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PHYTOCHEMICAL COMPOSITION AND THERAPEUTIC EFFICACY OF *CITRUS LIMON*: A REVIEW

Kashaf ul Khair [1], Zunaira Khalid [1], Muhammad Ahmad [2]* and Muhammad Mazhar Ali [3]

[1]Department of Botany, The University of Lahore, Sargodha Campus, 40100, Sargodha, Pakistan
[2]Department of Plant Breeding and Genetics, University of Agriculture, Faisalabad, 38040, Pakistan
[3]Institute of Horticultural Sciences, University of Agriculture, Faisalabad, 38040, Pakistan

*Corresponding author: ahmaduaf2013@gmail.com

ABSTRACT

The citrus fruit, known as lemon (*Citrus limon*), is widely cultivated for its numerous medicinal and nutritional benefits. Vitamins C and B, potassium, and flavonoid phytochemicals that give lemons their anti-inflammatory, antioxidant, antibacterial, and anticancer properties are among the essential nutrients found in abundance in lemons. About 17 constituents were found in the lemon peel essential oil, primarily limonene (68.65%) and γ-terpinene (10.81%). Similarly, the orange peel essential oil contained eight components, primarily limonene (95.51%) and β-myrcene (1.98%). Citrus acid, polyphenols, terpenes, limonene, flavonoids, vitamin C, sugar, pectin, citric acid, malic acid, carotenoids, terpineol, filander, compendium, citrine, calcium oxalates, and mucilage are among the many phytochemicals found in its fruit. In addition to substantial levels of aldehydes (citral), alcohols (linalool), and esters (coumarin), lemon oil is primarily composed of 70% limonene and 20% monoterpenes. Flavonoids, glycosides, coumarins, beta, gamma, and gamma steroids, as well as volatile oils, are all found in high amounts in lemon peel and are essential for proper growth and overall health. The fruit's peels, which are sometimes discarded, are a rich source of essential oils and polyphenols with a variety of health benefits, and their high citric acid content aids digestion and enhances flavor. These components highlight the lemon's role as a functional food with strong therapeutic potential by demonstrating preventive effects against conditions such as diabetes, cancer, and cardiovascular disease. The goal of the current study was to review the phytochemical composition, nutritional value, and medicinal applications of *Citrus limon* (lemon).

***Keywords*:** Antioxidant activity, Citrus limon, Citrus-derived product, Citrus peel, Nutritional properties, and Traditional use.

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1. INTRODUCTION

The genus Citrus belongs to the family of citrus fruits. Additionally, the term "citrus" is often used to refer to various citrus fruits (Russo et al., 2021). The lemon, scientifically known as *Citrus limon*, is commonly called *Nimbu* in Hindi, *Limon* in English, *Nimbuka* in Sanskrit, and *Goodiya* in Gujarati. Across the world, many species of this genus are grown for their fruits, and as consumer demand has increased, annual fruit production has risen (Mahato et al., 2019; Suri et al., 2022; Noor et al., 2024). Citrus fruits are very common worldwide, and large-scale industrial juice and food manufacturing produces many by-products (Imeneo et al., 2022). Citrus fruit peels, pulp, and seeds typically contain beneficial compounds that can be separated and used as natural antioxidants (Putnik et al., 2017). These antioxidants can be added to functional food products or used to stop specific foods from oxidizing and to enhance shelf life and nutritional value (Abd El-ghfar et al., 2016; Russo et al., 2021).

1.1. Decoding Spatial Distribution

The Mediterranean regions of Europe and North Africa, the Americas, South Africa, Australia, and the tropical and subtropical regions of Southeast Asia are the primary growing regions for them due to favorable climatic conditions, including temperature, rainfall and soil suitability (Mahato et al., 2019; Suri et al., 2022). Specifically, the world's output of CF for 2020–2021 is expected to reach 98 million tons, with the United States (USA), China, Brazil, and the European Union being the primary producers and contributors to global citrus trade and processing industries (FAO, 2021; Russo et al., 2021).

