Food Research International 143 (2021) 110231

Contents lists available at ScienceDirect

Food Research International

journal homepage: www.elsevier.com/locate/foodres

Review

Insights into the chemical composition and bioactivities of citrus peel essential oils☆

Balwinder Singh [a], Jatinder Pal Singh [b], Amritpal Kaur [b,*], Madhav P. Yadav [c,*]

[a] P.G. Department of Biotechnology, Khalsa College, Amritsar 143002, Punjab, India
[b] Department of Food Science and Technology, Guru Nanak Dev University, Amritsar 143005, Punjab, India
[c] Eastern Regional Research Center, Agricultural Research Service, United States Department of Agriculture, 600 East Mermaid Lane, Wyndmoor, PA 19038, USA

ARTICLE INFO

Keywords:
Citrus peel
Essential oil
Monoterpene hydrocarbons
Sesquiterpene hydrocarbons
Oxygenated monoterpenes
Oxygenated sesquiterpenes
Bioactivity

ABSTRACT

Citrus peel (CP), a by-product of the citrus fruit processing, comprises nearly forty to fifty percent of the fruit portion. Interestingly, the essential oil (EO) is primarily concentrated in the peel portion of the citrus fruit. Extraction of CP essential oil (CPEO) is an effective way of utilizing the citrus fruit processing waste. The CPEO can be more efficiently recovered from CP waste by improving the efficiency of conventional extraction processes. The main components of CPEO include monoterpenes, sesquiterpenes and their oxygenated derivatives. Specifically, limonene is the major oil component identified in the peel of different citrus species. The health promoting biological activities of CPEO are functioning as antioxidant, anti-inflammatory, analgesic, antimicrobial and anticancer agents, thereby can be used as a source of functional components and preservatives for the development of nutritionally safe newer food products. This paper provides an in-depth knowledge about the chemical constituents and bioactivities of EOs extracted from peels of different citrus species.

1. Introduction

Citrus fruits are one of the most popular fruit crops cultivated throughout the world as valuable sources of nutrients and phytochemicals that protect human health (Singh, Singh, Kaur, & Singh, 2020). Citrus is a genus of the *Rutaceae* family and is considered as one of the largest plant species (consisting of 40 different citrus species) widely distributed in the tropical, subtropical and temperate regions of the world. Many different varieties and hybrids of citrus have been produced as a result of natural or artificial crossbreeding. Oranges, grapefruits, mandarins, lemons and limes are not only popular for nutritional value but also are the main industrialized citrus crops (Satari & Karimi, 2018). The total global production of citrus was estimated as 135.9 million tons in the 2017 statistical bulletin (Food and Agriculture Organization of the United Nations, FAOSTAT, 2018). China, Nigeria, India, Iran and Mexico are the major citrus producing countries of the world (Food and Agriculture Organization of the United Nations, FAOSTAT, 2018). The total citrus production in these five countries from 2013 to 2017 is shown in Fig. S1. Citrus fruits are important constituents of daily human diet, consumed worldwide as fresh or used for juice extraction. These fruits have received a great deal of attention for their nutritional, antioxidant properties and favorable effects on human health (Guo et al., 2018; Shan, 2016).

Citrus peel (CP) accounts for about half (40–50%) of the fruit weight. During citrus processing (juicing and canning), thousands of tons of CP solid waste is generated, which is an important source of bioactive components such as phenolic compounds, essential oil (EO), carotenoids and ascorbic acids (Bustamante et al., 2016; Maurya, Mohanty, Pal, Chanotiya, & Bawankule, 2018; Raspo, Vignola, Andreatta, & Juliani, 2020; Singh et al., 2020). Treatment of CP is a major problem in the citrus by-product processing industries, as only a small quantity of it is utilized, while a large amount is buried and burned that can pollute the environment and waste resources. CP is the most familiar and rich source of EO (0.5–3.0 kg/ton of the citrus fruits). The annual worldwide production of citrus EO is approximately 16,000 tons, with a price in the global market as $14,000/ton (Shan, 2016). Citrus EO is in great demand throughout the world and has promising market prospects. It accounts for sales of $500 billion in the international market (Shan, 2016).

CP essential oil (CPEO) has pleasant sensory characteristics and is a

☆ Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture. USDA is an equal opportunity provider and employer.

* Corresponding authors.
E-mail addresses: amritft33@yahoo.co.in (A. Kaur), madhav.yadav@usda.gov (M.P. Yadav).

https://doi.org/10.1016/j.foodres.2021.110231
Received 25 July 2020; Received in revised form 31 January 2021; Accepted 13 February 2021
Available online 27 February 2021

rich source of biologically active compounds with many health benefits (Maurya et al., 2018). CPEO is composed of highly volatile components that are reactive to oxygen, heat, or light (Mahato et al., 2019). Among uses, it is used as a cough inhibitor, expectorant, digestive juice secretion enhancer and gastrointestinal motility promoter. Moreover, it also alleviates pain, relieves inflammation and dissolves gallstones. Additionally, CPEOs are the popular fragrances commonly used as uplifting and refreshing agents in the preparation of perfumes, toilet soaps, cosmetics, and other body care products (Bustamante et al., 2016). Apart from this, they are also used as flavoring agents in ice creams, drinks and other food products. Nowadays, they are in great demand in food, pharmaceutical, cosmetic, perfumery and confectionery industries owing to their fragrance, flavor, and bioactivities (Ajikumaran Nair, Rajani Kurup, Nair, & Sabulal, 2018; Li, Cai, Liu, & Sun, 2018; Sahraoui, Vian, El Maataoui, Boutekedjiret, & Chemat, 2011; Smeriglio et al., 2018). The present review provides comprehensive collective information available in recent studies on the extraction processes, chemical composition and bioactivities of CPEO of different citrus species.

2. Extraction of citrus peel essential oils

CP is a highly valuable raw material for the extraction of EOs. The EO is a concentrated hydrophobic liquid present in oil cells of CP. It comprises 0.5–5% of the fresh weight of CP and consist of volatile aromatic compounds. CPEOs are complex mixtures of polar and non-polar components. The synthesis of CPEOs in the citrus plants takes place by two definite biosynthetic processes, namely the phenylpropanoids and mevalonate pathway. In addition, the biosynthesis of terpenoids as well as phenylpropanoids occurs by distinct metabolic precursors (Mahato et al., 2019). The methods used for processing and extraction of CPEO are of particular interest. Many researchers focused on the extraction of EOs from citrus fruit processing wastes. EOs are extracted by methods such as steam distillation, solvent extraction, mechanical expression and critical fluid extraction. High proportion (93%) of CPEO is extracted commercially by traditional methods such as steam distillation and remaining (7%) by other methods (Masango, 2005).

Traditional methods demand long extraction times, high energy costs and additional chemical reagents (Bustamante et al., 2016). These processes for the extraction of CPEO are cold expression, hydro-distillation and steam distillation (Chen, Hu, Yao, & Liang, 2016). During mechanical cold pressing, oil sacs or glands of CP break and release EO in a watery emulsion, which is subsequently centrifuged to recover the EO (El Asbahani et al., 2015). Cold expression provides EO with a natural aroma without causing considerable changes in its chemical composition (El Asbahani et al., 2015). In some countries, distillation is commonly used to recover EO from citrus processing waste. During distillation, CPs are boiled or steamed to release EOs through evaporation, thereafter EOs vapors are collected in a vessel by condensation. The recovery of EO components depends on their separation between the oil and water phases of the distillate. The loss of polar components in the aqueous portion of the distillate is a drawback of the distillation process. The water phase is redistilled (cohobation) to recover dissolved oil components, so it increases cost of the extraction process (Masango, 2005). Cold expression and distillation have drawbacks such as low yield, losses of volatile components and degradation of target compounds (Chen et al., 2016).

Microwave extraction has received increasing attention over the years due to higher yields of EOs, shorter extraction time and less solvent consumption. A novel design for shortening the extraction time to around 20–60 min was documented in a recent study (Teigiserova, Tiruta-Barna, Ahmadi, Hamelin, & Thomsen, 2021). They reported that solvent-free microwave extraction was an effective method for EO extraction. The effectiveness of cold pressing, microwave-accelerated distillation and hydro-distillation were compared for isolation of CPEO (Ferhat, Meklati, & Chemat, 2007). The yield of EOs was relatively low in cold expression (0.05%) as compared to microwave-accelerated distillation (0.24%) and hydro-distillation (0.21%). The effectiveness of microwave steam distillation was compared with the conventional steam distillation (Sahraoui et al., 2011). Microwave steam distillation offers advantages over steam distillation such as shorter extraction time, cleaner features and provides an EO with better sensory properties (natural fresh fruit aroma) without affecting the chemical composition. Electro-fluidic pretreatment of CP is technically feasible, more effective, innovative, and eco-friendly approach for the extraction of high-quality EO. Induced electric field pretreatment of CP processing wastes prior to hydro-distillation was utilized for enhancing the subsequent extraction of EO (Wu, Jin, Xu, & Yang, 2017). Solvent-free microwave extraction was considered as a superior and feasible method compared to hydro-distillation for better processing and yield of CPEO (Chen et al., 2016). Methods used for conventional and microwave extraction of essential oil from CP are provided in Fig. 1. Conventional (steam hydro-diffusion and steam distillation), microwaves (microwave hydro-diffusion, solvent-free microwave extraction and gravity) and microwaves combined with steam (microwave steam diffusion and steam distillation) processes were compared for extraction of EO from orange peels (Razzaghi et al., 2019). Microwave steam distillation showed the best results among the aforementioned extraction processes. Extraction time, energy consumption, cost efficiency, yield and quality of CPEO are the main criteria to choose and optimize best extraction process among several existing and emerging processes (Razzaghi et al., 2019). Pomelo peels were utilized for extracting EO using the hydro-distillation method. Using gas chromatography coupled to mass spectrometry (GC–MS), it was found that the biggest component of EOs was α-limonene (around 96%), followed by α-pinene α-myrcene (around 1.5%) and α-phellandrene (around 0.8%) (Ngan, Muoi, Quan, & Cang, 2020a).

After the extraction of CPEO, the technique that is primarily used for the analyzing the individual compounds is GC–MS. The extracted compounds are concentrated using a rotary evaporator and are then reduced under a stream of nitrogen gas. For analysis on the GC machine, the concentrated CPEO sample is firstly diluted using an organic solvent (mostly pentane or hexane) and then introduced with the help of a direct injection (González-Mas, Rambla, López-Gresa, Blázquez, & Granell, 2019). However, even after the analysis of different compounds present in CPEO, the sensitivity of detection does not correspond considerably with what a human nose perceives. Therefore, for exactly knowing the aroma of CPEO components, GC coupled to olfactometry is generally used (González-Mas et al., 2019).

3. Citrus peel essential oil content and chemical composition

Citrus oils accumulate in secretary cavities scattered throughout the flavedo layer of citrus fruits (Ahmad, Rehman, Anjum, & Bajwa, 2006). CPs are recognized as rich sources of EO (0.5 to 3.0 kg/ton of the fruit). Citrus fruits with thick peel such as sour orange (*Citrus aurantium*), grapefruit (*C. paradisi*) and bergamot (*C. bergamia*) contain a high content of EO compared to citrus species with thin peels. The EOs content in peels of four selected Tunisian sweet orange (*C. sinensis*) cultivars viz. Meski, Maltaise blanc Valencia late and Thomson Navel were found to be 2.31, 2.2, 1.89, 1.49%, respectively (Hosni et al., 2010). The EO content varied with citrus species and was reported in the range of 0.5–5.0% (w/v) in different citrus species (Palazzolo, Laudicina, & Germanà, 2013). The EO content in CP of fully ripened fresh fruits of Malta (*C. sinensis*), Eureka lemon (*C. limon*), mousami (*C. sinensis*), grapefruit, kinnow (*C. reticulata*) and fewtrell's early (*C. reticulata*) was reported as 1.21, 1.12, 0.98, 0.73, 0.32, 0.22%, respectively (Ahmad et al., 2006). In peels of pomelo (*C. grandis*), sour orange and Tunisian mandarin (*C. reticulata*), the content of EOs were reported as 1.06, 1.24 and 4.62%, respectively (Hosni et al., 2010). The yield of EO in lumia (*Citrus lumia* Risso) peel was reported as 1.75% v/w (Smeriglio et al., 2018).

EOs of citrus are a complex mixture of volatile compounds belonging to various chemical classes such as alcohols, aldehydes, ketones, acids

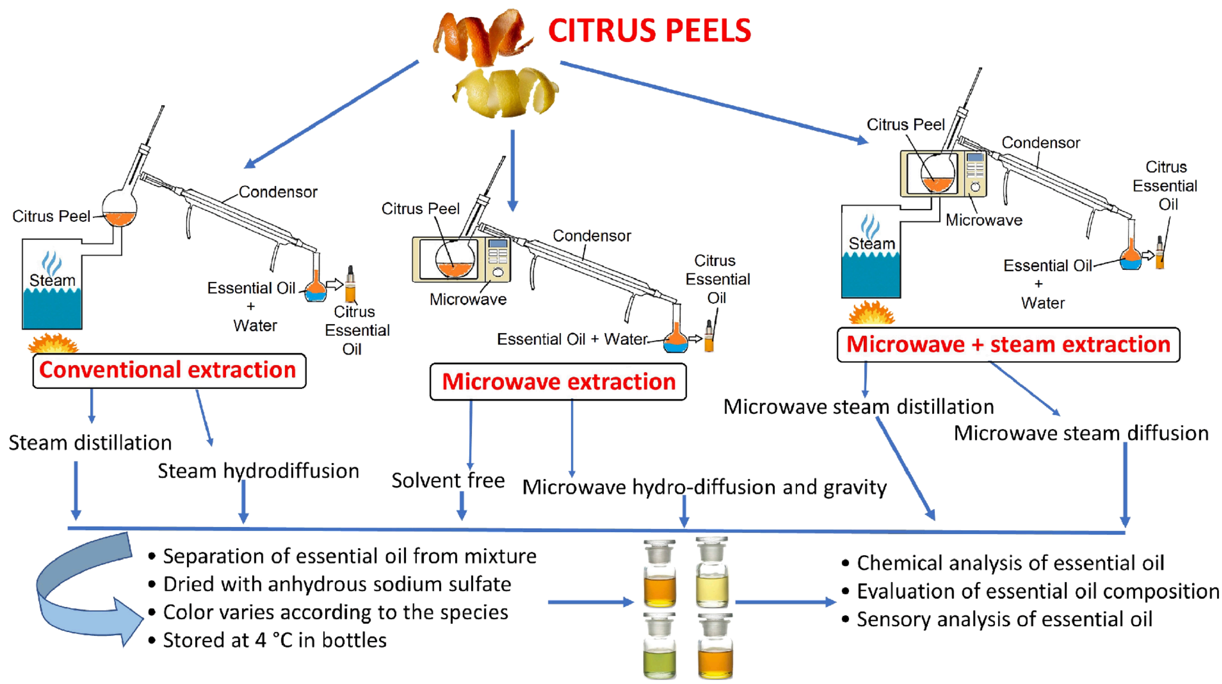


Fig. 1. Extraction methods for citrus peel essential oils.

and esters (Bustamante et al., 2016). Monoterpene hydrocarbons, sesquiterpene hydrocarbons, oxygenated monoterpenes and oxygenated sesquiterpenes are the main chemical classes of EO components identified in peels of different citrus species as shown in Table 1. The separation of terpenes and terpenoids (called as deterpenation) is sometimes required for analysis. In a recent study by Li et al. (2020), a successful method for deterpenation was reported having high extraction efficiency using green chemistry. It is widely accepted that the level of EO components varies in peels of citrus species and cultivars collected from different geographical locations. In peels of different Tunisian citrus species, level of these EO components was reported in the range of 97.59–99.3, 0.15–0.71, 0.36–0.84 and 0.12–0.53%, respectively (Hosni et al., 2010). However, these components were reported in the range of 80.2–79.1, 4.2–3.2, 4.8–6.9 and 2.5–1.6%, respectively in peel oil of two citron (*C. medica* cv. 'rugosa' and *C. medica* cv. 'liscia') cultivars (Aliberti et al., 2016). Monoterpene hydrocarbons (58.12%), monoterpene derivatives (13.89%), oxygenated monoterpenes (26.73%) and sesquiterpenes (0.93%) were reported in EO of lumia (*Citrus lumia* Risso) peel oil (Smeriglio et al., 2018).

