Nutritional and Phytochemical Characterization of Lemon Peel and Juice: Implications for Functional Food Applications

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Abstract

This study aimed to conduct a comprehensive comparative evaluation of lemon peel and lemon juice (Citrus limon L.) with respect to their proximate composition, mineral profile, vitamin content, total phenolic content, antioxidant activity, and individual flavonoid composition. Fresh lemons obtained from local Iraqi markets were manually processed, and analyses were performed using standard AOAC methods, atomic absorption techniques, and HPLC. The results revealed significant compositional differences between peel and juice fractions. Lemon peel exhibited higher levels of protein, fat, fiber, ash, and total carbohydrates compared to juice. Mineral analysis showed that peel samples contained greater concentrations of calcium, magnesium, potassium, copper, and zinc, indicating superior micronutrient density. Vitamin profiling demonstrated that lemon peel was richer in B-complex vitamins and fat-soluble vitamins (A, E, and K), whereas lemon juice contained higher levels of vitamin C. Total phenolic content was markedly higher in lemon peel (77) than in juice (45), which was reflected in stronger antioxidant activity (76.42 vs. 65.45, respectively). HPLC analysis identified hesperidin and naringenin as the predominant flavonoids in lemon peel, followed by other flavonoids in general. This confirms that the peel is a concentrated source of bioactive compounds with significant antioxidant and nutritional potential.. The valorization of lemon peel may contribute to functional food development and sustainable agro-industrial practices.

Keywords : Citrus limon, Lemon peel valorization, Total phenolic content, Flavonoid profiling, Antioxidant activity, HPLC analysis, Fat-soluble vitamins.

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Introduction

Citrus limon (L.) Burm. f. is one of the most economically important citrus species cultivated worldwide and represents a major component of the global fruit processing industry. Beyond its widespread culinary use, lemon has attracted increasing scientific interest due to its rich composition of bioactive compounds and micronutrients (1). Lemon juice is particularly valued for its high content of organic acids, primarily citric acid, vitamin C, simple carbohydrates, and essential minerals, contributing to both nutritional quality and functional properties (2). However, the nutritional and phytochemical potential of lemon extends beyond the juice fraction. Citrus processing generates substantial quantities of by-products, especially peels, which may constitute up to 40–50% of the total fruit weight. Traditionally regarded as agro-industrial waste, lemon peel has recently been recognized as a concentrated source of phenolic compounds, flavonoids, carotenoids, dietary fiber, pectin, essential oils, and mineral elements (3; 4). These phytochemicals are predominantly localized in the flavedo and albedo layers, where they function as protective metabolites against environmental stress and oxidative damage (1). The enrichment of such compounds in peel tissues suggests that citrus by-products may possess higher bioactive density than edible fractions. Oxidative stress, characterized by excessive production of reactive oxygen species (ROS), is strongly implicated in the pathogenesis of chronic disorders including cardiovascular diseases, diabetes, neurodegenerative diseases, and cancer. Consequently, the search for natural antioxidants derived from plant matrices has intensified, particularly as safer alternatives to synthetic additives (3). Total phenolic content (TPC), total flavonoid content (TFC), and detailed flavonoid profiling are widely employed as indicators of antioxidant potential, as these compounds exert radical-scavenging, metal-chelating, and redox-modulating activities (2; 1). In addition to phytochemicals, mineral composition significantly contributes to the nutritional and physiological value of citrus fruits. Macro- and microelements such as potassium, calcium, magnesium, iron, and zinc are essential for enzymatic function, electrolyte balance, and metabolic regulation. Nevertheless, mineral distribution within different fruit tissues remains insufficiently characterized in many citrus varieties (4). Despite the growing body of literature on citrus bioactive compounds, comparative investigations simultaneously evaluating proximate composition, mineral profile, water- and fat-soluble vitamins, total phenolics, antioxidant capacity, and individual flavonoid characterization between lemon peel and lemon juice remain limited. Most available studies focus on isolated fractions or specific compound classes rather than providing an integrated compositional assessment under standardized analytical conditions. Therefore, a comprehensive comparative evaluation is required to clarify the relative nutritional and functional value of lemon peel versus juice and to support evidence-based valorization of citrus processing by-products. Accordingly, the present study aims to perform an integrated chemical and phytochemical characterization of lemon peel and lemon juice, including proximate composition, mineral analysis, vitamin profiling, total phenolic content, antioxidant activity, and HPLC-based flavonoid identification. The findings are expected to provide scientific evidence supporting sustainable utilization strategies and functional food development based on lemon-derived materials.Despite the growing body of literature addressing citrus phytochemistry, comparative studies that systematically evaluate the chemical composition, mineral content, total phenolics, total flavonoids, and antioxidant activity of lemon peel and lemon juice under standardized analytical conditions remain limited. A direct comparison between these two fractions is essential to clarify their relative bioactive potential and to support the valorization of lemon peel as a high-value functional ingredient rather than a processing by-product. Accordingly, the present study aims to conduct a comprehensive comparative analysis of lemon peel and lemon juice, focusing on Chemical composition, mineral content, phenols, flavonoids, and antioxidant activity to assess their functional potential.