Over 40% of the eleven million metric tons of CF exported globally are oranges, and over 30% are mandarins, reflecting their higher market demand and extended shelf life (Gmitter et al., 2012; Suri et al., 2022). South Africa

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is the top exporter of CF, followed by Egypt, Turkey, and the United States, owing to advanced post-harvest handling and export-oriented production systems (Siddique & Garnevska, 2018; Mahato et al., 2019). The world's orange output has climbed to 48.6 million tons over the past two years, while the production of mandarins, grapefruits, and lemons has also increased to 33.3 million tons for 2020–2021, indicating a steady expansion of citrus cultivation worldwide (FAO, 2021; Suri et al., 2022).

1.2. Citrus production in Pakistan

Citrus fruit has been grown mostly in four provinces in Pakistan: Sindh, Punjab, Khyber Pakhtunkhwa (KPK), and Baluchistan due to favorable agro-climatic conditions and long-established horticultural practices (Mahato et al., 2019; Suri et al., 2022). Punjab, out of the four provinces, is thought to be the center of citrus production as shown in Table 1 (Siddique & Garnevska, 2018), contributing the largest share to national citrus yield and export volume (Rafique et al., 2020). According to PHDECo (2005), KPK produces the majority of the nation's oranges, whereas Punjab province accounts for over 90% of all kinnow output (Siddique & Garnevska, 2018), highlighting the economic importance of citrus cultivation for rural livelihoods and export earnings (Nawaz et al., 2021; Suri et al., 2022).

Table 1: Pakistan's Principal Citrus Growing Regions

Districts	Main Provinces
KPK (Khyber Pakhtunkhwa)	Haripur, Nowshera, Lower Dir, Mardan, Dera Ismail Khan, Malakand and Swat
Punjab	Sahiwal, Faisalabad, Sargodha, Khanewal, Vehari, Multan, Okara, Layyah, Jhang, Kasur, Toba Tek Singh, Bahawalpur and Mandi Bahauddin.
Baluchistan	Dolan, Lasbela, Nasirabad, Gwadar and Sibi.
Sindh	Khairpur, Nawabshah, Sukkur, Sanghar and Naushero Feroze.

1.3. *Citrus limon*

A notable citrus fruit belonging to the Rutaceae family is the lemon, as displayed in Table 2 (Khaledian et al., 2021), which is widely cultivated for both fresh consumption and industrial processing (Mahato et al., 2019; Russo et al., 2021). An estimated 143 million tonnes of Khaledians are produced annually, with oranges (*Citrus sinensis* L.) accounting for 76 million tons, mandarins (*Citrus reticulata* L.) for 37 million tons, Limon (*Citrus limon*), and limes (*Citrus aurantifolia*) for 20 million tons being the most important (Suri et al., 2022). Because of their delicious flavor and recognized health benefits like anti-oxidative, anti-inflammatory, anti-infective, anti-cancer, and neuroprotective qualities, citrus fruits (CF) are the most widely grown, processed, and consumed fruits worldwide (Cirmi et al., 2017; Mandalari et al., 2017), with lemon receiving particular attention due to its rich phytochemical profile and medicinal applications (Rizaldy et al., 2022; Haida et al., 2022).

Table 2: Classification of Lemon

Kingdom	Plantae
Class	Rosids
Order	Sapindales
Family	Rutaceae
Genus	Citrus
Species	*C. limon*

1.4. *Citrus limon* around the World

Large amounts of citrus fruit are produced in China, India, the United States, Pakistan, Japan, Korea, and Spain, although Brazil is the world's largest producer of citrus fruit (Mahato et al., 2019; Gonzatto & Santos, 2023; Mukhametzyanov et al., 2023). Spain, Brazil, India, China, and the United States of America are the top producers of citrus fruits. Pakistan is ranked 13th, in contrast. More than thirty different fruit varieties are produced in Pakistan; citrus dominates the market, accounting for over 30% of the country's total fruit production (Siddique & Garnevska, 2018). Punjab is one of Pakistan's five provinces that contribute significantly in both territory and output (Siddique & Garnevska, 2018). Citrus worth billions of dollars are shipped from Pakistan to several countries each year. In Punjab Province, citrus is primarily grown in the districts of Sargodha and Bhalwal. Every year, Pakistan exports over 0.44 million tons of citrus, worth about 166 million USD (Hammad et al., 2024; Nawaz et al., 2024).