EO of orange contained a high content of monoterpene hydrocarbons (87.51%), while oxygenated monoterpenes (13.62%) were found to be in more amounts in mandarin peel oil (Espina et al., 2011). Lemon peel oil contained 2–3 times higher content of sesquiterpene hydrocarbons and oxygenated sesquiterpenes than the orange and mandarin peel oils (Espina et al., 2011). EO composition in CP also changes with the maturation of citrus fruits. Monoterpene and sesquiterpene hydrocarbons were found higher in ripe peel, while oxygenated monoterpenes and sesquiterpenes were reported to be higher in the unripe peel of sour orange collected from southwest of Iran (Azhdarzadeh & Hojjati, 2016). Monoterpenes make up to 97% while other components such as alcohols, aldehydes and esters are present in a very low (1–3%) level in orange peel. Monoterpene hydrocarbons are the main components with limonene (92.52–97.3%) and β-pinene (1.37–1.82) as main components in peel oils of different Tunisian citrus species (Hosni et al., 2010). The percentage of monoterpene hydrocarbons recorded in CPEOs of mandarin, orange, lime (*C. aurantifolia*) and grapefruit from Egypt was 93.1, 90.6, 88.5 and 91.8%, respectively. While oxygenated monoterpenes were recorded at a level of 3.7, 4.7, 8.3 and 3.0%, respectively (Abd-Elwahab, El-Tanbouly, Moussa, Abdel-Monem, & Fayek, 2016). In Turkish lemon, grapefruit and bitter orange peels, monoterpene hydrocarbons (89.9, 96.4 and 97.3%, respectively), sesquiterpene hydrocarbons (3.3, 0.8 and 0.1%, respectively) and their oxygenated components (5.1, 1.2 and 2.5%, respectively) were identified as main compounds of CPEO (Kirbaşlar, Boz, & Kirbaşlar, 2006). Oil obtained by cold-pressing of Turkish bergamot (*C. bergamia*) ripe fruit peel contained monoterpenes hydrocarbons (50.5%), oxygenated compounds (47.7%), sesquiterpenes (1.5%), carbonyl compounds (0.6%), alcohols (8.3%) and esters (38.9%) as the major oil components (Kirbaşlar et al., 2006). Sour lime (*C. acida*) contained monoterpene hydrocarbons (22.43%), sesquiterpene hydrocarbons (15.63%) and their oxygenated components (21.85%) as main classes of citrus EO components (Mahmud et al., 2009).

The chemical structures of essential oil components identified in the CP are shown in Table 2. Chemical composition and pattern of CPEO in citrus species differs with genotype, origin, environmental factors and methods used for EO extraction and analysis (Hosni et al., 2010). The levels of main CPEO components differed in calamansi (*C. microcarpa*) grown at different geographical locations. The concentrations of β-myrcene (174, 227 & 321 ppm), α-pinene (34.9, 49.6 & 69.5 ppm), β-pinene (41.2, 50.5 & 65.5 ppm), β-phellandrene (29.1, 35.2, 51.9 ppm), sabinene (18.0, 22.8 & 30.9 ppm) and germacrene D (146, 137 & 203 ppm) varied in calamansi peel collected from Malaysia, Philippines and Vietnam, respectively (Cheong et al., 2012). Linalool (32.6, 25.3 & 36.5 ppm), β-eudesmol (17.9, 15.6 & 25.3 ppm), elemol (15.0, 16.0 & 25.2 ppm), α-terpineol (14.0, 11.5 & 16.6 ppm) are the notable terpene alcohols identified in calamansi peel collected from Malaysia, Philippines and Vietnam, respectively (Cheong et al., 2012). Limonene (55.4–91.7%), myrcene (2.1–32.1%), linalool (0.4–6.9%), α-pinene (0.6–1.6%), β-pinene (0.24–2.0%) and α-terpinolene (0.07–0.54%) are the main EO components reported in immature peels of fourteen citrus species collected from Jeju Island of Korea (Baik et al., 2008).

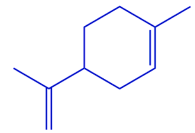
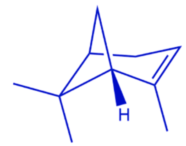
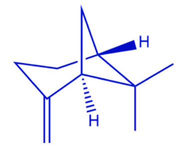
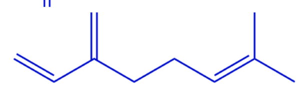
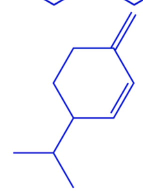
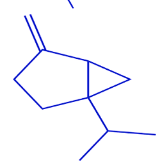
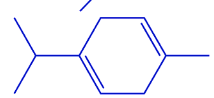
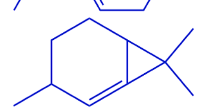
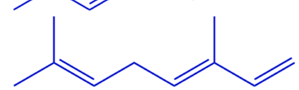
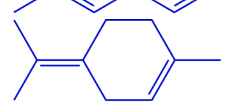
The identified individual compounds and their percentage contribution to the total CPEO content originating from different geographical regions is presented in Table 3. The major monoterpenes hydrocarbons identified in Turkish mandarin peel oils were limonene, myrcene, γ-terpinene, α-pinene and sabinene, while sesquiterpene hydrocarbon

Table 1
Chemical classes of oil components identified in peels of different citrus species.

Peel source	Botanical name	Monoterpene hydrocarbons (%)	Oxygenated monoterpenes (%)	Sesquiterpene hydrocarbons (%)	Oxygenated sesquiterpenes (%)	Miscellaneous (%)	Total (%)	Reference
Bergamot	*C. bergamia*	55.50	37.3	2.1	0.2	0.2	95.30	Tundis et al. (2012)
Citron	*C. medica* cv. 'liscia'*C. medica* cv. 'rugosa'	79.180.2	4.86.9	4.23.2	2.51.6	0.80.1	91.492.0	Aliberti et al. (2016)
Finger citron (immature) Finger citron (intermediate) Finger citron (mature)	*C. medica* L. var. *sarcodactylis*	80.8781.8083.06	13.2713.7812.07	2.071.951.84	0.490.210.30	2.861.642.27	99.5699.3899.54	Wu et al. (2013)
Lemon	*C. lemon*	80.56	5.74	5.33	4.20	0.16	95.99	Espina et al. (2011)
Lime	*C. aurantifolia*	77.70	6.0	5.5	1.7	2.7	93.60	Tundis et al. (2012)
Lumia	*C. lumia* Risso	58.12	26.73	0.93	nd	0.32	98.75	Smeriglio et al. (2018)
Mandarin	*C. reticulata* Blanco	98.9	0.65	0.25	0.12	0.05	100	Hosni et al. (2010)
Mandarin	*C. reticulata*	76.08	13.62	0.26	0.00	2.69	92.65	Espina et al. (2011)
MandarinSweet orangeLimeWhite grapefruit	*C. reticulata* Blanco cv. Egyptian*C. sinensis* (L.) Osbeck cv. Olinda Valencia*C. aurantiifolia* Swingle cv. Mexican*C. paradisi* Macfad. cv. Duncan	93.190.688.591.8	3.74.78.33.0	0.20.20.3nd	ndndndnd	1.03.5nd3.1	98.099.097.098.0	Abd-Elwahab et al. (2016)
Orange	*C. sinensis* Osbeck cv. Meski*C. sinensis* Osbeck cv. Valencia Late*C. sinensis* Osbeck cv. Thomson Naval*C. sinensis* Osbeck cv. Maltaise blanc	99.398.598.998.5	0.400.440.360.80	tr0.180.190.15	tr0.220.160.16	0.20.440.350.05	99.599.899.999.4	Hosni et al. (2010)
Orange	*C. sinensis*	87.51	5.21	0.70	0.18	0.90	94.50	Espina et al. (2011)
Ponderosa lemonRough lemon	*C. pyriformis* Hassk*C. jambhiri* Lush	93.8161.12	2.3118.31	1.449.70	0.261.44	0.564.94	98.3895.51	Hamdan et al. (2010)
Pomelo	*C. grandis* Osbeck	97.6	0.84	0.71	0.53	0.07	99.7	Hosni et al. (2010)
Sour orange	*C. aurantium* cv. Amara	99.1	0.40	0.39	0.12	nd	100	Hosni et al. (2010)
Sour orange	*C. aurantium*	72.50	6.8	2.4	1.1	1.4	84.20	Tundis et al. (2012)
Sour orange	*C. aurantium* L.	51.21	45.90	nd	nd	nd	97.11	Ben Hsouna et al. (2019)
Sour orange (ripe peel)Sour orange (Unripe peel)	*C. aurantiumC. aurantium*	91.7667.85	5.6916.47	0.6nd	0.027.49	0.751.39	98.8393.21	Azhdarzadeh and Hojjati (2016)

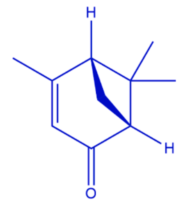
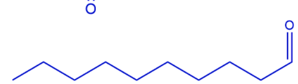
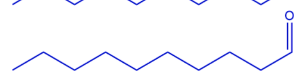
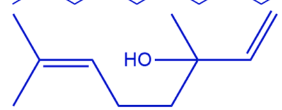
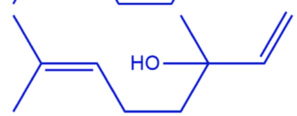
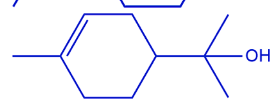
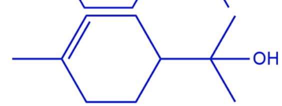
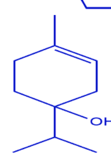
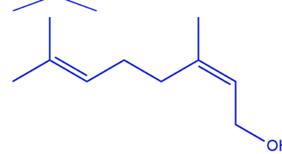
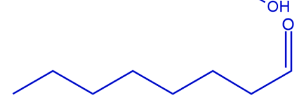
tr: trace amount; nd: not detected.

Table 2
Chemical components of citrus peel essential oils.

Components	Molecular formula	IUPAC name	Molecular weight (g/mol)	Chemical Structure	Physical description	Category
I. Monoterpene hydrocarbons						
Limonene	$C_{10}H_{16}$	1-methyl-4-prop-1-en-2-ylcyclohexene	136.238		Colorless liquid with lemon odor, insoluble in water, Vapors are heavier than air	Fragrances and flavoring agent
α-Pinene	$C_{10}H_{16}$	2,6,6-trimethylbicyclo[3.1.1] hept-2-ene	136.238		Colorless transparent liquid with turpentine odor, Less dense than water and insoluble in water. Vapors are heavier than air	Flavoring agent
β-Pinene	$C_{10}H_{16}$	6,6-dimethyl-2-methylidene bicyclo [3.1.1] heptane	136.238		Colorless transparent liquid, turpentine odor	Flavoring agent
β-Myrcene	$C_{10}H_{16}$	7-methyl-3-methylideneocta-1,6-diene	136.238		Yellow oily liquid, pleasant odor, Insoluble in water and less dense than water	Flavoring agent
β-Phellandrene	$C_{10}H_{16}$	3-methylidene-6-propan-2-ylcyclohexene	136.238		Liquid, pleasant odor, burning taste	Fragrances
Sabinene	$C_{10}H_{16}$	4-methylidene-1-propan-2-ylbicyclo[3.1.0] hexane	136.238		Woody, terpenic, spicy odor	Flavoring agent
γ-Terpinene	$C_{10}H_{16}$	1-methyl-4-propan-2-ylcyclohexa-1,4-diene	136.238		Liquid, lemon odor	Flavoring agent
Δ-Carene	$C_{10}H_{16}$	(1~{R},6~{S})-3,7,7-trimethylbicyclo[4.1.0] hept-3-ene	136.238		Colorless liquid, sweet and pungent odor, insoluble in water	Fragrances
(E)-β-Ocimene	$C_{10}H_{16}$	(3~{E})-3,7-dimethylocta-1,3,6-triene	136.238		Oil with a pleasant odor	Fragrances
α-Terpinolene	$C_{10}H_{16}$	1-methyl-4-propan-2-ylidenecyclohexene	136.238		Water-white to light amber colored liquid, insoluble in water.	Flavoring agent

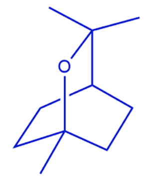
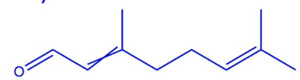
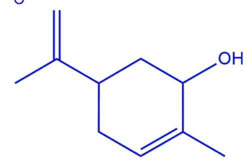
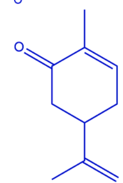
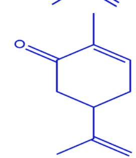
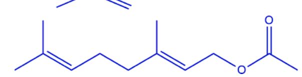
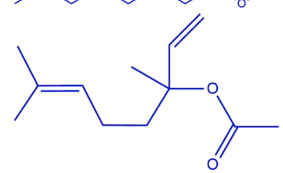
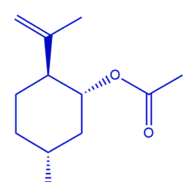
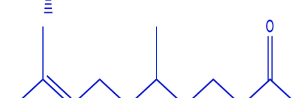
(*continued on next page*)

Table 2 (*continued*)