Materials and Methods

1. Materials and sample collection

imported lemon fruits (Citrus limon L.) were purchased from local retail markets in Iraq. Fruits showing uniform size, colour and absence of physical damage or spoilage were selected. All fruits were transported to the Food Science Laboratory at the College of Agriculture — Tikrit University on the same day of purchase for immediate processing (local handling and sources follow routine procedures described in regional studies on citrus by-products).

2. Sample preparation

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Washing and peeling: Fruits were washed thoroughly with potable water followed by distilled water rinse to remove surface debris. Peels were separated manually using stainless-steel knives. Juice extraction: The edible portion was hand-pressed (manual squeezing) to obtain fresh lemon juice; juice was filtered through muslin cloth to remove coarse pulp and stored at 4 °C in amber bottles prior to analysis (analyses performed within 48 h). Peel drying and powdering: Separated peels were spread in a single layer and dried in the shade (ambient laboratory conditions, ~25–30 °C) with good air circulation until constant weight (moisture stabilization). Dried peels were milled to a fine powder using a laboratory grinder and passed through a 0.5 mm sieve to obtain homogeneous peel powder. Powdered samples were stored in airtight, light-proof containers at room temperature until analysis. (Shade drying and powdered peel preparation follow procedures applied in Iraqi citrus peel studies).

3. Proximate (proximate composition) analyses

Proximate composition of lemon juice and peel powder was determined according to AOAC standard procedures: Moisture content: Determined by oven drying at 105 °C to constant weight (AOAC method). Crude protein: Determined by the Kjeldahl method; nitrogen × 6.25 reported as protein. Crude fat: Extracted by Soxhlet apparatus using petroleum ether (or hexane) and reported as % (w/w). Ash: Samples were incinerated in a muffle furnace at 550 ± 10 °C until white ash was obtained and weighed. Crude fiber: Determined by sequential acid/alkaline digestion (AOAC fiber method) (17). Total carbohydrates: Calculated by difference: All proximate determinations were carried out in triplicate and results reported as mean ± SD (AOAC methods are standard in the regional literature and were used in previous Tikrit studies).

4. Mineral (elemental) analysis

Mineral elements were estimated at the College of Engineering, University of Tikrit using the Automic system (Atomic Absorption Spectrophotometer (AAS, Shimadzu AA-6200, Japan) after wet digestion with nitric acid, following standard calibration procedures. in the faculty analytical facility). Sample preparation consisted of wet acid digestion: Wet digestion: Approximately 0.5–1.0 g dried

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sample (peel powder) or an aliquot of juice (after evaporation to dryness if needed) was digested with concentrated nitric acid (HNO□) and perchloric acid (HClO□) (or HNO□–H□O□ microwave/wet digestion depending on laboratory availability) until clear solution was obtained. Digests were cooled, filtered and diluted to a known final volume with deionized water. Instrumental determination: Elements quantified included K, Ca, Mg, Na, Fe (and others of interest) following instrument calibration against certified standards and blank corrections. Results were expressed as mg/100 g dry weight (for peel) or mg/100 mL (for juice) as appropriate. Instrumental analyses were performed according to the College of Engineering analytical protocols and manufacturer guidelines for the Automic system. Remark: Use of the College of Engineering facilities for mineral analysis (Automic) is consistent with prior analytical work performed in Tikrit University publications. (6)

5. Extraction procedures for phenolics, flavonoids and vitamins

5.1. Preparation of extracts

Phenolic/flavonoid extraction (polar fraction): For total phenolic and total flavonoid assays, 1.0 g of peel powder or a measured volume of juice equivalent to 1.0 g dry matter was extracted with 20 mL of 70% methanol (v/v) by sonication for 30 min (or stir extraction for 2 h) at room temperature. Extracts were centrifuged (4,000 rpm, 10 min) and supernatants collected(18). The residue was re-extracted once and the combined supernatants made up to a known volume. Water-soluble vitamins: Extracted using acidified aqueous solutions (e.g., 0.1 M HCl or phosphate buffer), protected from light and kept cold during extraction to prevent degradation. Fat-soluble vitamins and lipid-soluble flavonoids (if targeted): Extracted using n-hexane/ethyl acetate after saponification when necessary (for provitamin A, some carotenoids, and fat-soluble vitamins). Saponification (KOH in ethanolic solution) followed by partitioning into organic solvents was used to release esterified forms prior to HPLC analysis. All extracts were filtered through 0.45 μm PTFE or nylon syringe filters before chromatographic injection. The extraction schemes follow local protocols used in prior Tikrit studies and internationally accepted solvent systems for citrus matrices.