1.5. Tracing Lemon's Roots: The History and Origin

Although the origins of the Limon are unknown, it is thought that the original lemons were grown in China, northern Burma, or Assam in northeastern India. According to a study on the genetic origins of Limon, it is a hybrid of bitter and sour oranges. With 1.2 million tons produced, Argentina is currently the world's largest lemon producer. Limon contains significant amounts of vital natural ingredients, including minerals, flavonoids, citric acid, essential oils, and ascorbic acid (Makni et al., 2018). Because of the alkaloid component found in several sections of lemons, including the leaves, stem, roots, and flowers, lemon has anticancer and antibacterial properties (Dhanavade et al., 2011). Among the various types of lime are Avon, Berna, Baboon, Bears, and Cameron.

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1.6. The Botanical Details of *Citrus limon*

Fruits from round to oblong in shape and size are produced by citrus trees, which are evergreen and bursting with flavor, scent, and juice (Okwu, 2008). Lemon leaves are dark green as Fig. 1 illustrates ranging in size from 6.5 to 10 mm, and they are distributed sporadically on the stem. In Limon, there are five fragrant white petals as shown in Fig. 1. The lemon flower is bisexual and male, and its pulp has a strong acidic content. The lemon cultivar known as "Pink Lemonade" is where the lemon blossom is derived. This cultivar has variegated foliage and striped fruit. Typically, limon has an oval form and a smooth, porous surface (Zhao, 2007). Lemons come in a variety of sizes and forms; some resemble grapefruits, while others are slightly larger. When a limon reaches its maximum size, it no longer exhibits its characteristic greenish-yellow color and instead displays a dazzling yellow color. The fruit known as floppies contains tiny seeds (Gamarra et al., 2006).

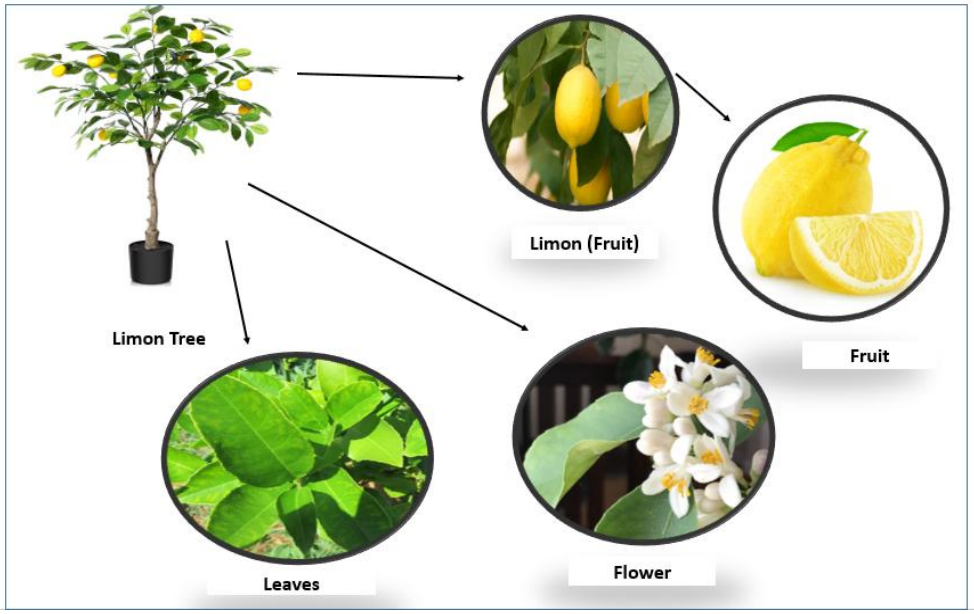

Fig. 1: Morphological features of *C. limon*: trees, leaves, flowers and fruit.