Components	Molecular formula	IUPAC name	Molecular weight (g/mol)	Chemical Structure	Physical description	Category
II. Oxygenated Monoterpenes						
Verbenone	$C_{10}H_{14}O$	2,6,6-trimethylbicyclo[3.1.1]hept-2-en-4-one	150.221		Colorless to yellow clear viscous liquid, camphoreous odor	Flavoring agent
Decanal	$C_{10}H_{20}O$	Decanal	156.269		Colorless to light yellow liquid, pleasant odor, floats on water.	Fragrances and flavoring agent
Decanone	$C_{10}H_{20}O$	decan-2-one	156.269		Colorless clear liquid, floral odor	Fragrances and flavoring agent
Linalool	$C_{10}H_{18}O$	3,7-dimethylocta-1,6-dien-3-ol	154.253		Colorless to pale yellow liquid, characteristic odor	Flavoring agent
Citronellal	$C_{10}H_{18}O$	3,7-dimethyloct-6-enal	154.253		Colorless to slightly yellow liquid, Intense lemon-citronella-rose odor	Flavoring agent
α-Terpineol	$C_{10}H_{18}O$	2-(4-methylcyclohex-3-en-1-yl)propan-2-ol	154.253		Colorless liquid, floral (lilac) odor, lime taste	Flavoring agent
Geraniol	$C_{10}H_{18}O$	(2~{E})-3,7-dimethylocta-2,6-dien-1-ol	154.253		Colorless to pale yellow oily liquid with a sweet rose odor	Flavoring agent
Terpinen-4-ol	$C_{10}H_{18}O$	4-methyl-1-propan-2-ylcyclohex-3-en-1-ol	154.253		Colorless to pale yellow liquid, Pine odor	Flavoring agent
Nerol	$C_{10}H_{18}O$	(2Z)-3,7-dimethylocta-2,6-dien-1-ol	154.253		Colorless oily liquid, sweet and rosy odor	Flavoring agent
Octanal	$C_8H_{16}O$	octanal	128.215		Colorless liquids with a strong fruity odor. Flash points 125°F. Less dense than water and insoluble in water.	Flavoring Agent, used in making perfumes and flavorings
Limonene oxide	$C_{10}H_{16}O$	1-methyl-4-prop-1-en-2-yl-7-oxabicyclo[4.1.0] heptane	152.237		Colorless to pale yellow clear liquid	Flavoring Agent

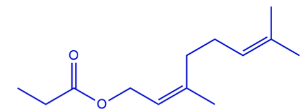
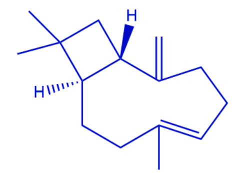
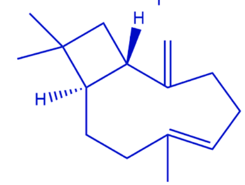
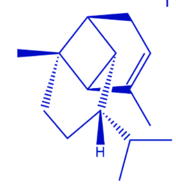
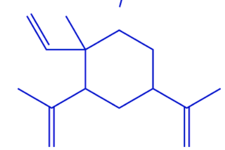
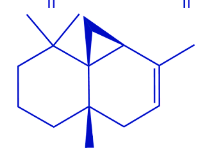
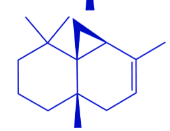
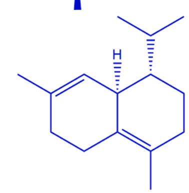
(*continued on next page*)

Table 2 (*continued*)

Components	Molecular formula	IUPAC name	Molecular weight (g/mol)	Chemical Structure	Physical description	Category
						
Citral	$C_{10}H_{16}O$	(2∼{E})-3,7-dimethylocta-2,6-dienal	152.237		Clear yellow colored liquid with a lemon-like odor. Less dense than water and insoluble in water.	Flavoring Agent
trans-Carveol	$C_{10}H_{16}O$	(1S,5R)-2-methyl-5-prop-1-en-2-ylcyclohex-2-en-1-ol	152.237		Clear colorless liquid. Insoluble in water	Flavoring Agent
Decadienal	$C_{10}H_{16}O$	deca-2,4-dienal	152.237		Pale yellow to yellow clear liquid, fatty odor	Flavoring Agent
d-Carvone	$C_{10}H_{14}O$	(5S)-2-methyl-5-prop-1-en-2-ylcyclohex-2-en-1-one	150.221		Pale-yellowish or colorless liquid	Flavoring Agent
4′-Methoxyacetophenone	$C_9H_{10}O_2$	1-(4-methoxyphenyl) ethanone	150.177		Crystalline solid, Pleasant odor	Flavoring Agent
Geranyl acetate	$C_{12}H_{20}O_2$	[(2∼{E})-3,7-dimethylocta-2,6-dienyl] acetate [(2Z)-3,7-dimethylocta-2,6-dienyl] acetate	196.29		Clear, colorless liquid, lavender odor	Flavoring agent
Linalool acetate	$C_{12}H_{20}O_2$	3,7-dimethylocta-1,6-dien-3-yl acetate	196.29		Clear, colorless, oily liquid, floral-fruity odor	Fragrances and flavoring agent
Isopulegol acetate	$C_{12}H_{20}O_2$	[(1R,2S,5R)-5-methyl-2-prop-1-en-2-ylcyclohexyl] acetate	196.29		Colorless clear liquid, mentholic odor	Fragrances and flavoring agent
Citronellyl acetate	$C_{12}H_{22}O_2$	3,7-dimethyloct-6-enyl acetate	198.306		Colorless clear liquid, floral odor	Flavoring agent

(*continued on next page*)

Table 2 (*continued*)

Components	Molecular formula	IUPAC name	Molecular weight (g/mol)	Chemical Structure	Physical description	Category
Neryl propionate	$C_{13}H_{22}O_2$	[(2Z)-3,7-dimethylocta-2,6-dienyl] propanoate	210.317		Colorless to pale yellow clear liquid, fruity odor	Flavoring agent
III. Sesquiterpene hydrocarbons						
β-Caryophyllene	$C_{15}H_{24}$	(1~{R},4~{E},9~{S})-4,11,11-trimethyl-8-methylidenebicyclo[7.2.0]undec-4-ene	204.357		Pale yellow oily liquid, odor midway between odor of cloves and turpentine	Flavoring Agent
Copaene	$C_{15}H_{24}$	1,3-dimethyl-8-propan-2-yltricyclo[4.4.0.0ˆ{2,7}]dec-3-ene	204.357		Colorless liquid, clear and viscous. woody spicy honey aroma	Extractive
α-Humulene	$C_{15}H_{24}$	(1E,4E,8E)-2,6,6,9-tetramethylcycloundeca-1,4,8-triene	204.357		Pale yellowish green clear liquid, woody odor	Flavoring Agent
β-Elemene	$C_{15}H_{24}$	(1~{S},2~{S},4~{R})-1-ethenyl-1-methyl-2,4-bis(prop-1-en-2-yl)cyclohexane	204.357		Colorless to yellow clear liquid, herbal, and waxy tasting	Flavor and fragrance agents
Thujopsene	$C_{15}H_{24}$	1aS,4aS,8aS)-2,4a,8,8-tetramethyl-1,1a,4,5,6,7-hexahydrocyclopropa[j]naphthalene	204.357		Pale yellow clear liquid	Extractive
Valencene	$C_{15}H_{24}$	(3~{R},4~{a}~{S},5~{R})-4~{a},5-dimethyl-3-prop-1-en-2-yl-2,3,4,5,6,7-hexahydro-1~{H}-naphthalene	204.357		Pale yellow to yellow clear liquid, characteristic juicy orange taste	Flavoring Agent
δ-Cadinene	$C_{15}H_{24}$	(1S,8aR)-4,7-dimethyl-1-propan-2-yl-1,2,3,5,6,8a-hexahydronaphthalene	204.357		Thyme herbal woody dry odor, insoluble in water	Extractive
β-Bisabolene	$C_{15}H_{24}$		204.357		Colorless clear liquid, balsamic odor	Flavoring Agent

(*continued on next page*)

Table 2 (*continued*)

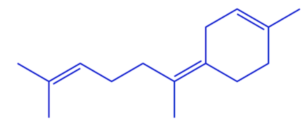
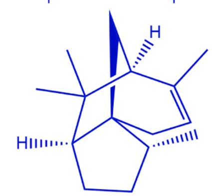
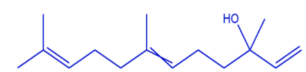
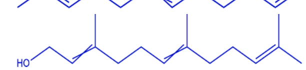
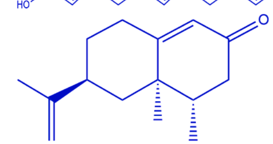
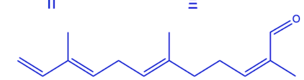
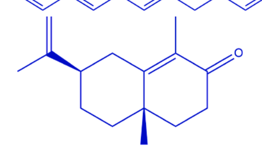
Components	Molecular formula	IUPAC name	Molecular weight (g/mol)	Chemical Structure	Physical description	Category
		(4~{S})-1-methyl-4-(6-methylhepta-1,5-dien-2-yl)cyclohexene				
α-Cedrene	$C_{15}H_{24}$	(1S,2R,5S,7S)-2,6,6,8-tetramethyltricyclo [5.3.1.01,5]undec-8-ene	204.357		Colorless clear oily liquid, woody odor	Fragrance and flavoring agent
IV. Oxygenated sesquiterpenes						
Nerolidol	$C_{15}H_{26}O$	(6~{E})-3,7,11-trimethyldodeca-1,6,10-trien-3-ol	222.372		colorless to pale yellow clear oily liquid, floral odor	Fragrance and flavoring agent
Farnesol	$C_{15}H_{26}O$	(2E,6E)-3,7,11-trimethyldodeca-2,6,10-trien-1-ol	222.372		Colorless liquid with a delicate floral odor	Flavoring agent
Nootkatone	$C_{15}H_{22}O$	(4~{R},4~{a}~{S},6~{R})-4,4~{a}-dimethyl-6-prop-1-en-2-yl-3,4,5,6,7,8-hexahydronaphthalen-2-one	218.34		colorless to yellowish liquid, powerful sweet citrus odor	Flavor and fragrance agents
α -Sinensal	$C_{15}H_{22}O$	(2~{E},6~{E},9~{E})-2,6,10-trimethyldodeca-2,6,9,11-tetraenal	218.34		Colorless clear liquid insoluble in water, citrus odor	Flavor and fragrance agents
α-Cyperone	$C_{15}H_{22}O$	(4~{a}~{S},7~{R})-1,4~{a}-dimethyl-7-prop-1-en-2-yl-3,4,5,6,7,8-hexahydronaphthalen-2-one	218.34		–	Extractive

Table 3
Identified compounds and their percentage contribution to the total essential oil content of citrus peels originating from different geographical regions.

Peel Source	Botanical Name	Country	Identified compounds and percentage (%) contribution to the total essential oil content	Reference
Mandarin	*C. reticulata*	Turkey	Limonene (90.7%), myrcene (2.1%), γ-terpinene (3.9%), α-pinene (0.5%) and sabinene (0.3%), E-β-farnesene (0.1%), decanal (0.1%), octanal (0.2%), neryl acetate (0.1%) and geranyl acetate (0.2%)	Kirbaşlar et al. (2009)
Mandarin	*C. reticulata*	Tunisia	Limonene (92.6%), γ-terpinene (3.39%), β-pinene (1.55%), α-pinene (0.61%), linalool (0.31%), α-humulene (0.08%), cubebol (0.06%) and α -sinensal (0.06%)	Hosni et al. (2010)
Mandarin	*C. reticulata*	Spain	Limonene (74.38%), *cis*-limonene oxide (2.75%), *cis*-para-mentha-2, 8-dien-1-ol (2.26%), carvone (1.87%), *trans*-carveol (1.75%), (E)-patchenol (0.80%), (Z)-patchenol (1.24%), p-mentha-1,8-dien-7-ol (0.90%), *trans*-para-mentha-2, 8-dienol (0.68%), myrcene (0.73%) and linalool (0.54%)	Espina et al. (2011)
Chenpi	*C. reticulata Blanco*	China	D-limonene (88.4), γ-terpinene (4.8%)	Duan et al. (2016)
Guangchenpi	*C. reticulata Chachi*	China	D-limonene (75.1%), γ-terpinene (13.5%)	Duan et al. (2016)
Lime	*C. aurantifolia*	Italy	Limonene (49.2%), γ-terpinene (6.6%), β-pinene (14.1%), β-myrcene (3.1%), α-pinene (1.7%), linalool (0.9%) and linalyl acetate (0.7%)	Tundis et al. (2012)
Sour lime	*C. acida*	Pakistan	o-cymene (16.62%), β-humulene (4.14%), Δ-carene (1.07%), α-terpinolene (0.61%), α-cedrene (10.57%) and bisabolene (5.07%), decadienal (8.04%), linalool acetate (2.37%), citronellyl acetate (2.83%), 4′-methoxyacetophenone (2.07%), carvone (1.81%), isopulegol acetate (1.29%), decanone (1.48%), farnesol (1.25%), dihydroxy linalool acetate (0.65%), caryophyllene oxide (0.43%), *cis*-nerone (0.57%) and 2,2-dimethyl-3,4-octadienal (0.38%)	Mahmud et al. (2009)
Sour lime	*C. acida*	Tunisia	Limonene (96.86%), β-pinene (1.37%), (E)-β-ocimene (0.31%), sabinene (0.28%) and α-pinene (0.27%), verbenone (0.12%), linalool (0.17%), α-calacorene (0.12%), α-humulene (0.15%) and α -cyperone (0.12%	Hosni et al. (2010)
Sweet Lime	*C. limetta*	India	Limonene (91.8%), β-myrcene (1.6%), linalool (0.9%), camphene (0.8%), *cis*-linalool oxide (0.3%), α-pinene (0.4%), n-octanol (0.3%), *trans*-carveol (0.2%), p-cymene (0.1%), *trans*-p-menth-2,8-dien-1-ol (0.1%), n-decanal (0.1%), *cis*-p-menth-2,8-dien-1-ol (0.1%) and *cis*-carveol (0.1%)	Maurya et al. (2018)
Sour orange	*C. aurantium*	Turkey	Limonene (94.1%), β-pinene (0.5%), myrcene (1.8%), β-caryophyllene (0.1%), geranyl acetate (0.08%), linalyl acetate (1.2%), geranial (0.1%), decanal (0.2%) and linalool (0.4%)	Kirbaşlar et al. (2006)
Sour orange	*C. aurantium*	Italy	Limonene (65.8%), β-myrcene (2.9%), linalool (1.8%), linalyl acetate (1.8%) and α-pinene (1.8%)	Tundis et al. (2012)
Sour orange	*C. aurantium*	Tunisia	Limonene (48.7%), linalool (32.4%), linalyl acetate (12%) and myrcene (1.2%)	(Ben Hsouna et al., 2019)
Sweet orange	*C. sinensis*	Turkey	Limonene (91.6%), myrcene (1.3%), sabinene (1.0%) and α-pinene (0.9%) as the major monoterpenes, while β-caryophyllene (0.1%), α-copaene (0.1%), octanal (1.4%), decanal (0.2%), geranial (0.2%), linalool (0.4%), α-terpineol (0.1%), geraniol (0.1%), geranyl acetate (0.1%) and neryl acetate (0.1%)	Kirbaşlar et al. (2009)
Sweet orange	*C. sinensis*	Tunisia	Limonene (96.0–97.3%), β-pinene (1.45–1.82%), linalool (0.04–0.22%), verbenone (0.17–0.36%), α-copaene (0.04–0.05%), β-elemene (0.02–0.06%), β -sinensal (0.04–0.09%)	Hosni et al. (2010)

