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Citrus Seeds as Potential Vegetable Oil Resources: Oil Content and Some Quality Characteristics of Oil

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Abstract: Evaluating citrus seeds, classified as agricultural and industrial waste, as a novel potential byproduct may offer a new strategy to mitigate the strain on vegetable oil supply. The present study aimed to identify potential use of citrus seed oil by analyzing the oil content, fatty acid composition, some quality paramaters of 7 citrus oil (bitter orange, kumquat, lemon, limequat, mandarin, pomelo and sweet orange) grown in Türkiye. The results indicate that citrus seeds include significant oil concentrations, with an oil content ranging from 26.62% (limequat) to 36.10% (bitter orange). Thirteen fatty acid components were identified from seed oils obtained by n-hexane extraction. The major fatty acids were palmitic acid (23.24-37.07%), oleic acid (19.90-30.21%), and linoleic acid (29.36-38.01%). The saturated fatty acids (SFA) in citrus seed oil ranged from 27.95% (kumquat) to 41.98% (sweet orange), whereas the unsaturated fatty acids ranged from 58.02% (sweet orange) to 72.05% (kumquat). The quality of citrus seed oils was assessed by calculating nutrition quality indices for lipids, including PUFA/SFA ratio, atherogenicity index, thrombogenicity index, peroxidation index, unsaturation index, and calculated oxidability. Computed nutritional quality indexes revealed significant differences among species. Hierarchical cluster analysis was used to examine the classification and correlation of the oil composition in citrus seeds, revealing that the results indicated that seed oil composition largely depended on the species and could be classified into three groups accordingly. The results of the study suggest that citrus seeds could be used as healthy edible oils for the creation of value-added products, due to their notable fatty acid composition and lipid nutritional quality.

Potansiyel Bitkisel Yağ Kaynakları Olarak Turunçgil Tohumları: Yağ İçeriği ve Yağın Bazı Kalite Özellikleri

Anahtar Kelimeler
Biyolojik atık,
Turunçgil tohumu,
Yağ asiti,
Besin indeksi,
Yağ kalitesi

Öz: Tarımsal ve endüstriyel atık olan turunçgil tohumlarının yeni potansiyel bir yan olarak değerlendirilmesi bitkisel yağ açığı üzerindeki baskıyı hafifletmekte yeni bir yaklaşım sağlayabilir. Bu çalışmada, Türkiye de yetiştiriciliği yaygın olarak yapılan yedi turunçgil (turunç, kamkat, limon, limkat, mandalina, pomelo ve tatlı portakal) tohum yağının yağ içeriği, yağ asidi bileşimi ve bazı kalite parametreleri belirlenerek, turunçgil tohum yağının kullanımına yönelik teorik bir temel oluşturulması amaçlanmıştır. Sonuçlar, turunçgil tohumlarının yüksek seviyede yağ içerdiğini ve %26.62 (limkat) ile %36.10 (turunç) arasında bir yağa sahip olduğunu göstermektedir. n-hekzan ile ekstrakte edilen tohum yağlarında 13 yağ asidi bileşeni belirlendi ve başlıca yağ asitleri palmitik asit (%23.24-37.07), oleik asit (%19.90-30.21) ve linoleik asit (%29.36-38.01) bileşenleridir. Turunçgil tohum yağındaki doymuş yağ asitleri (SFA) %27.95 (kamkat) ile %41.98 (tatlı portakal) arasında ve doymamış yağ asitleri ise %58.02 (tatlı portakal) ile %72.05 (kamkat) arasında değişim göstermiştir. Turunçgil tohum yağların kalitesi ise lipit besin kalite indekslerinin (PUFA/SFA, aterojenite indeksi, trombojenite indeksi, peroksidasyon indeksi, doymamışlık indeksi ve hesaplanan oksitlenebilirlik) hesaplanması ile belirlenmiştir. Hesaplanan besin kalitesi endeksleri türler arasında önemli farklılıklar göstermiştir. Turunçgil tohumlarının yağ bileşimi arasındaki sınıflandırmayı ve korelasyonu araştırmak için hiyerarşik kümeleme analizi kullanıldı ve sonuçlar tohum yağı bileşiminin büyük ölçüde türlere bağlı olduğunu ve buna göre üç grupta sınıflandırılabileceğini göstermiştir. Mevcut çalışmanın sonuçları, turunçgil tohum yağlarının önemli yağ asidi kompozisyonu içermesi ve değerli lipit besin kalite indekslerine sahip olmasından dolayı sağlıklı yenilenebilir yağ için potansiyel bir kaynak olarak ve katma değerli ürünlerin üretimi için kullanılabileceğini göstermektedir.