2. NUTRITIONAL APECTS OF *CITRUS LIMON*

Nutrients and phytochemicals found in citrus are good for your health. Citrus fruits and beverages provide carbohydrates, fiber, vitamin C, potassium, folate, calcium, thiamine, niacin, vitamin B6, vitamin A, phosphorus, magnesium, copper, riboflavin, pantothenic acid, and a variety of phytochemicals. While all of these substances are required for the body to function properly, several also provide extra protection against chronic diseases, in addition to basic nourishment. Citrus fruits also contain a water-soluble fiber called pectin, as shown in Fig. 2. Pectin is found in most plant cell walls, but it is particularly prevalent in citrus fruits, such as orange, grapefruit, lime, and lemon (Al-Snafi, 2016). Citrus fruits are a valuable source of phytochemicals that act as essential bioactive compounds for human health (Lv et al., 2015). Citrus has been used for food and folk medicine since ancient times to treat a variety of illnesses, including bronchitis, TB, colds, coughs, menstrual disorders, hypertension, anxiety, depression, and stress (Duarte et al., 2016).

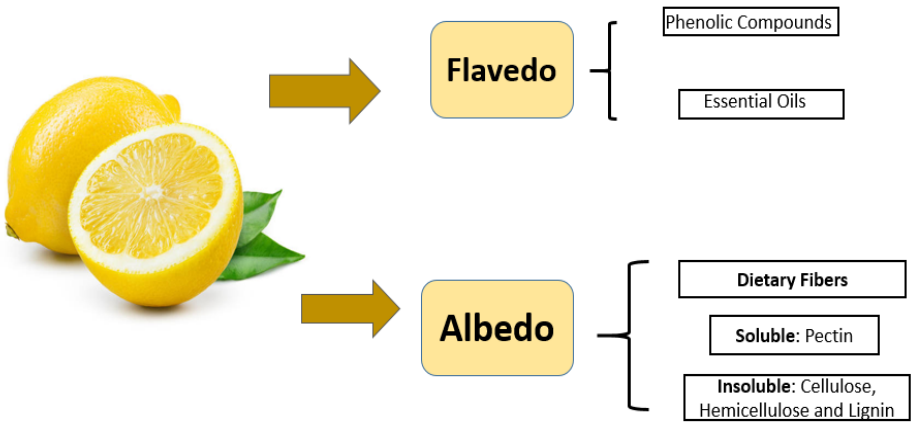

Fig. 2: Showing the primary structural components of *C. limon* peels.

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2.1. Phytoconstituent

The fruit juice is mostly made up of fruit acids, mainly sugar and citric acid, which form about 8% composition and are the main source of the typical sour taste and preservative quality that is observed in lemon juice (Haida et al., 2022; Rizaldy et al., 2022). Lemon peels are stratified into two layers: the pericarp, or zest, on the outside, contains an essential oil that makes up about 6% of the peel's weight. The aromatic monoterpenes (linalyl alcohol, alpha-terpineol, geranyl acetate, citral (approximately 5 percent), and limonene (approximately 90 percent)) found in this oil are linked to its strong smell and antimicrobial effect (Wu et al., 2021; Singh et al., 2020).

On the other hand, the mesocarp of the interior is bitterer flavone glycosides and a variety of coumarin derivatives, and much less essential oil. These are antioxidants and anti-inflammatory compounds (Haida et al., 2022; Russo et al., 2021). The mesocarp also contains insignificant amounts of gum, sugar, and potash, making its nutritional composition quite different from that of the outer peel layers (Mahato et al., 2019). Tartaric acid is dissolved in water, sulfuric acid is added, and lemon oil is used to make artificial lemon juice. The result of this process is the production of citral, an aldehyde amounting to 78-8 percent, which at the time of reduction forms geraniol, a small amount of citronellal, and pinene (Katoch et al., 2017); this is used as a flavoring and industrial, but not as a nutritional, agent in the majority of cases (Imeneo et al., 2022; Wu et al., 2021).