(continued on next page)

Table 3 (*continued*)

Peel Source	Botanical Name	Country	Identified compounds and percentage (%) contribution to the total essential oil content	Reference
			and α -sinensal (0.02–0.04%)	
Orange	*C. sinensis*	Spain	Limonene (85.5%), *cis*-limonene oxide (1.03%), myrcene (0.92%), 8-dien-1-ol (0.75%), carvone (0.65%), linalool (0.47%) and sabinene (0.43%), (E)-patchenol (0.41%) and valencene (0.34%)	Espina et al. (2011)
Blood orange	*C. sinensis* (L.) Osbeck	United States	Limonene (95.35%), β-myrcene (2.48%), α -terpineol (0.42%) and α-pinene (0.49%)	Murthy et al. (2012)
Lumia	*C. lumia*	Italy	Limonene (48.90%), linalool (18.24%), linalyl anthranilate (10.96%), β-Pinene (6.89%), α-terpineol (5.22%), citral (1.06%), nerol acetate (1.80%) and neryl propionate (1.10%)	Smeriglio et al. (2018)
Pumelo	*C. grandis Osbeck*	Tunisia	Limonene (95.4%), β-pinene (1.52%), (E)-β-ocimene (0.26%), α-pinene (0.15%). sabinene (0.19%), verbenone (0.35%), linalool (0.09%), β–elemene (0.42%), bicyclogermacrene (0.15%), β-copaene (0.06%), germacrene (0.05%), α-cyperone (0.04%), (E)-nerolidol (0.03%) and α-cadinol	Hosni et al. (2010)
Pomelo	*C. grandis* L.	Vietnam	α-limonene (96.491%), β-myrcene (1.644%), α-pinene (0.686%), β-pinene (0.248%), α-phellandrene (0.793%) and β-*cis*-ocimene (0.138%).	Ngan, Muoi, Quan, and Cang (2020b)
Grapefruit	*C. paradisi*	Turkey	Limonene (92.5%), myrcene (2.6%), δ-cadinene (0.2%), β-caryophyllene (0.4%), nootkatone (0.2%), decanal (0.2%), neral (0.1%), geranial (0.1%), octanal (0.2%), α-terpineol (0.1%), Linalool (0.2%); geranyl acetate (0.1%) and neryl acetate (0.1%)	Kirbaşlar et al. (2006)
Grapefruit	*C. paradisi*	Turkey	D-Limonene (82.9%), β-Phellandrene (4.2%), β-myrcene (2.5%), o-cymene (1.2%), β-Pinene (0.8%), decanal (0.6%), and linalol (0.4%)	Özogul, Özogul, and Kulawik (2021)
Lemon	*C. limon*	Turkey	Limonene (61.8%), β-pinene (8.1%), γ-terpinene (10.6%), β-bisabolene (1.6%), β-caryophyllene	Kirbaşlar et al. (2006)

Table 3 (*continued*)

Peel Source	Botanical Name	Country	Identified compounds and percentage (%) contribution to the total essential oil content	Reference
			(0.7%), *trans*-α-bergamotene (1.0%), geranial (1.3%), decanal (0.1%), neral (0.7%), octanal (0.1%), geranyl acetate (0.6%) and neryl acetate (1.2%)	
Lemon	*C. limon*	Spain	Limonene (59.10%), β-pinene (5.20%), γ-terpinene (9.66%), β-bisabolene (3.61%), *cis*-thujopsene (2.38%), p-cymene (3.3%), gerianal (2.11%), β-caryophyllene (0.99%), sabinene (0.94%) and citronellal (0.69%)	Espina et al. (2011)
Lemon	*C. limon*	Syria	Limonene (61.8–73.8%), γ-terpinene (9.4–10.4%), citral (0.8–5.4%), β- pinene (3.7–6.9%) and o-cymene (1–2.4%)	Jomaa et al. (2012)
Lemon	*C. limon*	Egypt	α-terpineol (3.5%), l-terpinen-4-ol (1.1%) and citral (1.0%)	Abd-Elwahab et al. (2016)
Lemon	*C. limon*	Italy	Limonene (57.65%), γ-terpinene (10.45%), β-pinene (9.31%), and citronellol (8.19%)	Caputo et al. (2020)
Bergamot	*C. bergamia*	Turkey	Limonene (37.2%), linalool (7.9%), linalyl acetate (36.3%), γ-terpinene (5.9%), β-pinene (3.9%) and myrcene (1.3%)	Kirbaşlar et al. (2009)
Bergamot	*C. bergamia*	United Kingdom	Limonene (45%), linalool (15%) and citral (0.7%)	Fisher and Phillips (2006)
Bergamot	*C. bergamia*	Italy	Limonene (38.1%), linalool (6.4%), linalyl acetate (28.9%), γ-terpinene (7.3%) and β-pinene (5.4%)	Tundis et al. (2012)
Bergamot	*C. bergamia*	Italy	Linalool (33.6%), limonene (32.3%), linalyl-acetate (9.2%), terpinene (6.4%), terpineol (4.6%), and pinene (4.3%).	Caputo et al. (2020)
Citron	*C. medica*	Italy	Limonene (62.8–67.2%), camphene (10.9–8.5%), β-pinene (1.7–1.4%) and α-pinene (1.2–0.8%)	Aliberti et al. (2016)
Myrtle-leaved orange tree	*C. myrtifolia*	Italy	Limonene (76.83%), linalool (10.01%) and terpineol (2.66%)	Caputo et al. (2020)

included (E)-β-farnesene as the notable EO component. The oxygenated components included aldehydes (decanal and octanal), alcohol (α-terpineol and linalool) and ester (neryl acetate and geranyl acetate) compounds (Kirbaşlar, Tavman, Dülger, & Türker, 2009). In Tunisian mandarin peel, the main EO components identified were monoterpene hydrocarbons that included limonene, γ-terpinene, β-pinene and

Table 4
Limonene content in peels of different citrus species.

Peel source	Botanical name	Limonene content (%)	Reference
Bergamot	*C. bergamia*	38.1	Tundis et al. (2012)
Bergamot	*C. bergamia*	45.0 37.2	Fisher and Phillips (2006)
Bergamot	*C. medica* var. *sarcodactylis* Swing	48.94	Guo et al. (2018)
Bitter orange	*C. benikoji*	91.68	Baik et al. (2008)
Blood orange	*C. sinensis* (L) Osbeck	95.35	Murthy et al. (2012)
Calamansi	*C. microcarpa*	92.67	Palma et al. (2019)
Citron	*C. medica* cv. 'liscia' *C. medica* cv. 'rugosa'	67.2 62.8	Aliberti et al. (2016) Abd-Elwahab et al. (2016)
Finger citron	*C. medica* L. var. *sarcodactylis*	52.44	Kim et al. (2013)
Finger citron (immature) Finger citron (intermediate) Finger citron (mature)	*C. medica* L. var. *sarcodactylis*	36.37 32.07 33.84	Wu et al. (2013)
Grapefruit	*C. paradisi* *C. paradisi* Macfad. cv. Duncan	92.5 89.3	Kirbaşlar et al. (2006) Abd-Elwahab et al. (2016)
Kumquat	*C. reticulata*	54.21	Guo et al. (2018)
Lemon	*C. limon*	61.8–73.8	Jomaa et al. (2012)
Lemon	*C. limon*	65.7	Amorim et al. (2016)
Lemon	*C. limon*	95.0	Fisher and Phillips (2006)
Lemon	*C. limon*	59.10	Espina et al. (2011)
Lemon	*C. limon*	61.72	Guo et al. (2018)
Lime	*C. aurantifolia*	53.0	Abd-Elwahab et al. (2016)
Lime	*C. aurantifolia*	49.2	Tundis et al. (2012)
Lime	*C. aurantifolia*	31.1	Amorim et al. (2016)
Lumia	*C. lumia* Risso	48.91	Smeriglio et al. (2018)
Mandarin	*C. reticulata* Blanco	92.6 90.7	Hosni et al. (2010) Kirbaşlar et al. (2009)
Mandarin	*C. reticulata* *C. reticulata* Blanco cv. Egyptian	74.38 78.10	Espina et al. (2011) Abd-Elwahab et al. (2016)
Mandarin Lime	*C. limonia*	35.4	Amorim et al. (2016)
Navel orange	*C. sinensis*	71.06	Guo et al. (2018)
Navel orange	*C. sinensis* L.	74.60	Yang et al. (2017)
Orange	*C. sinensis*	73.0	Fisher and Phillips (2006)
Orange	*C. sinensis* Osbeck cv. Meski *C. sinensis* Osbeck cv. Valencia Late *C. sinensis* Osbeck cv Thomson Naval *C. sinensis* Osbeck cv Maltaise blanc	97.3 96.3 96.6 96.0	Hosni et al. (2010)
Orange	*C. sinensis* *C. sinensis* (L.) Osbeck *C. sinensis* (L.) Osbeck cv. Olinda Valencia	85.50 91.6 88.5	Espina et al. (2011) Kirbaşlar et al. (2009) Abd-Elwahab et al. (2016)
Pomelo	*C. maxima*	46.36	Guo et al. (2018)
Ponkan	*C.poonensis* Hort. ex Tanaka	65.15	Guo et al. (2018)
Pomelo	*C. grandis* Osbeck	95.4	Hosni et al. (2010)
Satsuma	*C. unshiu*	64.21	Guo et al. (2018)
Sour orange	*C. aurantium* cv. Amara	96.9	Hosni et al. (2010)
Sour orange	*C. aurantium*	94.1 90.25	Kirbaşlar et al. (2006) Karoui and Marzouk (2013)
Sour orange	*C. aurantium*	65.8	Tundis et al. (2012)
Sour orange	*C. aurantium*	48.7	Ben Hsouna et al. (2019)
Sour orange (ripe peel) Sour orange (Unripe peel)	*C. aurantium*	81.60 59.88	Azhdarzadeh and Hojjati (2016)
Sweet lime	*C. limetta*	91.8	Maurya et al. (2018)
Sweet orange	*C. sinensis*	79.28	Guo et al. (2018)
Tahiti lime	*C. latifolia*	53.9	Amorim et al. (2016)

Table 5
Antioxidant activity of citrus peel essential oils.

Peel source	Botanical name	DPPH assay	ABTS assay	References
Bergamot Changshan huyou Lime	*C. medica* var. *sarcodactylis Swing* *C. Changshan huyou B. Chang* *C. aurantium* L.	44.08% 77.20% 34.85%	74.71% 42.50% 89.07%	Guo et al. (2018)
Chinotto (Green peel) Chinotto (Half ripe peel) Chinotto (Ripe peel)	*C. myrtifolia* Raf	6.1 μmol TE/g 7.8 μmol TE/g 8.1 μmol TE/g	11.1 μmol TE/g 10.8 μmol TE/g 9.4 μmol TE/g	Plastina et al. (2018)
Citron	*C. medica*	33%	–	Mitropoulou et al. (2017)
Finger citron (immature) Finger citron (intermediate) Finger citron (mature)	*C. medica* L. var. *sarcodactylis*	78.4% 64.7% 63.8%	–	Wu et al. (2013)
Grapefruit (8 varieties)	*C. paradisi*	84.87–74.73%	–	Ahmed et al. (2019)
Lime Bergamot Sour orange	*C. aurantifolia* *C. bergamia* *C. aurantium*	201.3 μg/ml IC_{50} 192.9 μg/ml IC_{50} 188.9 μg/ml IC_{50}	19.6 μg/ml IC_{50} 37.8 μg/ml IC_{50} 26.5 μg/ml IC_{50}	Tundis et al. (2012)
Lumia	*C. lumia* Risso	104 μg/mL IC_{50}	–	Smeriglio et al. (2018)
Nanfeng mandarin	*C. reticulata* Blanco cv. Kinokuni	22.60 mg/ml IC_{50}	1.62 mg/ml IC_{50}	Yi et al. (2018)
Navel orange	*C. sinensis* L.	2.19 mg/ml IC_{50}	–	Yang et al. (2017)
Orange	*C. sinensis*	9.45 μg/ml IC_{50}	–	Singh et al. (2010)
Ponderosa lemon Rough lemon	*C. pyriformis* Hassk *C. jambhiri* Lush	28.91 mg/ml IC_{50} 37.69 mg/ml IC_{50}	–	Hamdan et al. (2010)
Sour lime	*C. acida*	91.7%	–	Mahmud et al. (2009)
Sour orange	*C. aurantium*	190 μg/ml IC_{50}	–	Karoui and Marzouk (2013)

IC_{50} = half maximal inhibitory concentration; TE = trolox equivalents.

α-pinene. Oxygenated monoterpenes (linalool), sesquiterpene hydrocarbons (α-humulene) and oxygenated sesquiterpenes (cubebol and α -sinensal) were identified as other EO components in Tunisian mandarin peel (Hosni et al., 2010). Mandarin peel contained limonene, *cis*-limonene oxide, *cis*-para-mentha-2, 8-dien-1-ol, carvone, *trans*-carveol, *(E)*-patchenol, *(Z)*-patchenol, p-mentha-1,8-dien-7-ol, *trans*-para-mentha-2, 8-dienol, myrcene and linalool as notable EO components (Espina et al., 2011). Chemical composition of EO extracted from lime (*C. aurantifolia*) peel included limonene, γ-terpinene, β-pinene, β-myrcene, α-pinene, linalool and linalyl acetate (Tundis et al., 2012). The monoterpene hydrocarbons of sour lime peel oil included *o*-cymene, β-humulene, Δ-carene and α-terpinolene. While sesquiterpene hydrocarbons included α-cedrene and bisabolene (Mahmud et al., 2009). Limonene, a major monoterpene hydrocarbon of CPEO was not detected in sour lime. Citral and linalool were the potent aroma compounds in CPEO, while they were reported in a very low amount in peels of lemon (3%), mandarin (0.4%) and orange (0.35%). EOs of lemon and sweet orange contained linalool (0.4 and 0.3%, respectively) and citral (0.1 and 3%) other than limonene as the primary components (Fisher & Phillips, 2006). Linalool was identified as the main oxygenated monoterpenes in Tunisian bitter orange (1.56%) orange (2.6%), mandarin (1.0%) and grapefruit (0.6%) peel oil (Abd-Elwahab et al., 2016; Karoui & Marzouk, 2013).

