By focusing on these areas, significant value to the citrus fruit industry can be promoted.

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Conflict of interest

The authors declare no conflicts of interest relevant to this article.

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