6. Total phenolic content (TPC) and total flavonoid content (TFC) assays

Total phenolic content (TPC): Determined by the Folin–Ciocalteu method (Singleton & Rossi principle(19)(18). Briefly, aliquots of extract were mixed with Folin–Ciocalteu reagent, followed by addition of sodium carbonate; after incubation, absorbance was measured at 765 nm. TPC was expressed as mg gallic acid equivalents (GAE) per 100 g sample. (This colorimetric method is widely used in citrus research and in regional publications.) Total flavonoid content (TFC): Determined by aluminum chloride colorimetric assay (sample mixed with AlCl□ reagent, incubated, and absorbance measured at 415 nm). Results expressed as mg quercetin equivalents (QE) per 100 g sample. Standard curves were prepared using authentic reference standards.

7. Antioxidant activity assays (recommended/used)

If antioxidant assays were performed, the following procedures (commonly used) were applied: DPPH radical scavenging assay: Aliquots of extracts at different concentrations were mixed with DPPH• methanolic solution; after 30 min in the dark, absorbance was measured at 517 nm and percent inhibition calculated. IC□□ values reported when applicable. (Method based on Brand-Williams). FRAP (Ferric Reducing Antioxidant Power) or ABTS assays: Optionally used to complement DPPH and provide broader antioxidant profiling. All assays performed in triplicate and results expressed as mean ± SD.(7).

If you performed specific antioxidant assays (e.g., DPPH or FRAP), I can insert the precise reagent concentrations, incubation times, and calculation formulas used. (8).

8. HPLC conditions for quantification of flavonoids and vitamins

Quantitative determination of individual flavonoids and vitamins (both water- and fat-soluble) was carried out by HPLC: Instrument: HPLC equipped with a reverse-phase C18 column and UV–Vis (or photodiode array) detector. Mobile phases: Typical gradients include (A) water with 0.1% formic acid (or 0.1% acetic acid) and (B) acetonitrile or methanol. Gradient program and flow rate (e.g., 1.0 mL/min) were optimized for separation of target analytes.

Injection volume: 10–20 µL.

Detection wavelengths: Selected according to analyte – e.g., 280 nm for phenolic acids, 340 nm for flavonoids, and specific wavelengths for vitamins (e.g., 254, 280, 330 nm as appropriate). Identification and quantification: Based on comparison of retention times and spectral data with authenticated standards; quantification by external calibration using standard curves. Results expressed as mg per 100 g sample (dry weight) or mg per 100 mL for juice. (Exact HPLC gradient programs and column specifications can be inserted if you provide the brand/model of your instrument and standards used; methods follow HPLC practice used in regional food analysis studies). (9).

9. Replication and statistical analysis

All analyses were performed in triplicate (n = 3) for each sample type. Data are presented as mean ± standard deviation. Statistical comparisons between peel and juice values were performed using one-way analysis of variance (ANOVA) followed by Tukey's post-hoc test to identify significant differences at $p \leq 0.05$. Statistical analyses were conducted using SPSS (version X) or similar statistical software.

10.Results and Discussion

The proximate composition analysis revealed statistically significant differences ($p \leq 0.05$) between lemon peel and lemon juice in all measured parameters (Table 1).

Moisture

Lemon juice exhibited a significantly higher moisture content (90.63%) compared to lemon peel (7.02%). This finding is consistent with previous reports indicating that fresh citrus juices contain more than 85–90% water due to their physiological role in nutrient transport and metabolic activity (16). In contrast, the low moisture content of dried lemon peel enhances its storage stability and reduces microbial susceptibility, which supports its potential application as a shelf-stable functional ingredient (10).

Fat

The fat content of lemon peel (11.49%) was significantly higher than that of lemon juice (1.04%). Citrus peels are known to contain essential oils and lipid-soluble bioactive compounds, particularly limonene, concentrated in the flavedo layer (11). Similar trends were observed by (10), who reported that citrus processing by-products possess higher lipid fractions compared to the edible juice portion.

Crude Protein

Lemon peel showed a higher protein content (6.73%) compared to lemon juice (2.57%). Although citrus fruits are not considered rich protein sources, structural and enzymatic proteins are primarily located in the

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outer tissues, explaining the higher concentration in peel fractions (12). Comparable protein ranges in citrus peels have been documented in previous compositional studies (13).