The major EO constituents identified in Tunisian sour orange peel oil were monoterpene hydrocarbons such as limonene, β-pinene, *(E)*-β-ocimene, sabinene and α-pinene, while oxygenated monoterpenes (verbenone and linalool), sesquiterpene hydrocarbons (α-calacorene and α-humulene) and oxygenated sesquiterpenes (α-cyperone) were other notable EO components (Hosni et al., 2010). Karoui and Marzouk (2013) reported that Tunisian sour orange EO contained 93.49% monoterpene hydrocarbons with limonene (90.25%) and α-terpinene (1.10%) as the primary oil constituents. In sour orange peel, monoterpene hydrocarbons (limonene, β-pinene, myrcene) and sesquiterpene hydrocarbons (β-caryophyllene) were identified as major EO components (Kirbaşlar et al., 2006). The major oxygenated components of the sour orange peel oil included ester, aldehyde and alcohol. Ester included geranyl acetate and linalyl acetate, aldehyde included geranial and decanal, while alcohol included linalool as the main volatile oxygenated components (Kirbaşlar et al., 2006). Limonene, β-myrcene, linalool, linalyl acetate and α-pinene were identified as main CPEO components in sour orange (Tundis et al., 2012). In a recent study, limonene, linalool, linalyl acetate and myrcene were the main EO components reported in sour orange peels (Ben Hsouna et al., 2019). Turkish sweet orange peel oil contained limonene, myrcene, sabinene and α-pinene as the major monoterpenes, while β-caryophyllene and α-copaene as the main sesquiterpene hydrocarbons (Kirbaşlar et al., 2009). The major oxygenated components of Turkish sweet orange peel oils were octanal, decanal and geranial as aldehydes; linalool, α-terpineol and geraniol as alcohol, and geranyl acetate and neryl acetate as ester components (Kirbaşlar et al., 2009). The EO components identified in peel of four Tunisian sweet orange cultivars were limonene and β-pinene as monoterpene hydrocarbons, linalool and verbenone as oxygenated monoterpenes, α-copaene and β-elemene as sesquiterpenes hydrocarbons, while β-sinensal and α-sinensal as oxygenated sesquiterpenes (Hosni et al., 2010). Orange peel contained limonene, *cis*-limonene oxide, myrcene, 8-dien-1-ol, carvone, linalool and sabinene, *(E)*-patchenol and valencene as the primary EO components (Espina et al., 2011). EO of blood orange (*C. sinensis* (L.) Osbeck) contained limonene (95.35%), β-myrcene (2.48%), α -terpineol (0.42%) and α-pinene (0.49%) as main components (Murthy, Jayaprakasha, & Patil, 2012). Limonene, linalool, linalyl anthranilate, β-pinene, α-terpineol, citral, nerol acetate and neryl propionate were the primary volatile compounds identified in peel oil of lumia (Smeriglio et al., 2018).

Pomelo (*C. grandis* Osbeck) peel EO contained limonene, β-pinene, *(E)*-β-ocimene, α-pinene and sabinene as monoterpenes hydrocarbons, verbenone and linalool as oxygenated monoterpenes, β-elemene, bicyclogermacrene, β-copaene and germacrene as sesquiterpene hydrocarbons and α-cyperone, (E)-nerolidol and α-cadinol as oxygenated sesquiterpenes (Hosni et al., 2010). Monoterpene (limonene and myrcene) and sesquiterpene hydrocarbons (δ-cadinene, β-caryophyllene and nootkatone) were the major volatile components identified in Turkish grapefruit peel oil (Kirbaşlar et al., 2006). The oxygenated components of grapefruit peel EO were aldehydes, alcohol and ester components. Aldehydes included decanal, neral, geranial and octanal; alcohol included α-terpineol and linalool, and ester includes geranyl acetate and neryl acetate as the notable EO components of grapefruit peel (Kirbaşlar et al., 2006). Lemon peel oil contained limonene, β-pinene and γ-terpinene as the monoterpene hydrocarbons, while β-bisabolene, β-caryophyllene and *trans*-α-bergamotene as sesquiterpenes (Kirbaşlar et al., 2006). The oxygenated components of lemon oil included aldehydes (2.4%) ester (1.8%) and alcohol (0.9%) components. The aldehydes included geranial, decanal, neral and octanal; ester included geranyl acetate and neryl acetate; alcohol included linalool, geraniol and nerol as the considerable oxygenated oil components (Kirbaşlar et al., 2006). Oxygenated hydrocarbons identified in peel oil of sour lime included decadienal, linalool acetate, citronellyl acetate, 4′-methoxyacetophenone, carvone, isopulegol acetate, decanone, farnesol, dihydroxy linalool acetate, caryophyllene oxide, *cis*-nerone and 2,2-dimethyl-3,4-octadienal (Mahmud et al., 2009). Espina et al. (2011) identified limonene, β-pinene, γ-terpinene, β-bisabolene, *cis*-thujopsene, *p*-cymene, gerianal, β-caryophyllene, sabinene and citronellal in EO of lemon peel.

Limonene, linalool, linalyl acetate, γ-terpinene, β-pinene and myrcene were the main EO components identified in Turkish bergamot (*C. bergamia*) ripe fruit peel (Kirbaşlar et al., 2009). Linalyl acetate

Table 6
Beneficial effects of citrus peel essential oils.

Beneficial effects	References
Antiallergic and anti-inflammatory properties	Hamdan et al. (2010)
Anticancer activities	Palma et al. (2019), Castro et al. (2018), Ajikumaran Nair et al. (2018), Yang et al. (2017), Mitropoulou et al. (2017), Mitoshi et al. (2012); Jomaa et al. (2012); Manassero et al. (2013),
Anti-inflammatory properties	Ben Hsouna et al. (2019); Plastina et al. (2018); Amorim et al. (2016); Mitoshi et al. (2014); Hirota et al. (2010); Menichini et al. (2011); Kim et al. (2013); Kummer et al. (2013)
Antimicrobial properties	Guo et al. (2018); Yi et al. (2018); Mitropoulou et al. (2017); Jing et al. (2014); Hamdan et al. (2010); Fabio et al. (2007); Fisher and Phillips (2006)
Beneficial in disinfection of skin and healing of minor wounds	Navarra et al. (2015)
Beneficial in pain and anxiety	Ceccarelli et al. (2004)
Enhances memory in Alzheimer's disease patients	Tundis et al. (2012)
Hepatoprotective effects	Ben Hsouna et al. (2019)
Hypoglycemic effects	Peng et al. (2009)
Improves mood disorders and minimizes stress-induced anxiety	Bagetta et al. (2010)
Lipoxygenase inhibitory activity	Wei and Shibamoto (2010)
Neuroprotective effects	Menichini et al. (2011)
Protective effect against acute liver and kidney damage	Bouzenna et al. (2016)
Protective effects against neurodegenerative diseases	Smeriglio et al. (2018)
Sedative and antidepressant-like effects	Wolffenbüttel et al. (2018); Zhang et al. (2019)
Suppressive effects on colon cancer cells	Murthy et al. (2012); Patil et al. (2009)
Treatment of inflammatory skin diseases	Maurya et al. (2018)
Treatment of respiratory tract infections	Cirmi, Bisignano, Mandalari, and Navarra (2016)

reaches at maximum level upon maturation of bergamot fruits and is responsible for the yellow coloration of fruit peel. EOs of bergamot contained linalool and citral other than limonene as the main EO components (Fisher & Phillips, 2006). Limonene, linalool, linalyl acetate, γ-terpinene and β-pinene were the main EO components in bergamot peel (Tundis et al., 2012). EO components identified in peel of two citron (*C. medica* cv. 'rugosa and *C. medica* cv. 'liscia') cultivars from the Coast of Amalfi (Italy) were limonene, camphene, β-pinene and α-pinene (Aliberti et al., 2016). EO of lemon (*C. limon* L.) peels collected from four locations of Syria contained limonene, γ-terpinene, citral, β- pinene and o-cymene as the primary components (Jomaa, Rahmo, Alnori, & Chatty, 2012). The major oxygenated monoterpenes identified in lemon peel essential oil were α-terpineol, l-terpinen-4-ol and citral (Abd-Elwahab et al., 2016). The main volatile EO components identified in *Chenpi* (pericarp of *C. reticulata* Blanco) and *Guangchenpi* (pericarp of *C. reticulata* 'Chachi') were D-limonene and γ-terpinene (Duan et al., 2016). The main EO constituents identified in sweet lime (*C. limetta*) peel were limonene, β-myrcene, linalool, camphene, *cis*-linalool oxide, α-pinene, n-octanol, *trans*-carveol, p-cymene, *trans*-p-menth-2,8-dien-1-ol, n-decanal, *cis*-p-menth-2,8-dien-1-ol and *cis*-carveol (Maurya et al., 2018).

Limonene is a colorless aliphatic hydrocarbon identified as the major component in EO of different citrus species. It is a nonoxygenated cyclic monoterpene consisting of two isoprene units. Moreover, it is known for its pleasant citric fragrance and is commonly used as a flavoring agent in common food items. Limonene content varied in peels of different citrus species as shown in Table 4. Limonene content in sour orange, lime and bergamot was reported as 65.8, 49.2 and 38.1%, respectively (Tundis et al., 2012). In peels of sour orange, grapefruit (Marsh Seedless), mandarin (*C. deliciosa* "Avana''), lemon (Femminello), Carrizo citrange (*C. sinensis* × *Poncirus trifoliata*) and Troyer citrange (*C. sinensis* × *Poncirus trifoliata*) grown in Italy, limonene content reported was 94.27, 93.59, 72.71, 71.06, 65.39 and 71.63%, respectively. EOs of lemon, sweet orange and bergamot contained limonene content of 95, 73 and 45%, respectively (Fisher & Phillips, 2006). The peels of cold-pressed fresh fruits of orange (*C. sinensis*), lemon (*C. lemon*) and mandarin (*C. reticulata*) contained the greatest amount of limonene (85.50, 59.10 and 74.38%, respectively) among different components of EOs (Espina et al., 2011). The concentration of limonene in the hexane extract of calamansi peel collected from Malaysia, Philippines and Vietnam was reported as 8640, 11,000 and 15,600 ppm, respectively (Cheong et al., 2012). Limonene was identified as a major monoterpene hydrocarbon in peel essential oils of grapefruit (89.3%), orange (88.5%), mandarin (78.1%) and lime (53.0%) from Egypt (Abd-Elwahab et al., 2016). Limonene content in peel oil of lime, tahiti lime, lemon, and mandarin lime was reported as 31.1, 53.9, 65.7 and 35.4%, respectively (Amorim et al., 2016). Limonene was reported to be the major constituent in CPEOs of orange (84.75%), mandarin orange (*C. reticulata*) (83.65%), Kambili naragam (*C. maxima*) (87.54%), lemon (36.70%), Mathala naragam (*C. medica*, round) (71.98%) and *C. medica* (oblong) (65.13%) (Ajikumaran Nair et al., 2018).

4. Antioxidant activity

EO present in CP is a source of natural antioxidants that helps in the prevention of oxidative stress and related diseases. Antioxidant activity of CPEO is shown in Table 5. CPEO is a good substitute for chemical antioxidants in the food processing industry. Antioxidant activity of EOs extracted from peels of fourteen Citrus varieties cultivated in China was tested by DPPH and ABTS assays (Guo et al., 2018). The study reported that EO of lime, bergamot (*C. medica* var. *sarcodactylis Swing.*) and Changshan huyou (*C. Changshan huyou. B. Chang*) exhibited strong antioxidant activity and have a potential to be used as a natural food preservative to prevent oxidation. EO extracted from the peel of lumia (*Citrus lumia* Risso) has shown strong antioxidant properties due to the higher proportion of limonene and linalool (Smeriglio et al., 2018). EO of *C. pyriformis* Hassk and *Citrus jambhiri* Lush exhibited significant antioxidant activity (scavenging effect on 2,2-diphenyl-1-picrylhydrazyl (DPPH) with an IC_{50} values of 28.91 and 37.69 mg/ml, respectively (Hamdan et al., 2010). EO of *C. acida* showed strong antioxidant potential with 91.7% of DPPH scavenging effect (Mahmud et al., 2009) CPEO of *C. sinensis* exhibited good DPPH radical scavenging activity with IC_{50} values of 9.45 μl/ml indicating their strong antioxidant efficacy (Singh et al., 2010). CPEO of *C. aurantifolia*, *C. bergamia*, and *C. aurantium* exhibited significant DPPH radical scavenging activity with IC_{50} values of 201.3, 192.9 and 188.9 μg/ml, respectively (Tundis et al., 2012). EOs of finger citron (*Citrus medica* L. var. *sarcodactylis*) differed significantly in antioxidant activities during different maturation stages of the fruit (Wu, Li, Yang, Zhan, & Tu, 2013). EOs of fingered citron at immature, intermediate and mature stages showed good antioxidant and free radical scavenging activities with the DPPH scavenging ability of 78.4, 64.7 and 63.8%, respectively (Wu et al., 2013). EO of *C. reticulata* Blanco cv. Kinokuni (Nanfeng mandarin) peel exhibited IC_{50} values of 22.60 and 1.62 mg/ml in DPPH and ABTS assay (Yi, Jin, Sun, Ma, & Bao, 2018). The mechanisms by which EOs demonstrate their antioxidant activities depend on the content and composition of active constituents present in them. The major EO components of Nanfeng mandarin peel that accounted for DPPH and ABTS radical-scavenging activity were citral, thymol, α-sinensal, α-terpineol, γ-terpinene, and citronellal. The most effective EO constituents that contributed to antioxidant properties were thymol and citral, whose activities were comparable to that of α-tocopherol. EOs of bergamot (*C. bergamia*) can be utilized for the treatment of various chronic diseases characterized by oxidative damage as they exhibited antioxidant and lipoxygenase inhibitory effects (Wei & Shibamoto, 2010). EO from Navel Orange peel exhibited antioxidant activity in DPPH and ABTS assay with IC_{50} values of 2.19 and 2.00 mg/ml, respectively (Yang et al., 2017). DPPH and FRAP (ferric reducing/antioxidant power) values for EO from peels of eight grapefruit varieties varied from 84.87 to 74.73% and 7.76 to 5.73 mmol g^{-1}, respectively (Ahmed, Rattanpal, Gul, Dar, & Sharma, 2019). Antioxidant potential of CPEO increases with the ripening of citrus fruits. The DPPH scavenging activity of CPEO from green, half-ripe and ripe chinotto (*C. myrtifolia* Raf) fruits was reported as 6.1, 7.8 and 8.1 μmol trolox equivalents (TE)/g, respectively (Plastina et al., 2018). CPEO of sour orange showed strong antioxidant activity in a dose-dependent manner as compared to ascorbic acid in the DPPH test (Ben Hsouna et al., 2019).