2.2. Sugar Content

The maximum level of fructose and kappa should be 0.6 per cent and 0.75, which means that lemon juice has a relatively low intrinsic sugar profile compared to other citrus fruits like oranges and mandarins (Jana et al., 2021; Rizaldy et al., 2022). This small amount of sugar makes lemon a more favorable option among diabetic and weight-conscious consumers because it has little or no glycemic load (Rafique et al., 2020; Haida et al., 2022). Lemons are not considered an important source of dietary protein; the amount of protein in the fruit pulp is very low, often less than 0.9 percent (Naufalina et al., 2022; Patil et al., 2017). Additionally, lemon cannot be displayed as a high-fat food with the percentage of 0.1 as it is depicted in Table 4 (Adhamjon et al., 2023), which further supports its classification as a low-energy-density fruit that can be used in therapeutic diets (Rafique et al., 2020; Jana et al., 2021). The overall low sugar, protein, and fat value highlight the nutritional implications of lemon as a functional food and not a rich source of macronutrient fruit (Russo et al., 2021; Haida et al., 2022).

2.3. Protein Content

The evidence provided in Table 4 shows that lemon fruit is composed of about 0.9% protein (Indonesia, 2013) which is not significantly different compared to other citrus fruits (Bany Sayd, 2014). Modern studies support the idea that citrus fruits, by and large, provide an insignificant share of protein compared to the daily food needs (Jana et al., 2021). However, the study mentioned above records a wide range of free amino acids in lemon juice, according to the Indonesian Ministry of Health. These are asparagine, glutamine and alpha-amino-butyric acid, which play supportive roles in metabolism and cell operations (Haida et al., 2022; Naufalina et al., 2022). Therefore, fruit is not a source of protein, although it contains significant amounts of amino acids; its nutritional value is primarily derived from micronutrients and phytochemicals (Russo et al., 2021).

2.4. Fat Content

The insoluble nonpolar molecules of fats cannot fit in the aqueous phase as they are insoluble. Diffusion controls the process of infusion in water, which may be described as a mass transfer of soluble elements, that is, nutrients, within higher concentration areas (lemon tissue) to lower concentration areas (water) as shown in Table 4. Solvable molecules do not undergo this transfer; those that are insoluble in water (Molecules) do not (Klika, 2014). Since lemons have such a low intensity of lipid content, the role of fats in the overall nutritional value of the fruit is insignificant (Adhamjon et al., 2023). This insignificant amount of fat also supports the appropriateness of lemon in low-fat therapeutic approaches and cardiovascular diet programs (Rafique et al., 2020; Singh et al., 2020).

2.5. Potassium Content

Lemons have about 120-145mg of potassium per 100g. It might appear that this amount is small, but potassium is an essential mineral that helps regulate the contraction of skeletal and cardiac muscle, maintain nervous system integrity, and support a variety of other metabolic processes. There has been a consistent association between adequate potassium intake and blood pressure regulation and cardiovascular health, as confirmed by recent cohort studies (Russo et al., 2021; Haida et al., 2022). The contribution of the specific fruit to the total daily intake of potassium can be said to be minimal despite the fact that fruit like lemons do contain potassium. In turn, recent research has concluded that there is no need to implement a health-based recommendation to enrich drinking water with potassium, namely by infusing lemon water (Naufalina et al., 2022). However, including lemons in a balanced diet provides a small but significant contribution to achieving the recommended potassium levels (Jana et al., 2021).

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Table 4: Nutritional value of 100 grams of raw lemon without peel