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1. Introduction

Citrus, consisting of 140 genera and 1300 species, is a member of the *Rutaceae* family with high nutritional value and is farmed in more than 150 countries. Citrus species have emerged as a significant fruit crop globally, encompassing a cultivated area of 10,554,846 hectares and a production volume of 169,388,809.84 tons in 2023 [1]. Asia and America comprise 79.87% of total production, followed by Africa, Europe and Oceania. China, Brazil and India are the leading citrus-producing countries, whereas Türkiye ranks 5th with a production of 7,877,982 tons in 2023.

Citrus fruits have high economic value due to their diverse uses (juice, jam, marmalade, etc.); The edible part of citrus fruits is approximately 45-60% of the total amount. The remainder discarded as animal feed or waste; these parts consist mostly of peel, pulp and seeds [2]. The by-products utilization industry is experiencing attention; however, the emphasis on recovering value-added products has predominantly centered on peel and pulp, whereas citrus seeds have been largely overlooked due to processing [3, 4].

Seed oils are a significant source for nutritional, industrial, and pharmaceutical purposes. Some seed oils obtained from diverse taxa are used for various purposes in paints, plastics, lubricants, soaps, pharmaceuticals, organic pesticides, textiles, surface coatings, oleo-chemicals and cosmetics industry [5]. The global demand for vegetable oils has increased to around 125 million tons annually, driving industry expansion and population increase. Consequently, identifying alternative sources of vegetable oils with nutritional and pharmaceutical properties is important [6]. Given the nutritional and economic value of citrus seeds, they have recently begun to attract interest in the expansion of the citrus industry. Approximately 20-25% of citrus fruit seeds possess an oil content above 50%, surpassing the three traditionally used oil crops: olive (20%-25%), soybeans (17%-21%) and cotton seed (15%-24%) [6, 7]. Citrus seeds contain both saturated and unsaturated fatty acids, but the oil is not commercially extracted on a considerable level [8, 9]. The palmitic, oleic and linoleic acids are the predominant fatty acids of citrus seeds [10]. The human body cannot synthesize essential polyunsaturated fatty acids, necessitating their acquisition from nutritional foods. Citrus seeds with high polyunsaturated fatty acids could be beneficial for human health. [3]. Overall, the nutritional potential of citrus seed oil could be an alternative oil source, but research focused on fatty acid components among seeds of citrus cultivars is limited.

Citrus seed oils are used in products such as bath soaps, detergents, skin and hair care cosmetics and skin masks [11]. It functions as an emollient and skin conditioner in cosmetic formulations. It enhances the lipid barrier and revitalizes mature skin thanks to its hydrating and smoothing qualities. Simultaneously, it possesses skin toning capabilities that significantly improve skin firmness. Products containing vitamin C and zinc assist in preserving the skin's natural collagen levels. It has conventionally been utilized in facial masks and creams owing to its capacity to soften the skin, facilitate absorption, and impart a rejuvenating sensation. [12].

Türkiye has a vegetable oil deficit and supplies this deficit as imports of crude oil or oilseeds [13]. Substantial production, consumption and processing of citrus fruits in Türkiye, citrus seeds can be used as a source of seed oil and could help to relieve the pressure on vegetable oil deficit. Although recent systematic investigations on citrus seed oil [3, 5], its potential for further research remains unexplored, and knowledge regarding its application, especially in Türkiye, is quite inadequate. The aim of the study was to investigate oil content and fatty acid composition of seeds of citrus species commonly cultivated in Türkiye, and to examine the potential use of citrus seeds as oil sources.