5. Health-promoting activities

The EO are responsible for the pharmaceutical importance of citrus fruits. CPEOs exhibits antioxidant, analgesic, antimicrobial, anti-inflammatory and anticancer activities (Navarra, Mannucci, Delbò, & Calapai, 2015). The beneficial effects of CPEOs are listed in Table 6. The CPEO has received attention as a substitute for synthetic or chemical preservatives. It is listed generally recognized as safe (GRAS) for use in food products by the Food and Drug Administration (FDA) in the Code of Federal Regulations (Fisher and Phillips, 2006) The EOs present in CP have been reported for antiperoxidative, hepatoprotective and nephroprotective effects under various pathological conditions and drug-induced toxicities (Bouzenna et al., 2016; Navarra et al., 2015). In order to enhance the physicochemical properties and health-promoting activity of EOs, they can be incorporated into gelatin films (Mahato et al., 2019). The active compounds of EOs can be microencapsulated using a packaging shell composed of biodegradable components (such as chitosan and alginate). This way the direct interaction of EO components with food proteins can be inhibited. However, there is an issue of controlled release of active components from EOs which requires more research (de Araújo et al., 2020). CPEO can find applications in dietary components such as nanoemulsions for the preservation of fruits and vegetables, ingredients in soda/citrus concentrates and as flavoring agents (Zhao et al., 2018). In a recent report, nanoemusions composed of whey protein isolate-based films containing orange peel oil were prepared as an active packaging system (Amjadi, Almasi, Ghadertaj, & Mehryar, 2020). They reported that these nanoemulsions could be used effectively in the preservation of foods against oxidation as well as microbial spoilage.

The additive or synergistic effects of EO components of *C. jambhiri* Lush. (Rough lemon) and *C. pyriformis* Hassk (Ponderosa lemon) peels have been reported to be responsible for various biological activities such as functioning as antioxidants, anti-inflammatory, cytotoxic, anti-trypanosomal and antimicrobials (Hamdan et al., 2010). The EO of sour orange peel showed potential antioxidant and anti-inflammatory effects against carbon tetrachloride-mediated hepatotoxicity (Ben Hsouna et al., 2019). Citron EO possesses significant antimicrobial, anti-inflammatory and antiproliferative activities and is a promising pharmaceutical and chemo-preventive agent (Mitropoulou et al., 2017). The EO of lemon showed a protective effect against acute liver and kidney damage induced by a high dose of aspirin (Bouzenna et al., 2016). Bergamot oil showed hypoglycemic effects and proved beneficial in the treatment of type 2 diabetes mellitus (Peng et al., 2009). The hypoglycemic bioactivity is due to high contents of limonene and β-pinene in bergamot EO. In a recent study, it was found out that CPEO can be a valuable tool for the development of a drug against depression and anxiety. Inhalation of *C. sinensis* EO in mice presented sedative and antidepressant-like effects (Wolffenbüttel et al., 2018). Antidepressant-like effects of EO from orange was reported in chronic unpredictable mild stress mice model (Zhang et al., 2019). They reported improvements in neurotrophic, neuroendocrine and monoaminergic systems of mice model after inhalation of EO.

The EO extracted from Rough lemon and Ponderosa lemon peels could be considered as interesting candidates for antiallergic and anti-inflammatory agents as they demonstrated a very good inhibitory activity for 5-lipoxygenase (5-LOX) with an IC_{50} values of 40 and 38 μg/ml, respectively (Hamdan et al., 2010). EO isolated from peel of Yuzu (*Citrus junos* Tanaka) have shown anti-inflammatory efficacy on human eosinophilic leukemia HL-60 clone 15 cells by inhibiting ROS production, cytokines and inactivating eosinophil migration (Hirota et al., 2010). The EO extracted by hydro-distillation from peels of citron *(C. medica* L.) showed anti-inflammatory activity in lipopolysaccharide (LPS)-stimulated macrophages with an IC_{50} value of 17.0 mg/ml (Menichini et al., 2011). The EO exerted significant inhibitory effects on the nitric oxide production in macrophages with no cytotoxic effects up to a concentration of 200 mg/ml. The EO from Yuzu peel has potential efficacy for the treatment of bronchial asthma due to its anti-inflammatory effects in decreasing the production of ROS and ameliorating oxidative damage to the lung. The EO from fingered citron peels exhibited anti-inflammatory effects on lipopolysaccharide (LPS) – stimulated mouse macrophage (RAW 264.7) cells by blocking the nuclear factor-κB (NF-κB), c-Jun N-terminal kinase (JNK) and extracellular signal-regulated kinase (ERK) pathways (Kim et al., 2013). Limonene isolated from peel of tahiti lime (*Citrus latifolia* Tanaka) exhibited anti-inflammatory effects in male BALB/c mice by decreasing the levels of inflammatory cytokines (TNF-α), inhibiting proinflammatory mediators present in the inflammatory exudate and leukocyte chemotaxis (Kummer et al., 2013). The CPEO contains components that effectively inhibit pro-inflammatory cytokine production. The EO of fingered citron decreases the levels of cytokines (tumor necrosis factor-α, interleukin-1b, and interleukin-6) and pro-inflammatory mediators (nitric oxide, inducible nitric oxide synthase, prostaglandin E2, and cyclooxygenase-2) in LPS-stimulated inflammation of macrophages. Limonene present in CPEO strongly inhibited the activity of 5-LOX enzyme and probably acted as a good natural anti-inflammatory agent. The EO of lemon (*Citrus limon* L.) showed anti-inflammatory effects by inhibiting the production of tumor necrosis factor-α (TNF-α) in RAW264.7 murine macrophages treated with lipopolysaccharide (Mitoshi et al., 2014). The EO obtained from the peel of lime, tahiti lime, lemon, and mandarin lime exhibited significant anti-inflammatory effects by reducing cytokine production, cell migration and protein extravasation in chemical and carrageenan-induced mouse air pouch model of inflammation (Amorim et al., 2016). The CPEO from half ripe chinotto (*C. myrtifolia* Raf) effectively reduced the production of nitric oxide and attenuated LPS-induced expression of pro-inflammatory genes encoding for cyclooxygenase-2 (COX-2), interleukin-1β (IL-1β), interleukin-6 (IL-6), inducible nitric oxide synthase (iNOS), and chemokine monocyte chemotactic protein-1 (MCP-1) in RAW264.7 macrophages (Plastina et al., 2018). The synergistic effects of limonene, linalool, linalyl acetate, and γ-terpinene (main EO components) might be responsible for the anti-inflammatory potential of EO from half ripe chinotto peel. CPEO of sour orange at the concentration of 100 μg/ml significantly inhibited (>50%) the production of nitric oxide (a key mediator in inflammatory diseases) by LPS-stimulated RAW264.7 macrophages (Ben Hsouna et al., 2019). They further confirmed that CPEO of sour orange attenuated transcription of the genes related to inflammatory responses. Maurya et al. (2018) reported the preventive potential of EO extracted from sweet lime (*C. limetta*) peel for the treatment of inflammatory skin diseases. This study indicated the suitability of CP oil in formulations of skin care products for the treatment of skin inflammation.

Antimicrobial and antiseptic properties of bergamot peel EO is useful in disinfection of skin and healing of minor wounds (Navarra et al., 2015). Linalool present in EOs has high potential in the food industry as it showed the strongest antimicrobial potential against bacteria and yeasts (Guo et al., 2018). The EOs of lemon, sweet orange, and bergamot peel have been demonstrated to present potent antimicrobial properties against common food-borne microbes such as bacteria, molds and yeast (Fisher and Phillips, 2006) EOs of lemon (*C. limon*), sweet orange (*C. sinensis*) and bergamot (*C. bergamia*) showed antimicrobial properties against common food borne pathogens. Bergamot EO significantly inhibited the growth of both gram-positive and gram-negative bacteria (Fisher & Phillips, 2006). The growth of bacteria (*Haemophilus influenzae* and *Stenotrophomonas maltophilia*) causing respiratory tract infection was significantly inhibited by EO of bergamot peel (Fabio, Cermelli, Fabio, Nicoletti, & Quaglio, 2007). CPEO have been reported to be effective in the treatment of respiratory tract infections caused by microbes (Cirmi et al., 2016) Terpene compounds have role in antimicrobial properties of EO. The chemical components of EOs target microbial cell membranes and exert toxic effect by disrupting cellular permeability or affecting membrane-associated functions (Jing et al., 2014; Romano et al., 2005). EO of citron (*C. medica*) acted as therapeutic agents against certain diseases due to their useful antimicrobial properties against pathogenic and spoilage microorganisms (Mitropoulou et al., 2017). CPEOs are effective, safe and economic alternative to traditional food fungicides for the future food industry (Jing et al., 2014). EO obtained from CP a byproduct of the citrus-processing industries can eliminate the need for synthetic fungicides.

Investigations have proved that EOs of citrus has potential application as antimicrobial agents or food additives in the food industry due to their antimicrobial potential against common food-borne and spoilage microorganisms (Guo et al., 2018). CPEO may be recommended as a plant-based antimicrobial for enhancement of shelf life of food products. The EO of bergamot peel can be used in the topical treatment of *Candida* infections as it showed antifungal activity against *Candida* (*C. albicans* and *C. glabrata*) species recovered from vaginal swabs of patients with vulvovaginal candidiasis (Romano et al., 2005). An earlier study reported bergamot oil was useful for the treatment of dermatophytoses as it exhibited antifungal activity against several common species (*Trichophyton rubrum*, *T. mentagrophytes*, *T. interdigitale*, *T. tonsurans*, *Epidermophyton floccosum Microsporum canis,* and *M. gypseum*) of dermatophytes (Sanguinetti et al., 2006). EOs of mandarin, lemon, orange and grapefruit peels showed antifungal activity by reducing or inhibiting the growth of molds (*Aspergillus flavus, A. niger, Penicillium chrysogenum,* and *P. verrucosum)* commonly associated with food spoilage (Viuda-Martos, Ruiz-Navajas, Fernández-López, & Pérez-Álvarez, 2008). CPEO of *C. sinensis* exhibited antifungal activity against *A. flavus* with 46.2% growth inhibition at 500 ppm and complete inhibition at 750 ppm (Singh et al., 2010). EO of Rough lemon and Ponderosa lemon peels showed substantial antifungal activity against *Saccharomyces cerevisiae* and *C. parapsilosis* (Hamdan et al., 2010). Chitosan-based films containing EO (3%) of bergamot peel showed strong antifungal properties against *P. italicum* (Sánchez-González, Cháfer, Chiralt, & González-Martínez, 2010). These films could be used to increase the shelf life of fruits and vegetables by controlling fungal decay along with preventing moisture losses.

The EO isolated from peels of Rough lemon and Ponderosa lemon exhibited a substantial antibacterial activity against gram-positive (*Bacillus subtilis, Staphylococcus capitis* and *Micrococcus luteus*) and gram-negative (*Klebsiella planticola, Escherichia coli* and *Pseudomonas fluorescens*) bacteria (Hamdan et al., 2010). The EO of Nanfeng mandarin exhibited broad-spectrum antimicrobial activity against gram-positive (*S. aureus* and *B. subtilis*), gram-negative (*E. coli* and *P. aeruginosa*) bacteria and two fungal strains (*A. niger* and *P. chrysogenum*). The EO of Nanfeng mandarin can act as a natural preservative against bacterial and fungal pathogens in food preservation to enhance the safety and shelf-life of food (Yi et al., 2018). The antimicrobial activity of EO was mainly attributed to limonene, linalool, decanal, octanal, citral, citronellal, thymol and α-sinensal. The synergistic effect of EO components disturbs cell membrane which results in disruption of the proton motive force, electron flow, active transport and coagulation of microbial cell contents (Yi et al., 2018). The EOs of Changshan huyou and bergamot exhibited strong antimicrobial activity against *E. coli, S. aureus*, *Salmonella paratyphi*, *P. aeruginosa*, *Listeria monocytogenes*, *C. albicans*, *B. subtilis* and *A. flavus* among EOs of fourteen citrus species (Guo et al., 2018). The antimicrobial effect of EOs was reported greater on Gram-positive bacteria compared to gram-negative bacteria while yeasts were more susceptible than bacteria (Guo et al., 2018). CPEOs can be used as an eco-friendly approach for the control of mosquitoes. EOs isolated from sour orange (*C. aurantium*) peel showed larvicidal properties against the larvae of malarial vector *Anopheles labranchiae* (El-Akhal, Lalami, & Guemmouh, 2015). In a recent study, grapefruit and lemon EOs had a good antimicrobial activity (with minimum inhibitory concentrations ranging from 0.33 to 0.55 mg/ml) against *Leuconostoc mesenteroides*, *E. coli* and *Lactoplantibacillus plantarum* (Raspo et al., 2020).

Inhibitors of acetylcholinesterase (AChE) and butyrylcholinesterase (BChE) were commonly used for the treatment of Alzheimer's disease and other forms of dementia. EO of lime, sour orange and bergamot showed strong radical scavenging capacity and inhibitory activity against major enzymes (AChE and BChE) target for Alzheimer's disease (Tundis et al., 2012). The therapeutic approach of using CPEO enhances memory in Alzheimer's disease patients and is useful for the treatment of various neurological disorders. The CPEO of *C. medica* L. cv. Diamante obtained by hydro-distillation extraction exhibited the highest inhibitory activities against AChE and BChE with an IC_{50} value of 171.3 and 154.6 mg/ml, respectively (Menichini et al., 2011). EO of *C. limon* peel showed AChE inhibitory activity with an IC_{50} value of 849 μg/ml (Aazza, Lyoussi, & Miguel, 2011). Monoterpene hydrocarbons present in CPEO were identified for their potential role in cholinesterase inhibitory activity (Menichini et al., 2011; Tundis et al., 2012). The interaction of cyclic or acyclic hydrocarbon skeleton of monoterpenoids with the hydrophobic active site of AChE may be related to their bioactive potential (Tundis et al., 2012). Limonene, α-terpinene, α-pinene, γ-terpinene and terpinen-4-ol were the main identified EO components responsible for neuroprotective effects in *C. medica* L. cv. Diamante peel (Menichini et al., 2011). Alzheimer's disease and other forms of dementia can be treated using CPEO through inhibition of AChE and BChE. CPEOs are valuable food or nutraceutical supplements for elder peoples due to their anti-cholinesterase properties. The neuroprotective effect of CPEO is attributed to its remarkable antioxidant activity. The CPEO has an interesting neuronal inhibitory and free radical scavenging activities. The long-term exposure to lemon EO odor can induce significant changes in a neuronal pathway involved in pain and anxiety (Ceccarelli, Lariviere, Fiorenzani, Sacerdote, & Aloisi, 2004). The EO are potentially useful in the detoxification mechanisms due to their ability to neutralize different reactive oxygen species (ROS) produced during the onset of neurodegenerative diseases (Smeriglio et al., 2018). EO of bergamot have been used in aromatherapy for improving mood disorders and minimizing stress-induced anxiety due to their interesting neurobiological and antinociceptive effects (Bagetta et al., 2010). The high content of linalyl acetate and linalool in bergamot oil is beneficial in the treatment of clinical pain and is responsible for the antinociceptive and antiallodynic effect.