Nutritional Component	Content	Description	Citation
Carbohydrates	9.32g	It provides energy; the exact value is not specified but essential for basic nourishment.	(Al-Snafi, 2016; Jana et al., 2021; Russo et al., 2021; Rizaldy et al., 2022)
Fiber	2.8g	Water-soluble fiber pectin found in citrus fruits contributes to digestive health.	(Al-Snafi, 2016; Jana et al., 2021; Russo et al., 2021; Haida et al., 2022)
Vitamin C	53.0mg (88%)	Supports immune function and acts as an antioxidant.	(Lv et al., 2015; Singh et al., 2020; Haida et al., 2022; Rizaldy et al., 2022)
Potassium	138mg (3%)	Important for muscle function, metabolism, and nerve function.	(Naufalina et al., 2022; Jana et al., 2021; Russo et al., 2021)
Folate	11 µg (3%)	Plays a role in cell division and growth, vital during pregnancy.	(Jana et al., 2021; Haida et al., 2022; Naufalina et al., 2022)
Calcium	26mg (3%)	Supports bone health and metabolic processes.	(Al-Snafi, 2016; Jana et al., 2021; Rizaldy et al., 2022)
Thiamine (Vitamin B1)	0.040mg (3%)	Help convert food into energy.	(Al-Snafi, 2016; Jana et al., 2021; Russo et al., 2021)
Niacin (Vitamin B3)	0.100mg (1%)	Supports metabolism and skin health.	(Al-Snafi, 2016; Jana et al., 2021; Haida et al., 2022)
Vitamin B6	0.080mg (6%)	Involved in amino acid metabolism and neurotransmitter synthesis.	(Jana et al., 2021; Qurban et al., 2024; Prakash et al., 2024)
Phosphorus	16mg (2%)	Vital for bone health and energy production.	(Al-Snafi, 2016; Panwar et al., 2023; Uthman & Garba, 2023)
Magnesium	8mg (2%)	Supports muscle and nerve function, bone health, and energy production.	(Al-Snafi, 2016; Sengupta et al., 2023; Panwar et al., 2023)
Riboflavin (Vitamin B2)	0.020mg (1%)	Supports energy production and cellular function.	(Al-Snafi, 2016; Oloye et al., 2023; Sengupta et al., 2023)
Pantothenic Acid (Vitamin B5)	0.190mg (4%)	Important for synthesizing coenzyme A, which is vital for energy production and metabolism.	(Jana et al., 2021; Hrubša et al., 2023; Wedman et al., 2024)
Protein	0.9%	Minimal protein content.	(Patil et al., 2017; Sengupta et al., 2023; Magalhães et al., 2025)
Fat	~0.1%	Very low-fat content.	(Adhamjon et al., 2023)
Sugar Content	Fructose ~0.6% and Kappa ~0.75%	Low sugar content, primarily fructose.	(Rizaldy et al., 2022; Haida et al., 2022; Adhamjon et al., 2023)
Phytochemicals	Flavonoids, limonoids, terpenes	Includes compounds like eriocitrin (anti-inflammatory) and limonin (anticancer, antibacterial, antiviral).	(Patil et al., 2017; Singh et al., 2020; Rizaldy et al., 2022)

2.6. Lemonade

Citrus limon is mostly composed of intensely oxygenated, modified triterpenes called limonoids. The bitter compound in citrus seeds, limonin, was first identified in 1841 and gave rise to the term "limonoid." Numerous biological characteristics, including antiviral, antibacterial, antifungal, and anticancer effects, are displayed by this class of secondary metabolites (Aragon et al., 2015). Limonoids can prevent neuroblastoma, ovarian cancer, and colon cancer and stop the spread of estrogen receptor-negative and human breast cancer cells that are positive (Patil et al., 2017).

3. MEDICINAL USES OF *CITRUS LIMON*

Fifty to sixty percent of the weight of a lemon is made up of its peel. Peels are frequently thought of being the main cause of pollution in the environment (Nawaz et al., 2021). The large volume of peel residues generated by industrial citrus processing has created serious environmental and economic issues, particularly in the juice and beverage industry (Russo et al., 2021; Imeneo et al., 2022). However, there is a significant quantity of polyphenols in lemon peels. Moreover, they include compounds that are beneficial to health, such as flavonoids and vitamin C (Fig. 5), which strengthen their inherent antioxidant capacity (Haida et al., 2022; Rizaldy et al., 2022). Recent studies have shown that lemon peel polyphenolic compounds have strong antioxidant activity via free-radical scavenging and metal-chelating properties, which support cytoprotective mechanisms against oxidative stress (Singh et al., 2020; Rizaldy et al., 2022).

By preventing calcium oxalate solid concretions from forming, lemon peel extract helps regulate the development of calcifications in the urinary system. As a result, it protects the urinary tract from kidney or gallstone injury (Sridharan et al., 2016). Moreover, lemon peel extracts have shown nephroprotective effects by regulating

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oxidative stress symptoms and proinflammatory cytokines involved in urolithiasis (Rafique et al., 2020; Haida et al., 2022). Lemon peels contain naringin and hesperidin, which are beneficial compounds that enhance antigenic activity in artery-related illnesses (Singh et al., 2020). Recent studies have reported that these flavonoids play a definite role in improving endothelial function, reducing lipid peroxidation, and mediating anti-atherosclerotic effects, thereby strengthening cardiovascular homeostasis (Rizaldy et al., 2022). Overall, these findings highlight the potential of lemon peel as a sustainable source of bioactive compounds for use in the pharmaceutical, nutraceutical, and functional food sectors (Imeneo et al., 2022).