2. Material and Method

Bitter orange (*Citrus aurantium*), lemon (*Citrus limon*), mandarin (*Citrus reticulata*) and sweet orange (*Citrus sinensis*) fruits were supplied from the Alanya district (36°32′52′′ N and 32°03′31′′ E, 21 m) of Antalya

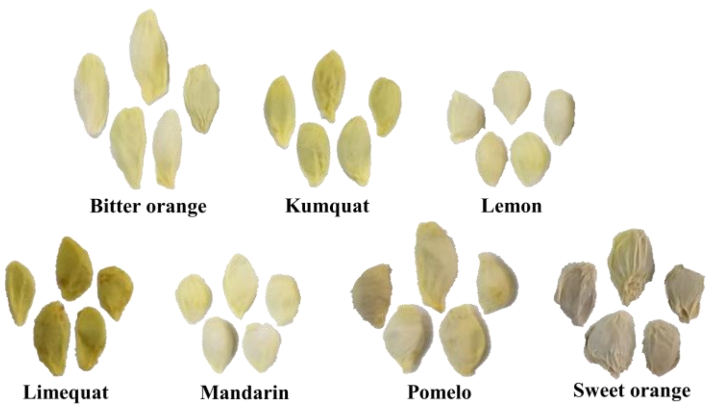

Figure 1. Appearance of seeds used in the study.

province of Türkiye in 2025, kumquat (*Citrus japonica*) fruit from the Gazipaşa district (36°19′55′′ N and 32°19′32′′ E, 211 m), and pomelo (*Citrus maxima*) fruit from a commercial grower in the Aksu district (37°01′01′′ N and 30°48′28′′ E, 84 m). Limequat (hybrid of *Citrus japonica* and *Citrus floridana*) fruits were supplied by Batı Akdeniz Agricultural Research Institute in Antalya (Table 1). Seeds were removed from the fruits, washed with distilled water to remove sticky residues on the seeds and dried at room temperature (Figure 1).

Table 1. Information on the Citrus species used in the study

Samples	Variety Name	Harvest time
Bitter orange	Tuzcu 891 T	15.12.2024
Kumquat	Fukushu	10.03.2025
Lemon	Molla Mehmet	15.09.2024
Limequat	-	20.03.2025
Mandarin	Klemantin Fino	15.09.2024
Pomelo	-	20.11.2024
Sweet orange	Alanya Dilimli	20.11.2024

2.1. Seed oil content and fatty acids composition

The fixed oil content (~2 g) in air-dried citrus seeds was determined using a nuclear magnetic resonance (NMR) instrument (Brüker mq-one, Germany) and expressed as a percentage of seed weight [14].

Fatty acids methyl esters (FAME) was prepared using sodium methoxide [15]. *n*-hexane (10 mL) was mixed with 2 g of ground citrus seeds to obtain crude seed oil. The test tube was then closed with a stopper, vortexed vigorously for 1 min, and incubated overnight on a shaker at room temperature. The supernatant was taken to a new tube, evaporated at 40 °C using an evaporator (IKA RV 10 digital) to remove the solvent in the supernatant. Subsequently, 0.25 mL of crude oil, 0.75 mL of derivatizer and 1 mL of *n*-hexane were mixed in a test tube and vortexed. The mixture was incubated overnight to convert crude fatty acids into methyl esters, followed by the addition of 1 mL of *n*-hexane. After phase separation, the upper phase (derivatizer phase) was used for analysis. The fatty acid components were analyzed with Shimadzu GC-2010 Plus system equipped with a flame ionization detector (FID). A CP-WAX 52 CB column (60 m × 0.32 mm × 1.20 μm) was used for the separation. Helium was used as carrier gas, and the column flow rate was adjusted to 3 mL min-1. Samples (1 μL) were injected with a split ratio of 10:1. The injection block temperature is 250 °C and the detector temperature is 265 °C. The initial GC column temperature was maintained at 80 °C for 4 min, then increased to 250 °C with gradual increases in temperature of 3 °C per min, and sustained at this temperature for 20 min. The total time of the analysis is 85 min. Fatty acid identification was accomplished by using relative retention times to a commercial standard mixture of a FAME mix (Sigma, Supelco® 37 Component FAME Mix). The amount of each fatty acid was expressed as relative percentage [16].