Ash

Ash content, which reflects total mineral matter, was higher in lemon peel (3.80%) than in lemon juice (3.06%). This result agrees with earlier findings indicating that citrus peels accumulate higher concentrations of minerals such as potassium, calcium, and magnesium due to their structural role in plant tissues (11). The mineral richness of peels enhances their nutritional and technological value in food fortification applications.

Fiber

A significant difference was also observed in crude fiber content, where lemon peel (4.78%) greatly exceeded lemon juice (1.08%). Citrus peel is widely recognized as a valuable source of dietary fiber and pectin, mainly composed of cellulose, hemicellulose, and soluble polysaccharides (14). The high fiber content supports the utilization of lemon peel in developing functional foods aimed at improving digestive health and glycemic control.

Total Carbohydrates

Total carbohydrate content was markedly higher in lemon peel (65.83%) compared to lemon juice (1.45%). The elevated carbohydrate percentage in peel is attributed to structural polysaccharides and pectic substances concentrated after drying. Similar compositional patterns have been reported in comparative citrus studies (13; 16).

General Interpretation

Overall, the findings demonstrate that lemon peel possesses significantly higher nutrient density than lemon juice in terms of dry matter components, including protein, fat, fiber, ash, and carbohydrates. These results align with the growing scientific consensus that citrus by-products should be valorized as functional ingredients rather than treated as waste (10; 14). The compositional superiority of lemon peel supports its potential incorporation into nutraceutical formulations and sustainable food systems.

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Table 1 represents the difference in the chemical composition of lemon juice and its peel at the level of P≤0.05.

Carbohydrates%	Fiber%	Ash%	Protein%	Fat%	Moisture%	Transactions
65.83 a	**4.78 a**	**3.80 a**	**6.73 a**	**11.49 a**	**7.02 b**	lemon peels
1.45 b	**1.08 b**	**3.06 b**	**2.57 b**	**1.04 b**	**90.63 a**	lemon juice

11.Mineral Composition: Results and Discussion

The mineral profile of lemon peels and lemon juice (Table 2) demonstrated noticeable quantitative differences between the two fractions, confirming that mineral distribution in citrus fruits is not uniform across tissues.

Magnesium (Mg)

Magnesium concentration was substantially higher in lemon peels (15.73 ppm) compared to lemon juice (5.52 ppm). Magnesium is an essential cofactor in numerous enzymatic reactions and plays a critical role in energy metabolism and antioxidant defense systems. The higher Mg content in peel tissues may be attributed to its structural involvement in cell wall stabilization and metabolic processes occurring in outer fruit layers. Similar findings were reported by (11), who observed that citrus peels contain significantly higher levels of macro- and microelements than juice fractions. Comparable trends were also documented in citrus mineral profiling studies by (13).

Copper (Cu)

Copper levels were markedly higher in lemon peels (2.66 ppm) than in lemon juice (0.37 ppm). Copper is a trace element essential for redox reactions and functions as a component of antioxidant enzymes such as superoxide dismutase. The higher concentration in peels may reflect the localization of oxidative defense mechanisms in outer tissues exposed to environmental stress (14). This observation agrees with previous research indicating that citrus by-products accumulate higher trace mineral levels compared to edible juice portions (10).

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Zinc (Zn)

Zinc content followed a similar pattern, with peels (0.88 ppm) showing greater concentrations than juice (0.22 ppm). Zinc plays a crucial role in immune function, DNA synthesis, and antioxidant protection. The enrichment of Zn in peel tissues may be linked to its participation in enzymatic systems associated with stress tolerance and tissue integrity (12). Comparable distributions of zinc in citrus fractions have been reported in mineral composition studies (11).

Calcium (Ca)

Calcium was significantly higher in lemon peels (117.74 ppm) compared to lemon juice (6.90 ppm). Calcium is a major structural component of plant cell walls, particularly in the form of calcium pectate within the middle lamella. Therefore, its elevated concentration in peel tissue is physiologically expected. Similar findings were reported by (16), who demonstrated that citrus peels contain substantially higher Ca concentrations than juice due to their structural function. The high calcium content further enhances the technological value of lemon peel in food fortification and pectin extraction processes (14).

Potassium (K)

Potassium was the predominant mineral detected in both samples, with higher levels in peels (158.06 ppm) than in juice (132.26 ppm). Potassium is the principal intracellular cation in plant tissues and plays a vital role in osmotic regulation and metabolic processes. Although citrus juice is known to be rich in potassium, several studies have indicated that peels may contain comparable or even higher concentrations due to cellular density and reduced dilution effects (13; 11). The high potassium content in both fractions highlights their nutritional contribution to electrolyte balance in human diets.