The CPEOs are gaining substantial recognition and currently being studied for their role in cancer prevention (Ajikumaran Nair et al., 2018). Monoterpene compound (Limonene) present in CPEO is non-toxic to normal cell and can induce cytotoxicity in proliferating cancerous cells (Murthy et al., 2012). The blood orange EO had induced apoptosis and suppresses angiogenesis in colon cancer cells (Murthy et al., 2012). Lime (*C. aurantifolia*) EO components showed an anti-proliferative effect by inducing apoptosis-mediated cells death in human colon carcinoma (SW-480) cells. This study reported 78% inhibition of human colon cancer cells at 100 μg/ml of lime EO concentration and incubation of 48 h (Patil et al., 2009) Lime EO induced DNA fragmentation, elevated caspase-3 content (up to 2- folds) and expression ratio of Bax/Bcl2 after 48 h of treatment. EOs of lemon (*C. limon*) and lime (*C. aurantifolia*) at a concentration of 100 μg/ml exhibited cytotoxic effect against human colon carcinoma (HCT116) cell line (Mitoshi et al., 2012). The components of CPEO of mandarin exhibited additive or synergistic antiproliferative effects against two human tumour (hepatocarcinoma HepG2 and lung adenocarcinoma A549) cell lines (Manassero, Girotti, Mijailovsky, García de Bravo, & Polo, 2013). EO of mandarin orange showed antiproliferative activity against DLA cell line in MTT assay with 100% cell death at a level of 50 μg/ml (Ajikumaran Nair et al., 2018). EO of navel orange peel showed good antiproliferative effect against human lung cancer (A549) and prostate cancer (22RV-1) cell lines at concentrations ranging from 6.25 to 200 μg/ml (Yang et al., 2017). Limonene is recognized as major antiproliferative component of CPEOs. EOs of sweet orange, grapefruit and lemon strongly induced apoptosis in human leukemic (HL-60) cells and the apoptotic activity was related with the limonene content of the EOs. The clinical trial suggested limonene as a potential chemotherapeutic agent in CPEO for the treatment of colorectal cancer (Jia et al., 2013). Limonene inhibited PI3K/ Akt pathway and activated apoptosis via caspase-dependent mitochondrial and cell death pathway in LS174T human colon cancer cells.

Many studies have been focusing on the potential of citrus EO as an anticancer agent. EOs was recently shown to have promising anti-proliferative effects through activation of pathways leading to apoptotic cell death (Mitropoulou et al., 2017). EO of mandarin (*C. reticulata* Blanco cv. Dancy) peel possessed significant antitumor activity on *in vivo* human tumor cells implanted in a murine model at a level of 5.25 mg/ mouse/day (Castro et al., 2018). The mandarin peel EO exerted decreased viability and inhibited growth of pulmonary-carcinoma A549 cell lines by modulating lipid metabolic pathways, inducing cell cycle arrest and apoptosis. The EOs of *C. pyriformis* and *C. jambhiri* peels exhibited cytotoxic effect against the hepatocellular carcinoma (HepG2) cell line (IC_{50} value of 374.36 and 588.06 g/ml, respectively) and pancreatic cancer (MIA-PaCa-2) cell line (IC_{50} value of 213.87 and 512.45 g/ml, respectively) in MTT cell viability assay (Hamdan et al., 2010). The higher cytotoxic effect of *C. pyriformis* peel EO might be due to the presence of higher content of *d*-limonene. Calamansi (*C. microcarpa*) peel being an excellent source of EO is a promising natural low-cost product for potential chemopreventive and chemo-therapeutic effect against cancer cell lines. Limonene and other terpenes in EO of Calamansi have shown synergistic cytotoxic effects against human mammary tumor (MCF-7) cells with an IC_{50} value of 7.98 μg/ml (Palma, Cruz, Cruz, Bugayong, & Castillo, 2019). The liposomal encapsulation of bergamot peel EO showed anticancer activity by inhibiting the survival and proliferation of human neuroblastoma cells (Celia et al., 2013). Liposomal formulation facilitates target delivery and protects EO components from enzymatic degradation in the living system. Nanoemulsion of CP oil also has the potential for use in food products and beverages. Nanoemulsion significantly affected long-term stability and the antimicrobial ability of finger citron (*C. medica* L. var. *sarcodactylis*) EO against *B. subtilis*, *E. coli*, and *S. aureus* (Li et al., 2018).

6. Conclusion and future prospects

The CP forms a major portion of the wet fruit mass in citrus juice processing industry. Its valorization plays an important role in converting the citrus fruits processing waste into value-added and therapeutic products. The CPEO is generating substantial interest in food, pharmaceutical and cosmeceutical industries. The potential of CPEO as a source of natural low-cost antioxidant, anti-inflammatory, antimicrobial, chemotherapeutic and chemopreventive agents has attracted the attention of scientists in recent scientific reports for benefitting humans. The CPEO can be used as a source of biologically active components and preservatives in the development of novel food products which are not only expected to be safe but also considered to have effective bioactivities. The EO obtained from CP is a significant growth inhibitor of food microbes, thus emerges as a promising antimicrobial agent. EO may be included in different products to assure food safety. Furthermore, research aimed at the exact mode of action of antimicrobial components from CPEO in countering the action of pathogenic and spoilage microorganisms in food is needed. Antimicrobial potential of EOs, as well as their long-term effect on food spoilage and pathogenic microorganisms in real ecosystems also requires further investigations. The biological activities of CPEO are mainly reported by *in vitro* studies and animal models, so more clinical trials are needed to determine the potential and safety of long-term potential use in humans. The major limitation in the use of CPEO in the pharmaceutical industry is its susceptibility to oxidation, hydrolysis, evaporation, and degradation of the active components. Development of innovative extraction techniques to reduce oxidation of chemical components of EO and to enhance their stability by encapsulation in different matrix systems needs attention and further investigations. Last but not the least, extensive research is necessary for overcoming the challenges related with allergies and achieving safer dosage limits. Taking this into consideration, there has been a gradual shift towards greener technologies which primarily aim at the safer utilization of CPEO components.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Authors are thankful to Science and Engineering Research Board, India and Council of Scientific and Industrial Research (CSIR), New Delhi (Project No. 38(1419)/16/EMR-II) for providing financial assistance.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodres.2021.110231.

References

Aazza, S., Lyoussi, B., & Miguel, M. G. (2011). Antioxidant and antiacetylcholinesterase activities of some commercial essential oils and their major compounds. *Molecules, 16*(9), 7672–7690.

Abd-Elwahab, S. M., El-Tanbouly, N. D., Moussa, M. Y., Abdel-Monem, A. R., & Fayek, N. M. (2016). Antimicrobial and antiradical potential of four agro-waste Citrus peels cultivars. *Journal of Essential Oil-Bearing Plants, 19*(8), 1932–1942.

Ahmad, M. M., Rehman, S. U., Anjum, F. M., & Bajwa, E. E. (2006). Comparative physical examination of various citrus peel essential oils. *International Journal of Agriculture and Biology, 8*(2), 186–190.

Ahmed, S., Rattanpal, H. S., Gul, K., Dar, R. A., & Sharma, A. (2019). Chemical composition, antioxidant activity and GC-MS analysis of juice and peel oil of grapefruit varieties cultivated in India. *Journal of Integrative Agriculture, 18*(7), 1634–1642.

Ajikumaran Nair, S., Rajani Kurup, S. R., Nair, A. S., & Sabulal, B. (2018). Citrus peels prevent cancer. *Phytomedicine, 50*, 231–237.

Aliberti, L., Caputo, L., De Feo, V., De Martino, L., Nazzaro, F., & Souza, L. F. (2016). Chemical composition and in vitro antimicrobial, cytotoxic, and central nervous system activities of the essential oils of *Citrus medica* L. cv. 'Liscia'and C. medica cv. 'Rugosa'cultivated in Southern Italy. *Molecules, 21*(9), 1244.

Amjadi, S., Almasi, H., Ghadertaj, A., & Mehryar, L. (2020). Whey protein isolate-based films incorporated with nanoemulsions of Orange peel (*Citrus sinensis*) essential oil: Preparation and characterization. *Journal of Food Processing and Preservation, e15196*.

Amorim, J. L., Simas, D. L., Pinheiro, M. M., Moreno, D. S., Alviano, C. S., da Silva, A. J., & Fernandes, P. D. (2016). Anti-inflammatory properties and chemical characterization of the essential oils of four citrus species. *PLoS One, 11*, Article e0153643. https://doi.org/10.1371/journal.pone.0153643.

Azhdarzadeh, F., & Hojjati, M. (2016). Chemical composition and antimicrobial activity of leaf, ripe and unripe peel of bitter orange (Citrus aurantium) essential oils. *Nutrition and Food Sciences Research, 3*(1), 43–50.

Bagetta, G., Morrone, L. A., Rombolà, L., Amantea, D., Russo, R., Berliocchi, L., … Corasaniti, M. T. (2010). Neuropharmacology of the essential oil of bergamot. *Fitoterapia, 81*(6), 453–461.

Baik, J. S., Kim, S. S., Lee, J. A., Oh, T. H., Kim, J. Y., Lee, N. H., & Hyun, C. G. (2008). Chemical composition and biological activities of essential oils extracted from Korean endemic citrus species. *Journal of Microbiology and Biotechnology, 18*(1), 74–79.

Ben Hsouna, A., Gargouri, M., Dhifi, W., Ben Saad, R., Sayahi, N., Mnif, W., & Saibi, W. (2019). Potential anti-inflammatory and antioxidant effects of *Citrus aurantium* essential oil against carbon tetrachloride-mediated hepatotoxicity: A biochemical, molecular and histopathological changes in adult rats. *Environmental Toxicology, 34* (4), 388–400.

Bouzenna, H., Dhibi, S., Samout, N., Rjeibi, I., Talarmin, H., Elfeki, A., & Hfaiedh, N. (2016). The protective effect of Citrus limon essential oil on hepatotoxicity and nephrotoxicity induced by aspirin in rats. *Biomedicine & Pharmacotherapy, 83*, 1327–1334.

Bustamante, J., van Stempvoort, S., García-Gallarreta, M., Houghton, J. A., Briers, H. K., Budarin, V. L., … Clark, J. H. (2016). Microwave-assisted hydro-distillation of essential oils from wet citrus peel waste. *Journal of Cleaner Production, 137*, 598–605.

Caputo, L., Cornara, L., Bazzicalupo, M., De Francesco, C., De Feo, V., Trombetta, D., & Smeriglio, A. (2020). Chemical composition and biological activities of essential oils from peels of three citrus species. *Molecules, 25*, 1890.

Castro, M. A., Rodenak-Kladniew, B., Massone, A., Polo, M., de Bravo, M. G., & Crespo, R. (2018). Citrus reticulata peel oil inhibits non-small cell lung cancer cell proliferation in culture and implanted in nude mice. *Food & Function, 9*(4), 2290–2299.

Ceccarelli, I., Lariviere, W. R., Fiorenzani, P., Sacerdote, P., & Aloisi, A. M. (2004). Effects of long-term exposure of lemon essential oil odor on behavioral, hormonal and neuronal parameters in male and female rats. *Brain Research, 1001*(1–2), 78–86.

Celia, C., Trapasso, E., Locatelli, M., Navarra, M., Ventura, C. A., Wolfram, J., … Paolino, D. (2013). Anticancer activity of liposomal bergamot essential oil (BEO) on human neuroblastoma cells. *Colloids and Surfaces B: Biointerfaces, 112*, 548–553.

Chen, Q., Hu, Z., Yao, F. Y. D., & Liang, H. (2016). Study of two-stage microwave extraction of essential oil and pectin from pomelo peels. *LWT-Food Science and Technology, 66*, 538–545.

Cheong, M. W., Chong, Z. S., Liu, S. Q., Zhou, W., Curran, P., & Yu, B. (2012). Characterisation of calamansi (Citrus microcarpa). Part I: Volatiles, aromatic profiles and phenolic acids in the peel. *Food Chemistry, 134*(2), 686–695.

Cirmi, S., Bisignano, C., Mandalari, G., & Navarra, M. (2016). Anti-infective potential of Citrus bergamia Risso et Poiteau (bergamot) derivatives: A systematic review. *Phytotherapy Research, 30*, 1404–1411.

de Araújo, J. S. F., de Souza, E. L., Oliveira, J. R., Gomes, A. C. A., Kotzebue, L. R. V., da Silva Agostini, D. L., … Cavalcanti, M. T. (2020). Microencapsulation of sweet orange essential oil (Citrus aurantium var. dulcis) by liophylization using maltodextrin and maltodextrin/gelatin mixtures: Preparation, characterization, antimicrobial and antioxidant activities. *International Journal of Biological Macromolecules, 143*, 991–999.

Duan, L., Guo, L., Dou, L. L., Zhou, C. L., Xu, F. G., Zheng, G. D., … Liu, E. H. (2016). Discrimination of Citrus reticulata Blanco and Citrus reticulata 'Chachi'by gas chromatograph-mass spectrometry based metabolomics approach. *Food Chemistry, 212*, 123–127.

El Asbahani, A., Miladi, K., Badri, W., Sala, M., Addi, E. A., Casabianca, H., … Elaissari, A. (2015). Essential oils: From extraction to encapsulation. *International Journal of Pharmaceutics, 483*(1–2), 220–243.

El-Akhal, F., Lalami, A. E. O., & Guemmouh, R. (2015). Larvicidal activity of essential oils of Citrus sinensis and Citrus aurantium (Rutaceae) cultivated in Morocco against the malaria vector Anopheles labranchiae (Diptera: Culicidae). *Asian Pacific Journal of Tropical Disease, 5*(6), 458–462.