Based on fatty acids profile of citrus seeds, six different lipid nutrient quality indices were calculated following these formulas: PUFA/SFA [17], atherogenicity index [18], thrombogenicity index [18], peroxidation index [19], unsaturation index [17], calculated oxidability [20].

$$PUFA/SFA = \Sigma_{PUFA}/\Sigma_{SFA}$$

$$\text{Atherogenicity index} = [C_{12:0} + (4 * C14{:}0) + C_{16:0}] \;/\; [\Sigma_{MUFA} + \Sigma_{(n-3)} + \Sigma_{(n-6)}]$$

$$\text{Thrombogenicity index} = [C_{14:0} + C_{16:0} + C_{18:0}] \;/\; [(0.5 * \Sigma_{MUFA}) + (0.5 * \Sigma_{(n-6)}) + (3 * \Sigma_{(n-3)}) + (n-3/n-6)]$$

$$\text{Peroxidation index} = [(0.025 \times \text{monoenoic }\%) + (1 \times \text{dienoic }\%) + (2 \times \text{trienoic }\%) + (4 \times \text{tetraenoic }\%) + (6 \times \text{pentaenoic }\%) + (8 \times \text{hexaenoic }\%)]$$

$$\text{Unsaturation index} = (1 \times \text{monoenoic }\%) + (2 \times \text{dienoic }\%) + (3 \times \text{trienoic }\%) + (4 \times \text{tetraenoic }\%) + (5 \times \text{pentaenoic }\%) + (6 \times \text{hexaenoic }\%)$$

$$\text{Calculated oxidability} = [C_{18:1} + (10.3 * C_{18:2}) + (21.6 * C_{18:3})] \;/\; 100$$

2.2. Statistical analysis

The results were shown as mean ± standard deviation (SD). Results of GC-MS analysis was conducted using LabSolutions software (version 2.72, Shimadzu). Hierarchical cluster analysis (HCA) and an associated heatmap were conducted with the ClustVis online application [21], employing Pearson's correlation for distance metrics and average cluster analysis and prioritizing the tightest cluster for the phylogenetic relationship.

3. Results and Discussion

Plant fruits and seeds are the primary sources of vegetable oils. In addition, leaves, barks and stems, roots and flowers also contribute to the production of vegetable oils [3]. The oil content of seeds examined in this study ranged from 26.62% (limequat) to 36.10% (bitter orange) (Table 2). Furthermore, the study identified the oil content as 34.19% in kumquat,

Table 2. Seed oil content of different citrus species

	Bitter orange	Kumquat	Lemon	Limequat	Mandarin	Pomelo	Sweet orange
Total oil contents (%)	36.10±1.42	34.19±0.72	27.64±1.50	26.62±0.17	32.17±1.45	31.72±2.52	33.29±2.26

33.29% in sweet orange, 32.17% in mandarin, 31.72% in pomelo and 27.64% in lemon. Juhaimi et al. [22] indicated that citrus seeds from Saudi Arabia and Türkiye had 21% (eureka lemon) to 32.2% (fremont tangerine) oil content. Matthaus and Özcan [5] found that the oil content of seeds from citrus fruits in Türkiye was significantly higher than that of citrus samples from Vietnam. The seed oil content of four citrus species (sweet lemon, bitter orange, sweet orange and mandarin) cultivated in Pakistan ranged from 27.0% to 36.5% following hexane extraction [6]. Two orange cultivars grown in Ghana had a high oil content; Late Valencian at 57.45% and Blood orange at 55.77% [23]. Also, the seed oil content of five citrus species (mandarin, bitter orange, lemon and grapefruit) cultivated in Mersin, Türkiye was between 27.6% and 36.42% [24]. The oil content of citrus seeds analyzed in this study surpassed some other important oil crops, including cotton, soybean and olive fruits [6], suggesting that the production of fixed oil from citrus seeds is viable. These differences in oil content can be attributed to production factors, climatic conditions, processing and storage as stated by [23]. Consequently, the assessment and advancement of citrus seeds, regarded as agricultural-industrial waste, as a novel potential resource is promising.