Sodium (Na)

Sodium concentrations were relatively low in both fractions; however, peels (5.52 ppm) exhibited higher levels than juice (0.97 ppm). Citrus fruits are generally considered low-sodium foods, which makes them suitable for sodium-restricted diets (10). The slightly higher Na value in peel tissue may be attributed to mineral accumulation in peripheral fruit layers.

Overall Interpretation

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The mineral composition results clearly indicate that lemon peel possesses a higher concentration of most essential macro- and microelements compared to lemon juice. This pattern reflects the structural and protective roles of the peel in plant physiology, where minerals are involved in cell wall formation, enzymatic defense systems, and environmental stress responses. These findings are consistent with previous reports emphasizing that citrus processing by-products, particularly peels, represent valuable sources of essential minerals and should be valorized within sustainable food systems rather than discarded as waste (14; 10). From a nutritional perspective, the elevated levels of calcium, magnesium, potassium, and trace elements in lemon peel support its potential application as a functional ingredient in mineral-enriched food products and nutraceutical formulations.

Table 2 represents the mineral content of lemon peels and juice.

Na (ppm)	K (ppm)	Ca (ppm)	Zn (ppm)	Cu (ppm)	Mg(ppm)	Transactions
5.516935	**158.0645**	**117.7419**	**0.876613**	**2.658587**	**15.72581**	lemon peels
0.967742	**132.2581**	**6.895161**	**0.222581**	**0.365905**	**5.524194**	lemon juice

12.Total Phenolic Content and Antioxidant Activity: Results and Discussion

The results demonstrated that lemon peels exhibited higher total phenolic content (77) compared to lemon juice (45). Similarly, antioxidant activity was greater in lemon peels (76.42) than in lemon juice (65.45). These findings clearly indicate that lemon peel possesses a stronger antioxidant potential than the juice fraction.

Total Phenolic Content (TPC)

Phenolic compounds are secondary plant metabolites known for their strong reducing properties and free radical scavenging capacity. The significantly higher TPC observed in lemon peel is consistent with the structural and protective role of outer fruit tissues. Citrus peels are known to accumulate phenolic acids, flavanones (such as hesperidin and eriocitrin), and polymethoxylated flavones, which function as defense molecules against environmental stressors (11).
(13) reported that citrus peel contains

considerably higher phenolic concentrations than pulp or juice due to the localization of phenolic biosynthesis pathways in epidermal tissues. Similarly, (14) emphasized that citrus processing by-products are rich reservoirs of phenolic compounds and should be valorized as functional ingredients. The elevated phenolic content in lemon peel observed in the present study may also be associated with the drying process, which reduces moisture content and consequently concentrates bioactive compounds on a dry weight basis.

Antioxidant Activity

The antioxidant activity followed a similar trend, with lemon peel (76.42) exhibiting stronger radical scavenging capacity compared to lemon juice (65.45). This result is expected, as antioxidant activity in citrus fruits is strongly correlated with phenolic concentration (16). Several studies have confirmed a positive correlation between total phenolic content and antioxidant capacity in citrus species (11; 13). Phenolic hydroxyl groups donate hydrogen atoms to neutralize free radicals, thereby reducing oxidative stress. The higher antioxidant value of lemon peel in the present study reflects its enriched composition of phenolics, flavonoids, and fat-soluble antioxidant vitamins such as vitamin E. In addition, the synergistic interaction between vitamin C (abundant in juice) and phenolic compounds (concentrated in peel) may enhance overall antioxidant effectiveness (14). However, since peel exhibited higher phenolic density, its overall antioxidant capacity surpassed that of juice.

Integrated Interpretation

The combined results of phenolic content and antioxidant activity confirm that lemon peel represents a superior source of natural antioxidants compared to lemon juice. These findings align with the growing scientific consensus that citrus by-products contain concentrated bioactive compounds with significant health-promoting properties (10). From a functional food perspective, the high antioxidant potential of lemon peel supports its application in nutraceutical development, food preservation systems, and natural antioxidant formulations. Moreover, the valorization of lemon peel contributes to waste reduction and sustainable food processing strategies, reinforcing circular economy principles in agro-industrial systems.