Espina, L., Somolinos, M., Lorán, S., Conchello, P., García, D., & Pagán, R. (2011). Chemical composition of commercial citrus fruit essential oils and evaluation of their

antimicrobial activity acting alone or in combined processes. *Food Control, 22*(6), 896–902.
Fabio, A., Cermelli, C., Fabio, G., Nicoletti, P., & Quaglio, P. (2007). Screening of the antibacterial effects of a variety of essential oils onmicroorganisms responsible for respiratory infections. *Phytotherapy Research, 21*(4), 374–377.
Ferhat, M. A., Meklati, B. Y., & Chemat, F. (2007). Comparison of different isolation methods of essential oil from Citrus fruits: Cold pressing, hydrodistillation and microwave 'dry' distillation. *Flavour and Fragrance Journal, 22*, 494–504.
Fisher, K., & Phillips, C. A. (2006). The effect of lemon, orange and bergamot essential oils and their components on the survival of *Campylobacter jejuni*, *Escherichia coli* O157, *Listeria monocytogenes*, *Bacillus cereus* and *Staphylococcus aureus* in vitro and in food systems. *Journal of Applied Microbiology, 101*(6), 1232–1240.
Food and Agriculture Organization of the United Nations, FAOSTAT (2018). http://www.fao.org/faostat/en/#home. Accessed 18 November, 2018.
González-Mas, M. C., Rambla, J. L., López-Gresa, M. P., Blázquez, M. A., & Granell, A. (2019). Volatile compounds in citrus essential oils: A comprehensive review. *Frontiers in Plant Science, 10*, 12.
Guo, J. J., Gao, Z. P., Xia, J. L., Ritenour, M. A., Li, G. Y., & Shan, Y. (2018). Comparative analysis of chemical composition, antimicrobial and antioxidant activity of citrus essential oils from the main cultivated varieties in China. *LWT-Food Science and Technology, 97*, 825–839.
Hamdan, D., El-Readi, M. Z., Nibret, E., Sporer, F., Farrag, N., El-Shazly, A., & Wink, M. (2010). Chemical composition of the essential oils of two Citrus species and their biological activities. *Pharmazie, 65*, 141–147.
Hirota, R., Roger, N. N., Nakamura, H., Song, H. S., Sawamura, M., & Suganuma, N. (2010). Anti-inflammatory effects of limonene from yuzu (Citrus junos Tanaka) essential oil on eosinophils. *Journal of Food Science, 75*(3), H87–H92.
Hosni, K., Zahed, N., Chrif, R., Abid, I., Medfei, W., Kallel, M., … Sebei, H. (2010). Composition of peel essential oils from four selected Tunisian Citrus species: Evidence for the genotypic influence. *Food Chemistry, 123*(4), 1098–1104.
Jia, S. S., Xi, G. P., Zhang, M., Chen, Y. B., Lei, B., Dong, X. S., & Yang, Y. M. (2013). Induction of apoptosis by D-limonene is mediated by inactivation of Akt in LS174T human colon cancer cells. *Oncology Reports, 29*(1), 349–354.
Jing, L., Lei, Z., Li, L., Xie, R., Xi, W., Guan, Y., … Zhou, Z. (2014). Antifungal activity of citrus essential oils. *Journal of Agricultural and Food Chemistry, 62*(14), 3011–3033.
Jomaa, S., Rahmo, A., Alnori, A. S., & Chatty, M. E. (2012). The cytotoxic effect of essential oil of Syrian Citrus limon peel on human colorectal carcinoma cell line (Lim1863). *Middle East Journal of Cancer, 3*(1), 15–21.
Karoui, I. J., & Marzouk, B. (2013). Characterization of bioactive compounds in Tunisian bitter orange (*Citrus aurantium* L.) peel and juice and determination of their antioxidant activities. *BioMed Research International, 2013*.
Kim, K. N., Ko, Y. J., Yang, H. M., Ham, Y. M., Roh, S. W., Jeon, Y. J., … Oda, T. (2013). Anti-inflammatory effect of essential oil and its constituents from fingered citron (*Citrus medica* L. var. sarcodactylis) through blocking JNK, ERK and NF-κB signaling pathways in LPS-activated RAW 264.7 cells. *Food and Chemical Toxicology, 57*, 126–131.
Kirbaşlar, F. G., Tavman, A., Dülger, B., & Türker, G. (2009). Antimicrobial activity of Turkish citrus peel oils. *Pakistan Journal of Botany, 41*(6), 3207–3212.
Kirbaşlar, Ş. I., Boz, I., & Kirbaşlar, F. G. (2006). Composition of Turkish lemon and grapefruit peel oils. *Journal of Essential Oil Research, 18*(5), 525–543.
Kummer, R., Fachini-Queiroz, F. C., Estevão-Silva, C. F., Grespan, R., Silva, E. L., Bersani-Amado, C. A., & Cuman, R. K. N. (2013). Evaluation of anti-inflammatory activity of Citrus latifolia Tanaka essential oil and limonene in experimental mouse models. *Evidence-Based Complementary and Alternative Medicine, 2013*.
Li, J., Wang, J., Wu, M., Cheng, H., Chen, L., & Qi, Z. (2020). Deep deterpenation of citrus essential oils intensified by in situ formation of a deep eutectic solvent in associative extraction. *Industrial & Engineering Chemistry Research, 59*, 9223–9232.
Li, Z. H., Cai, M., Liu, Y. S., & Sun, P. L. (2018). Development of finger citron (*Citrus medica* L. var. sarcodactylis) essential oil loaded nanoemulsion and its antimicrobial activity. *Food Control, 94*, 317–323.
Mahato, N., Sharma, K., Koteswararao, R., Sinha, M., Baral, E., & Cho, M. H. (2019). Citrus essential oils: Extraction, authentication and application in food preservation. *Critical Reviews in Food Science and Nutrition, 59*, 611–625.
Mahmud, S., Saleem, M., Siddique, S., Ahmed, R., Khanum, R., & Perveen, Z. (2009). Volatile components, antioxidant and antimicrobial activity of Citrus acida var. sour lime peel oil. *Journal of Saudi Chemical Society, 13*(2), 195–198.
Manassero, C. A., Girotti, J. R., Mijailovsky, S., García de Bravo, M., & Polo, M. (2013). In vitro comparative analysis of antiproliferative activity of essential oil from mandarin peel and its principal component limonene. *Natural Product Research, 27*(16), 1475–1478.
Masango, P. (2005). Cleaner production of essential oils by steam distillation. *Journal of Cleaner Production., 13*(8), 833e839.
Maurya, A. K., Mohanty, S., Pal, A., Chanotiya, C. S., & Bawankule, D. U. (2018). The essential oil from Citrus limetta Risso peels alleviates skin inflammation: In-vitro and in-vivo study. *Journal of Ethnopharmacology, 212*, 86–94.
Menichini, F., Tundis, R., Bonesi, M., De Cindio, B., Loizzo, M. R., Conforti, F., … Menichini, F. (2011). Chemical composition and bioactivity of *Citrus medica* L. cv. Diamante essential oil obtained by hydrodistillation, cold-pressing and supercritical carbon dioxide extraction. *Natural Product Research, 25*(8), 789–799.
Mitoshi, M., Kuriyama, I., Nakayama, H., Miyazato, H., Sugimoto, K., Kobayashi, Y., … Mizushina, Y. (2012). Effects of essential oils from herbal plants and Citrus fruits on DNA polymerase inhibitory, cancer cell growth inhibitory, antiallergic, and antioxidant activities. *Journal of Agricultural and Food Chemistry, 60*, 11343–11350.
Mitoshi, M., Kuriyama, I., Nakayama, H., Miyazato, H., Sugimoto, K., Kobayashi, Y., … Mizushina, Y. (2014). Suppression of allergic and inflammatory responses by essential oils derived from herbal plants and citrus fruits. *International Journal of Molecular Medicine, 33*(6), 1643–1651.
Mitropoulou, G., Fitsiou, E., Spyridopoulou, K., Tiptiri-Kourpeti, A., Bardouki, H., Vamvakias, M., … Kourkoutas, Y. (2017). Citrus medica essential oil exhibits significant antimicrobial and antiproliferative activity. *LWT-Food Science and Technology, 84*, 344–352.
Murthy, K. N. C., Jayaprakasha, G. K., & Patil, B. S. (2012). D-limonene rich volatile oil from blood oranges inhibits angiogenesis, metastasis and cell death in human colon cancer cells. *Life Sciences, 91*(11–12), 429–439.
Navarra, M., Mannucci, C., Delbò, M., & Calapai, G. (2015). Citrus bergamia essential oil: From basic research to clinical application. *Frontiers in Pharmacology, 6*, 36.
Ngan, T. T. K., Muoi, N. V., Quan, P. M., & Cang, M. H. (2020a). Evaluation of physical and chemical properties of pomelo (*Citrus grandis* L.) essential oil using steam distillation process. *Asian Journal of Chemistry, 32*, 1433–1436.
Ngan, T. T. K., Muoi, N. V., Quan, P. M., & Cang, M. H. (2020b). Evaluation of physical and chemical properties of pomelo (*Citrus grandis* L.) essential oil using steam distillation process. *Asian Journal of Chemistry, 6*, 1433–1436.
Özogul, Y., Özogul, F., & Kulawik, P. (2021). The antimicrobial effect of grapefruit peel essential oil and its nanoemulsion on fish spoilage bacteria and food-borne pathogens. *LWT- Food Science and Technology, 136*, Article 110362.
Palazzolo, E., Laudicina, V. A., & Germanà, M. A. (2013). Current and potential use of citrus essential oils. *Current Organic Chemistry, 17*, 3042–3049.
Palma, C. E., Cruz, P. S., Cruz, D. T. C., Bugayong, A. M. S., & Castillo, A. L. (2019). Chemical composition and cytotoxicity of Philippine calamansi essential oil. *Industrial Crops and Products, 128*, 108–114.
Patil, J. R., Jayaprakasha, G. K., Chidambara Murthy, K. N., Tichy, S. E., Chetti, M. B., & Patil, B. S. (2009). Apoptosis-mediated proliferation inhibition of human colon cancer cells by volatile principles of *Citrus aurantifolia*. *Food Chemistry, 114*, 1351–1358.
Peng, C. H., Ker, Y. B., Weng, C. F., Peng, C. C., Huang, C. N., Lin, L. Y., & Peng, R. Y. (2009). Insulin secretagogue bioactivity of finger citron fruit (*Citrus medica L.* var. Sarcodactylis Hort, Rutaceae). *Journal of Agricultural and Food Chemistry, 57*(19), 8812–8819.
Plastina, P., Apriantini, A., Meijerink, J., Witkamp, R., Gabriele, B., & Fazio, A. (2018). In Vitro anti-inflammatory and radical scavenging properties of Chinotto (*Citrus myrtifolia* Raf.) essential oils. *Nutrients, 10*(6), 783.
Raspo, M. A., Vignola, M. B., Andreatta, A. E., & Juliani, H. R. (2020). Antioxidant and antimicrobial activity of citrus essential oils from Argentina and the United States. *Food Bioscience, 100651*.
Razzaghi, S. E., Arabhosseini, A., Turk, M., Soubrat, T., Cendres, A., Kianmehr, M. H., … Chemat, F. (2019). Operational efficiencies of six microwave based extraction methods for orange peel oil. *Journal of Food Engineering, 241*, 26–32.
Romano, L., Battaglia, F., Masucci, L., Sanguinetti, M., Posteraro, B., Plotti, G., … Fadda, G. (2005). In vitro activity of bergamot natural essence and furocoumarin-free and distilled extracts, and their associations with boric acid, against clinical yeast isolates. *Journal of Antimicrobial Chemotherapy, 55*(1), 110–114.
Sahraoui, N., Vian, M. A., El Maataoui, M., Boutekedjiret, C., & Chemat, F. (2011). Valorization of citrus by-products using Microwave Steam Distillation (MSD). *Innovative Food Science & Emerging Technologies, 12*(2), 163–170.
Sánchez-González, L., Cháfer, M., Chiralt, A., & González-Martínez, C. (2010). Physical properties of edible chitosan films containing bergamot essential oil and their inhibitory action on Penicillium italicum. *Carbohydrate Polymers, 82*(2), 277–283.
Sanguinetti, M., Posteraro, B., Romano, L., Battaglia, F., Lopizzo, T., De Carolis, E., & Fadda, G. (2006). In vitro activity of *Citrus bergamia* (bergamot) oil against clinical isolates of dermatophytes. *Journal of Antimicrobial Chemotherapy, 59*(2), 305–308.
Satari, B., & Karimi, K. (2018). Citrus processing wastes: Environmental impacts, recent advances, and future perspectives in total valorization. *Resources, Conservation and Recycling, 129*, 153–167.
Shan, Y. (2016). *Comprehensive utilization of citrus by-products*. Cambridge, MA, USA: Academic Press.
Singh, B., Singh, J. P., Kaur, A., & Singh, N. (2020). Phenolic composition, antioxidant potential and health benefits of citrus peel. *Food Research International, 109114*.
Singh, P., Shukla, R., Prakash, B., Kumar, A., Singh, S., Mishra, P. K., & Dubey, N. K. (2010). Chemical profile, antifungal, antiaflatoxigenic and antioxidant activity of Citrus maxima Burm. and Citrus sinensis (L.) Osbeck essential oils and their cyclic monoterpene, DL-limonene. *Food and Chemical Toxicology, 48*(6), 1734–1740.
Smeriglio, A., Alloisio, S., Raimondo, F. M., Denaro, M., Xiao, J., Cornara, L., & Trombetta, D. (2018). Essential oil of Citrus lumia Risso: Phytochemical profile, antioxidant properties and activity on the central nervous system. *Food and Chemical Toxicology, 119*, 407–416.
Teigiserova, D. A., Tiruta-Barna, L., Ahmadi, A., Hamelin, L., & Thomsen, M. (2021). A step closer to circular bioeconomy for citrus peel waste: A review of yields and technologies for sustainable management of essential oils. *Journal of Environmental Management, 280*, Article 111832.
Tundis, R., Loizzo, M. R., Bonesi, M., Menichini, F., Mastellone, V., Colica, C., & Menichini, F. (2012). Comparative study on the antioxidant capacity and cholinesterase inhibitory activity of *Citrus aurantifolia* Swingle, *C. aurantium* L., and *C. bergamia* Risso and Poit. peel essential oils. *Journal of Food Science, 77*, H40–H46.
Viuda-Martos, M., Ruiz-Navajas, Y., Fernández-López, J., & Pérez-Álvarez, J. (2008). Antifungal activity of lemon (*Citrus lemon* L.), mandarin (*Citrus reticulata* L.), grapefruit (*Citrus paradisi* L.) and orange (*Citrus sinensis* L.) essential oils. *Food Control, 19*(12), 1130–1138.
Wei, A., & Shibamoto, T. (2010). Antioxidant/lipoxygenase inhibitory activities and chemical compositions of selected essential oils. *Journal of Agricultural and Food Chemistry, 58*(12), 7218–7225.

Wolffenbüttel, A. N., Zamboni, A., Becker, G., dos Santos, M. K., Borille, B. T., de Cássia, M. K., … de Moura, L. V. (2018). Citrus essential oils inhalation by mice: Behavioral testing, GCMS plasma analysis, corticosterone, and melatonin levels evaluation. *Phytotherapy Research, 32*(1), 160–169.

Wu, F., Jin, Y., Xu, X., & Yang, N. (2017). Electrofluidic pretreatment for enhancing essential oil extraction from citrus fruit peel waste. *Journal of Cleaner Production, 159*, 85–94.

Wu, Z., Li, H., Yang, Y., Zhan, Y., & Tu, D. (2013). Variation in the components and antioxidant activity of Citrus medica L. var. sarcodactylis essential oils at different stages of maturity. *Industrial Crops and Products, 46*, 311–316.

Yang, C., Chen, H., Chen, H., Zhong, B., Luo, X., & Chun, J. (2017). Antioxidant and anticancer activities of essential oil from Gannan navel orange peel. *Molecules, 22*, 1391.

Yi, F., Jin, R., Sun, J., Ma, B., & Bao, X. (2018). Evaluation of mechanical-pressed essential oil from Nanfeng mandarin (*Citrus reticulata* Blanco cv. Kinokuni) as a food preservative based on antimicrobial and antioxidant activities. *LWT-Food Science and Technology, 95*, 346–353.

Zhang, L. L., Yang, Z. Y., Fan, G., Ren, J. N., Yin, K. J., & Pan, S. Y. (2019). Antidepressant-like effect of *Citrus sinensis* (L.) osbeck essential oil and its main component limonene on mice. *Journal of Agricultural and Food Chemistry, 67*, 13817–13828.

Zhao, S., Gao, W., Tian, G., Zhao, C., DiMarco-Crook, C., Fan, B., … Zheng, J. (2018). Citrus oil emulsions stabilized by citrus pectin: The influence mechanism of citrus variety and acid treatment. *Journal of Agricultural and Food Chemistry, 66*, 12978–12988.