GC/MS-FID analysis identified 13 fatty acids in citrus seed oil samples (Table 3). Palmitic (23.24-37.07%), linoleic (29.36-38.01%) and oleic (19.90-30.21%) acids were identified as the main fatty acids in citrus seed oils. Similar to our results, Liu et al. [3], Juhaimi et al. [22] and Reazai et al [25] identified linoleic, oleic and palmitic acids as the main fatty acids in citrus seed oils. Anwar et al. [6] reported that the major fatty acids in citrus seed oil from Pakistan were linoleic (36.1-39.0%), oleic (21.9-24.1%) and linolenic acids (3.4-4.4%) that differed from our findings, which might be due to variations in cultural and environmental conditions. The fatty acid composition in seeds is unstable, with variations in fatty acid synthesis influenced by genetic, ecological, morphological, physiological factors and cultural practices [26]. Increasing air temperatures during the seed maturation phase decreased linoleic acid levels while increasing oleic, palmitic and stearic acid concentrations [27, 28]. This hypothesis was also supported by [29], who observed significant changes in oil content and fatty acid composition of four mandarin (*Citrus reticulata*) and three lemon (*Citrus limon*) cultivars harvested at three different harvest times. Therefore, the fatty acid composition of seeds varies based on geographical regions/locations and the annual temperature and precipitation of those regions. Minor fatty acids varied among citrus seeds, and certain minor fatty acids were not detected in some samples. It was established that myristic acid was not synthesized in kumquat, pentadecanoic acid was not synthesized in kumquat and limequat, and alpha-linolenic acid was not synthesized in kumquat, lemon and limequat seeds. Linoleic and linolenic acids are essential fatty acids with potential health benefits; the linoleic acid content of citrus seeds analyzed in this study was notably high (29.359-38.006%), whereas the gamma and alpha linolenic acid levels were relatively low. Moreover, given that citrus seeds contain saturated fatty acids, including stearic and palmitic acid, their oil can be utilized for raw consumption in salads, for culinary purposes, or margarine production [4].

The fatty acid composition is a crucial determinant of quality of the cooking oils. Different national and international organizations provide daily recommended consumption levels for SFA, MUFA and PUFA in edible oils [30]. The World Health Organization recommends an SFA:MUFA:PUFA dietary ratio of 1:1.5:1 [31]. The fatty acid composition of citrus seeds examined in this study, closely relates with recommended values, suggesting that the nutritional value of citrus seeds is aligned well with the recommended consumption levels. The citrus seed oils examined in the study contain saturated fatty acids in concentrations varying from 27.95% (kumquat) to 41.98% (sweet orange). Monounsaturated fatty acids include 20.68 to 30.93%, predominantly consisting of oleic acid (19.90-27.79%), with minor amounts of palmitoleic acid (0.25-0.61%) and cis-11-eicosenoic acid (0.17-0.28%). Polyunsaturated fatty acids range from 34.45% (pomelo) to 44.52% (limequat), predominantly including linoleic acid and gamma-linolenic acid. Total PUFA content was found to be higher than the total SFA content in other citrus seeds, with the exception of pomelo and sweet orange. Notably, limequat had the highest total PUFA at 44.52%, followed by kumquat at 43.53%, mandarin at 39.78%, bitter orange at 39.20%, lemon at 37.81%, sweet orange at 37.21% and pomelo at 34.45%. Among citrus species cultivated (*C. sinensis*, *C. aurantium*, *C. aurantifolia, C. paradisi*, *C. reticulata*, *C. paradisi* x *C. reticulate* hybid) in Nigeria, the seed oils had high amounts of unsaturated fatty acids (67% to 86.2%) [32]. The results indicated that sweet orange seed oil is rich in unsaturated fatty acids (71%) [9], suggesting its potential as a source of various omega fatty acids. Total SFA content of four citrus species (sweet lemon, bitter orange, sweet orange and mandarin) in Pakistan ranged from 29.70% to 36.10% [6]. The fatty acid composition of citrus seeds has a balanced ratio of SFA, MUFA and PUFA content, rendering it a potentially healthful oil. The seven different citrus seed oils analyzed in this study contained high levels of unsaturated fatty acids, and citrus oils differed significantly among themselves in their fatty acid levels.