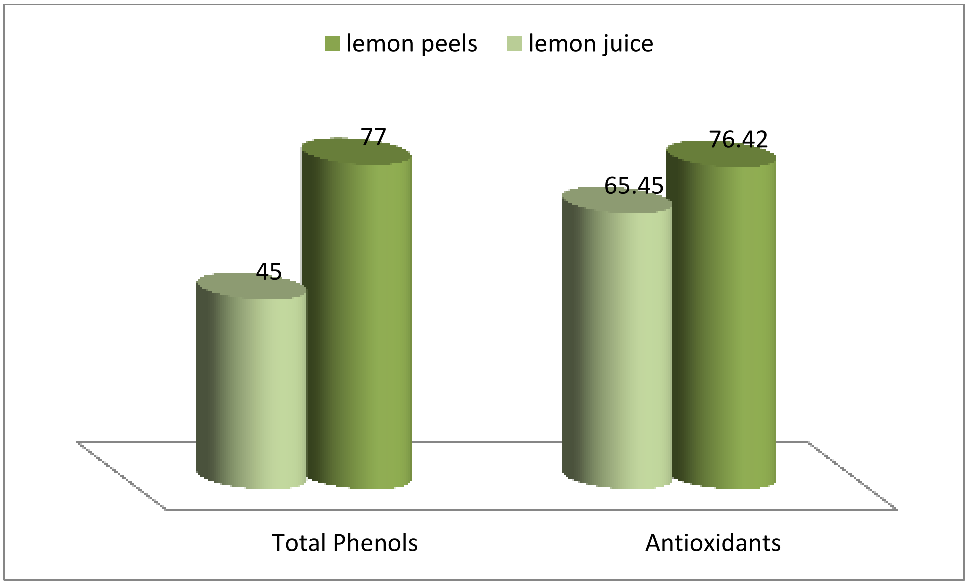

Figure 1 of antioxidants and total phenols

Vitamin C (Ascorbic Acid)

Vitamin C content was higher in lemon juice (391.297) compared to lemon peels (301.230). This finding is consistent with the well-established role of citrus juice as a primary source of ascorbic acid. Vitamin C is predominantly located in the vacuoles of juice vesicles, where it functions as a key antioxidant and protective molecule against oxidative stress (11). Similar concentrations of vitamin C in citrus juices have been reported by (16), who confirmed that juice fractions generally exhibit higher ascorbic acid levels compared to outer tissues. However, the substantial amount detected in lemon peels in the present study highlights that peel tissues also serve as important reservoirs of antioxidant vitamins, likely contributing to protective defense mechanisms against environmental stress and UV exposure (13).

Vitamin B9 (Folic Acid)

Lemon peels (5.385) contained higher levels of vitamin B9 compared to juice (1.999). Folate plays a critical role in DNA synthesis and cellular metabolism. The elevated concentration in peel tissues may reflect the presence of metabolically active cells involved in growth and structural maintenance. Similar distribution patterns have been observed in plant tissues where folates

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are concentrated in actively dividing or structurally protective regions (14).

Vitamin B7 (Biotin)

Biotin was detected in lemon juice (1.018) but was not detected in peel samples. Biotin is involved in carboxylation reactions and energy metabolism. The absence in peel samples may be related to lower metabolic turnover in dried tissues or possible degradation during shade drying, as biotin can be sensitive to environmental conditions (15).

Vitamin B6 (Pyridoxine)

Vitamin B6 concentration was markedly higher in lemon peels (10.572) than in juice (0.669). Pyridoxine functions as a coenzyme in amino acid metabolism and antioxidant defense. The higher level in peel tissue may be associated with its role in stress-response pathways and enzymatic reactions occurring in structurally active plant layers (12). This enrichment enhances the nutritional potential of lemon peel as a functional ingredient.

Vitamin B5 (Pantothenic Acid)

Pantothenic acid was significantly higher in lemon peels (20.995) compared to lemon juice (3.478). Vitamin B5 is a precursor of coenzyme A, essential for fatty acid metabolism and energy production. Its higher concentration in peel tissues may correlate with lipid-associated metabolic processes occurring in the flavedo layer, where essential oils and lipid-soluble compounds are abundant (10).

Vitamin B2 (Riboflavin)

Vitamin B2 was detected in lemon peels (8.390) but was not clearly detected in juice samples. Riboflavin is crucial for oxidative metabolism as a precursor of FAD and FMN coenzymes. The higher concentration in peel tissues may be linked to mitochondrial density and oxidative enzymatic systems in outer plant layers (15).

Vitamin B1 (Thiamine)

Thiamine content was substantially higher in lemon peels (15.662) than in lemon juice (0.455). Thiamine plays a fundamental role in carbohydrate metabolism and energy production. Its concentration in peel tissues may reflect higher enzymatic and structural metabolic requirements compared to juice vesicles (13).

General Interpretation

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The vitamin profile demonstrates a clear nutritional differentiation between lemon peel and juice fractions. While lemon juice remains the dominant source of vitamin C, lemon peel exhibited significantly higher concentrations of most B-complex vitamins (B1, B5, B6, B9, and B2). These findings align with previous reports emphasizing that citrus by-products, particularly peels, contain concentrated micronutrients and bioactive compounds that are often underutilized (14; 10). From a functional food perspective, the elevated levels of B-complex vitamins in lemon peel enhance its value as a potential nutraceutical ingredient. Moreover, the coexistence of vitamin C and B vitamins suggests possible synergistic antioxidant and metabolic benefits, reinforcing the importance of valorizing citrus processing residues within sustainable food systems.

Table 3 shows the Water-soluble vitaminsof lemon peels and juice.

Vitamin B1	Vitamin B2	Vitamin B5	Vitamin B6	Vitamin B7	Vitamin B9	Vitamin C	Transactions
15.662	**8.390**	**20.995**	**10.572**	**-**	**5.385**	**301.230**	lemon peels
0.455	**-**	**3.478**	**0.669**	**1.018**	**1.999**	**391.297**	lemon juice

Fat-Soluble Vitamins: Results and Discussion

The HPLC analysis of fat-soluble vitamins revealed markedly higher concentrations in lemon peels compared to lemon juice (Table 4), indicating that lipid-associated micronutrients are predominantly localized in the outer tissues of the fruit.

Vitamin A

Vitamin A content was substantially higher in lemon peels (54.607) than in lemon juice (0.857). This significant difference may be attributed to the presence of carotenoids in the flavedo layer of citrus peels. Carotenoids, which function as provitamin A compounds, are lipid-soluble pigments concentrated in chromoplasts of outer fruit tissues and contribute to both coloration and antioxidant protection (11). (13) reported that citrus peels contain higher levels of carotenoid-derived

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compounds than juice fractions due to their role in photoprotection and oxidative stress mitigation. Therefore, the elevated vitamin A value in lemon peel observed in the present study is consistent with previous phytochemical investigations.

Vitamin E

Vitamin E showed the highest concentration among the fat-soluble vitamins analyzed, with lemon peels (109.905) containing dramatically higher levels than lemon juice (1.843). Vitamin E (tocopherols and tocotrienols) is a powerful lipid-phase antioxidant that protects cellular membranes against lipid peroxidation. The flavedo and albedo layers of citrus fruits are known to accumulate tocopherols as part of the plant's defense system against oxidative damage caused by environmental exposure (10). Similar trends were documented by (14), who emphasized that citrus by-products are richer in lipid-soluble antioxidants than edible juice portions. The remarkably high vitamin E content in lemon peel enhances its nutraceutical value and supports its potential use in functional food formulations aimed at oxidative stress reduction.

Vitamin K

Vitamin K concentration was also considerably higher in lemon peels (12.636) compared to lemon juice (0.209). Vitamin K is associated with plant chloroplast membranes and plays a role in photosynthetic electron transport (phylloquinone). Because peel tissues are more structurally complex and closer to photosynthetically active plant tissues during development, higher accumulation in peel fractions is physiologically plausible (15). Previous studies have indicated that lipid-soluble micronutrients tend to accumulate in structurally protective tissues rather than aqueous compartments such as juice vesicles (11).

Overall Interpretation

The results clearly demonstrate that lemon peel is a significantly richer source of fat-soluble vitamins than lemon juice. This distribution pattern reflects the biochemical and structural localization of lipid-associated compounds within citrus fruit tissues.

The high concentrations of vitamins A and E in particular suggest that lemon peel possesses strong antioxidant potential within lipid environments, complementing its previously reported phenolic and flavonoid content (14; 10). From a functional and industrial perspective, these findings reinforce the importance of valorizing lemon peel as a high-value by-product in food fortification,

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nutraceutical production, and sustainable processing systems. The presence of substantial levels of lipid-soluble antioxidants further supports its application in formulations aimed at improving oxidative stability and nutritional quality.

Table 4shows the fat-soluble vitamins in lemon peel and juice.

Vitamin E	Vitamin A	Vitamin K	Transactions
109.905	**54.607**	**12.636**	lemon peels
1.843	**0.857**	**0.209**	lemon juice

Individual Flavonoids Profile: Results and Discussion

The HPLC analysis revealed a markedly higher concentration of individual flavonoids in lemon peels compared to lemon juice (Table X), confirming that citrus peel represents the primary reservoir of flavonoid compounds.

Hesperidin

Hesperidin was the predominant flavonoid detected in both samples, with a substantially higher concentration in lemon peels (368.291) compared to lemon juice (105.506). Hesperidin is a major flavanone glycoside in citrus species and is known for its antioxidant, anti-inflammatory, and cardioprotective properties (11). The significantly elevated level in peel tissue aligns with previous reports indicating that hesperidin accumulates mainly in the flavedo and albedo layers rather than in juice vesicles (14). This localization reflects its protective function against environmental stress and oxidative damage.