Furthermore, lipid nutritional quality indices were assessed based on the fatty acid profiles in seeds of various citrus species (Table 2). In this context, the PUFA/SFA ratio, atherogenicity index, thrombogenicity index, peroxidation index, unsaturation index and calculated oxidability indices were assessed. The PUFA/SFA ratio is an index typically used to evaluate the influence of fats on cardiovascular health; a higher ratio indicates a better influence [17]. The atherogenicity index indicates the relationship between the total of saturated (excluding $C_{18:0}$) and unsaturated fatty acids. The thrombogenicity index shows the relationship between pro-thrombogenic ($C_{14:0}$, $C_{16:0}$ and $C_{18:0}$) and anti-thrombogenic fatty acids (monounsaturated fatty acids, n-3 and n-6 families) [18]. Consumption of oils with reduced atherogenicity and thrombogenicity index values exert an anti-atherogenic impact. The PUFA/SFA ratio ranged was between 0.73 (sweet orange) to 1.56 (kumquat) in the study. Consequently, the atherogenicity and thrombogenicity indexes' values were the lowest in kumquat and the highest in sweet orange. The atherogenicity index among citrus oils was recorded as follows: kumquat (0.32), lemon (0.41), limequat (0.50), pomelo (0.55), mandarin (0.56), bitter orange (0.56) and sweet orange (0.65). The thrombogenicity index was determined as kumquat (0.75), lemon (0.88), limequat (1.03), pomelo (1.16), bitter orange (1.17), mandarin (1.21) and sweet orange (1.40). These values were found to be higher than the results of the study conducted with different extraction methods for acid-lime (atherogenicity index: 0.36-0.42 and thrombogenicity index: 0.32-0.36) and sweet orange (atherogenicity index: 0.39-0.45 and thrombogenicity index: 0.44-0.51) [33]. The reason for this difference may be due to the extraction method and the selection of different types of solvents. Lipid peroxidation is a dynamic process characterized by the continuous production and degradation of compounds, necessitating precise measurement and evaluation of its extent. The higher the total PUFA value in an oil sample, the more sensitive it is to peroxidative damage [34]. The current study determined limequat, which exhibits the highest PUFA content, to have the highest peroxidation index value at 57.76. The unsaturation index indicates the level of unsaturation in oils and is determined by multiplying the proportion of unsaturated fatty acids by the number of bonds present in those fatty acids [17]. The index demonstrates the relative impact of both highly unsaturated fatty acids and those with a low degree of unsaturation.

Consequently, the unsaturation index serves as a criterion for assessing oils with high levels of PUFA content. The unsaturation index values indicate that the seven studied oils were ranked as follows: Kumquat (122.65) > limequat (120.82) > lemon (116.49) > bitter orange (108.73) > mandarin (106.33) > sweet orange (104.27) > pomelo (102.27). A high unsaturation index value signifies a substantial level of total unsaturation. These results were similar to the values reported by Garrido et al. [33] for acid-lime (130.07-132.32) and sweet orange (114.46-119.89). Calculated oxidability was determined based on the concentration of unsaturated C_{18} fatty acids

Table 3. Fatty acid composition (%) and lipid quality of different citrus seed oils.