Naringenin

Naringenin concentration was also markedly higher in lemon peels (213.444) than in juice (8.373). Naringenin is a flavanone with strong antioxidant and anti-inflammatory activity. Citrus peels are known to contain higher concentrations of flavanones compared to juice fractions due to their involvement in plant defense mechanisms (13). The difference observed in the present study is consistent with (16), who reported that citrus peel extracts show

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significantly higher flavanone content compared to juice.

Quercetin

Quercetin levels were significantly higher in lemon peels (52.504) compared to juice (5.403). Quercetin is a potent antioxidant flavonol widely distributed in plant outer tissues. Its accumulation in peel tissues is attributed to its role in UV protection and oxidative stress resistance (14). Similar distribution patterns have been documented in citrus phytochemical studies (11).

Rutin

Rutin concentration was also substantially higher in lemon peels (100.397) than in juice (10.767). Rutin, a glycosylated form of quercetin, exhibits strong antioxidant and vascular protective effects. Previous investigations have emphasized that rutin is primarily concentrated in citrus peels rather than pulp or juice (13).

Apigenin and Luteolin

Apigenin and luteolin followed the same trend, with significantly higher concentrations in lemon peel (16.300 and 13.871, respectively) compared to juice (3.990 and 2.140). These flavones contribute to antioxidant activity and possess anti-inflammatory and antimicrobial properties. Their higher presence in peel tissue supports the concept that outer plant layers synthesize and accumulate phenolic compounds as protective phytochemicals (11).

Integrated Interpretation

The collective results demonstrate that lemon peel contains substantially higher concentrations of all identified flavonoids compared to lemon juice. This enrichment directly explains the higher total phenolic content and antioxidant activity previously observed in peel samples. Flavonoids contribute significantly to radical scavenging capacity through hydrogen donation, metal chelation, and modulation of oxidative enzymes (14). The dominance of hesperidin and naringenin in lemon peel further enhances its functional and nutraceutical value. From an applied perspective, these findings strongly support the valorization of lemon peel as a high-value source of bioactive flavonoids suitable for incorporation into functional foods, dietary supplements, and natural antioxidant formulations. The results are consistent with the growing body of literature highlighting citrus by-products as sustainable and economically valuable resources (10).

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Table 5 of flavonoids in lemon peel and juice

LUTEOLIN	RUTIN	QUERETIN	HESPERIDN	NARINGENIN	APIGENIN	Transactions
13.871	**100.397**	**52.504**	**368.291**	**213.444**	**16.300**	lemon peels
2.140	**10.767**	**5.403**	**105.506**	**8.373**	**3.990**	lemon juice

Conclusion

The present study provided a comprehensive comparative evaluation of lemon peel and lemon juice in terms of proximate composition, mineral content, water- and fat-soluble vitamins, total phenolic content, antioxidant activity, and individual flavonoid profile. The results clearly demonstrated that lemon peel possesses significantly higher nutritional density than lemon juice in most evaluated parameters, particularly in protein, fat, fiber, ash, and total carbohydrates. Mineral analysis revealed that peel samples contained greater concentrations of essential macro- and microelements, including calcium, magnesium, potassium, copper, and zinc, reflecting the structural and physiological roles of outer fruit tissues. HPLC analysis further confirmed that lemon peel is substantially richer in both water-soluble B-complex vitamins and fat-soluble vitamins (A, E, and K), while lemon juice remained the primary source of vitamin C. The elevated levels of lipid-soluble antioxidants, especially vitamin E, enhance the oxidative stability potential of peel-derived ingredients. Moreover, lemon peel exhibited markedly higher total phenolic content and antioxidant activity compared to lemon juice. The detailed flavonoid profiling revealed that hesperidin and naringenin were the dominant compounds, followed by rutin, quercetin, apigenin, and luteolin, all of which were significantly more concentrated in peel tissues. These compounds collectively contribute to the superior antioxidant capacity observed in lemon peel. Overall, the findings highlight that lemon peel, often considered an agro-industrial by-product, represents a highly valuable source of bioactive compounds with strong antioxidant and nutritional potential. The valorization of lemon peel in functional food development,

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nutraceutical applications, and natural antioxidant formulations could contribute to sustainable processing strategies and circular bioeconomy systems. Future research should focus on bioavailability studies, extraction optimization, and the incorporation of lemon peel powder or extracts into food systems to further explore its technological and health-promoting potential.

Recommendations

We recommend further advanced analyzes of lemon peels to identify active compounds and assess their biological and nutritional efficacy. Research should be conducted on the safety and appropriate dosages of lemon peel extract as a dietary supplement, and the use of lemon peels as a natural functional source of active compounds (phenols, flavonoids, antioxidants, and vitamins) that surpass those found in the juice should be promoted.

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