Fatty acids[b] (%)			Bitter orange	Kumquat	Lemon	Limequat	Mandarin	Pomelo	Sweet orange
RT[a]	Nomenclature	SFA[c]							
17.631	C14:0	Myristic	0.13	-	0.17	0.13	0.11	0.14	0.15
21.087	C15:0	Pentadecanoic	0.03	-	0.04	-	-	0.03	0.04
26.024	C16:0	Palmitic	34.46	23.24	27.45	32.10	34.05	33.53	37.07
32.918	C17:0	Heptadecanoic	0.11	0.10	0.11	0.10	0.13	0.11	0.12
39.597	C18:0	Stearic	3.07	4.62	3.50	2.48	4.15	3.68	4.60
		Total SFA	37.79	27.95	31.26	34.80	38.44	37.50	41.98
		MUFA[d]							
27.647	C16:1	Palmitoleic	0.25	0.47	0.44	0.58	0.61	0.37	0.31
40.660	C18:1n9c	Oleic	22.58	27.79	30.21	19.90	20.94	27.47	20.27
48.545	C20:1n9	*cis*-11-eicosenoic	0.17	0.26	0.28	0.21	0.23	0.23	0.23
		Total MUFA	23.01	28.52	30.93	20.68	21.78	28.06	20.82
		PUFA[e]							
42.854	C18:2n6c	Linoleic	33.43	38.01	29.36	35.07	36.30	30.49	29.62
45.653	C18:3n6	Gama-linolenic	4.94	4.73	7.71	8.62	2.70	3.22	6.78
49.437	C18:3n6	Alfa-linolenic	0.06	-	-	-	0.05	0.06	0.06
59.679	C20:4n6	Arachidonic	0.37	0.42	0.38	0.44	0.35	0.33	0.40
67.811	C22:6n3	*cis*-4.7.10.13.16.19-docosahexaenoic	0.40	0.38	0.37	0.40	0.39	0.35	0.35
		Total PUFA	39.20	43.53	37.81	44.52	39.78	34.45	37.21
Nutritional quality									
PUFA/SFA			1.04	1.56	1.21	1.28	1.04	0.92	0.73
Atherogenicity index			0.56	0.32	0.41	0.50	0.56	0.55	0.65
Thrombogenicity index			1.17	0.75	0.88	1.03	1.21	1.16	1.40
Peroxidation index			48.66	52.87	50.01	57.76	46.82	41.83	48.21
Unsaturation index			108.73	122.65	116.49	120.82	106.33	102.27	104.27
Calculated oxidability			4.75	5.21	4.99	5.67	4.54	4.13	4.73

- : Not detected; [a]RT: Retention times in minutes; [b]Fatty acids are listed in order of elution on CP-WAX 52 CB column; [c]SFA: saturated fatty acids; [d]MUFA: monounsaturated fatty acids; [e]PUFA: polyunsaturated fatty acids according to Fatemi and Hammond [20]. The calculated oxidability value signifies the oil's propensity for autoxidation. The calculated oxidabilities of limequat, kumquat, lemon, bitter orange, sweet orange, mandarin and pomelo oils were found to be 5.67, 5.21, 4.99, 4.75, 4.73, 4.53 and 4.13, respectively. The oils with the highest oxidation values are the most susceptible to oxidation due to their higher amount of $C_{18:2}$ and $C_{18:3}$ [20]. In comparison, the calculated oxidability values were as follows: acid-lime and sweet orange (4.84-6.28), black cumin (6.6), grape (7.3), tomato (6.5) and wheat (7.8) seeds [33, 35, 36], demonstrating the relatively high oxidative stability of citrus seed oils. The lipid nutrient quality index ratios for citrus seeds in this investigation suggested nutritional acceptability.

Fatty acids are characterized by a long carbon chain that includes at least one carboxyl (–COOH, –CO_2H or –C(=O)OH) group, and they are categorized as either unsaturated or saturated based on the types of bonds present. The current study identified 13 fatty acids in the seeds of seven citrus species, with their distribution by quantity (Figure 2a). The fatty acids profile in citrus seeds significantly influences oxidative stability and nutritional value. Hierarchical clustering accompanied by a heat map was employed to determine the classification and correlation among citrus cultivars and fatty acids (Figure 2b). Citrus seed oils possess varying characteristics and can be categorized into three distinct classes accordingly. Mandarin, pomelo, and sweet orange were categorized together based on their similar concentrations of heptadecanoic, cis-4.7.10.13.16.19-docosahexaenoic, cis-11-eicosenoic and arachidonic acids. Kumquat and lemon were categorized in the second category, unlike the other samples, according to their amount of palmitic, palmitoleic, cis-4.7.10.13.16.19-docosahexaenoic, cis-11-eicosenoic, and oleic acids. Bitter orange and limequat possessed analogous fatty acid characteristics and formed a third category.

4. Conclusion

Citrus seeds, generated as waste from consumption and processing of fruits represent a significantly overlooked biological resource. This resource can be utilized in different industries to procure nutritious and healthful oil. Fatty acid composition and lipid quality affect final nutritional value of lipids. Research on the impact of lipid nutrient quality indices on fatty acid profiles in citrus seeds is scarce, yet use of seed oils as edible oils necessitates additional research for utilization of such oils. This study indicates that citrus seeds represent a promising source for edible oil production, as they possess high oil content comparable to other oleiferous seeds. Palmitic, oleic and linoleic acids constitute the main fatty acids among the citrus species examined. Kumquat and bitter orange seed oil can be a significant source to produce edible vegetable oils due to their high oil content and fatty acid compositions. On the other hand, these citrus species production is low according to other citrus species. In addition, since all citrus species contain high levels of palmitic, oleic and linoleic acids, they have a high potential for moisturizing and improving skin texture in cosmetic products, which may open more areas of use in this area. The results indicate that citrus seeds, rich in unsaturated fatty acids, provide a greater lipid nutrient value. PUFA/SFA ratio is a fundamental indicator that considers the total polyunsaturated fatty acids and total saturated fatty acids. The atherogenicity, thrombogenicity, peroxidation, unsaturation indexes and calculated oxidizability were derived based on PUFA/SFA ratios, considering the contribution of various molecular types of saturated fatty acids as well as mono- and poly-unsaturated fatty acids. Determination of lipid

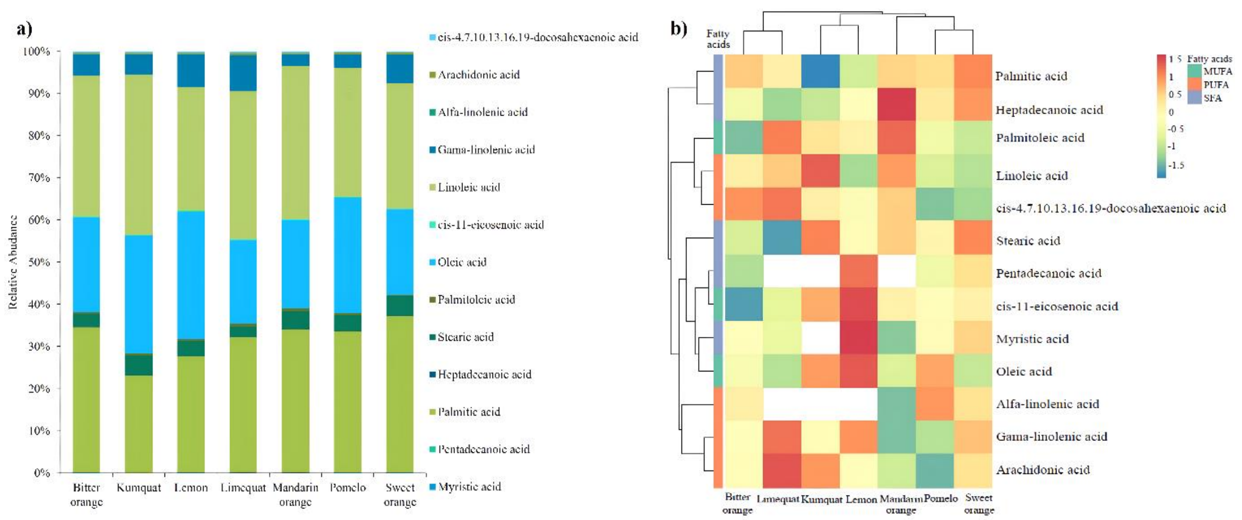

Figure 2. The ratios of 13 fatty acids detected in different citrus seed oils (a) and the heat map and dendrogram obtained by hierarchical clustering of fatty acid components (b). Red boxes indicate concentrations above average, blue boxes indicate lower concentrations, and white boxes indicate that the fatty acid component is not synthesized.

nutrient quality indices as a new approach to fatty acid analysis can help evaluate research materials more comprehensively. This study elucidated the significance of citrus seed oils. It is expected that Türkiye, which ranks 5th in the world for citrus fruit production, could recycle waste citrus seeds for the industry and that seed oil will become a resource for healthy edible oils and other value-added products.

Etik Beyanı/Declaration of Ethical Code

Bu çalışmada, "Yükseköğretim Kurumları Bilimsel Araştırma ve Yayın Etiği Yönergesi" kapsamında uyulması gerekli tüm kurallara uyulduğunu, bahsi geçen yönergenin "Bilimsel Araştırma ve Yayın Etiğine Aykırı Eylemler" başlığı altında belirtilen eylemlerden hiçbirinin gerçekleştirilmediğini taahhüt ederiz.

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