3.1. Citrus Flavonoid

The acronym flavonoids, which comes from the Latin word "flavus," which means yellow, refers to phenolic compounds that have biological properties such as antiviral, antiallergenic, anti-inflammatory, and vasodilator effects (Fig. 3).

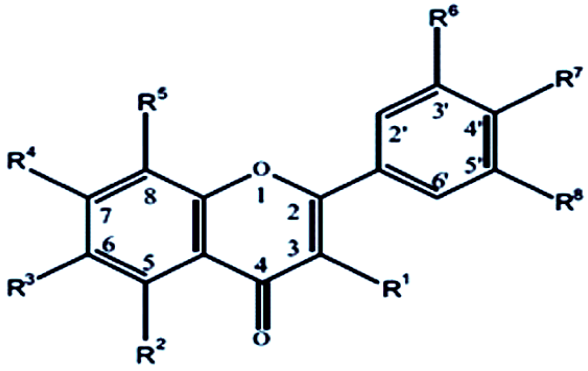

Fig. 3: General Structure of Flavonoids (Damián-Reyna et al., 2016).

Lemon peels are rich in the flavonoid eriocitrin, which has been shown to have anti-inflammatory properties both in vivo and in vitro (Rustam et al., 2022). More precisely, research has demonstrated that this flavonoid provides a variety of health benefits, including antioxidant and anticancer properties as well as acting as an anti-oxidative stress agent (Yao et al., 2022). Additionally, hesperidin has antibacterial, anticancer, antihypertensive, and antiulcer properties (Choi et al., 2022; Subhan & Siddique, 2024).

3.2. Effects of Hesperetin against Alzheimer's Disease

Hesperetin effects were examined in one study using a rat model of Alzheimer's disease. The researchers concluded that by reducing oxidative stress, hesperidin and hesperetin nanoparticles administered at doses for three weeks considerably alleviated learning and cognitive deficits. Additionally, they proposed that hesperetin nanoparticles are more effective than hesperetin powder alone (Kwon et al., 2018). These results indicate that the neuroprotective action of hesperetin is mainly mediated by its antioxidant and anti-inflammatory properties, which are essential for preventing neuronal damage in Alzheimer's disease (Parhiz et al., 2015; Yao et al., 2022). Recent research has also indicated that hesperetin can regulate major neurodegenerative pathways, including the inhibition of neuroinflammatory mediators and the activation of endogenous antioxidant defenses (Russo et al., 2021; Rizaldy et al., 2022). In addition, the hedgesperetin nano-formulation has been reported to enhance blood-brain barrier permeability and bioavailability, thereby increasing its therapeutic effect in neurodegenerative disorders (Haida et al., 2022; Yao et al., 2022). Taken together, these investigations present hesperetin as a promising citrus-based neuroprotective compound in the prevention and treatment of Alzheimer disease (Rafique et al., 2020; Russo et al., 2021).

3.3. Effects of Hesperetin against Parkinson's Disease

Another debilitating neurodegenerative illness is Parkinson's disease. Motor and cognitive impairment are caused by the loss of dopaminergic neurons in the substantia nigra, which is a pathophysiology of Parkinson's disease (PD). Animals are given environmental neurotoxins such as 6-hydroxydopamine (6-OHDA) to induce Parkinson's disease-like symptoms. A weekly dose of hesperetin was administered to assess its efficacy in treating PD-like symptoms. The results showed that hesperetin reduced oxidative stress by controlling neuroinflammation (NF-κB), the transcription factor Nrf2, and the loss of apoptotic cells (mitochondrial apoptosis). Additionally, table number 5 demonstrated that hesperetin significantly decreased motor impairment in the PD rats produced by 6-OHDA (Batista et al., 2019).

Recent studies have confirmed that flavonoids, in particular hesperetin, exhibit strong neuroprotective effects, including scavenging of reactive oxygen species and inhibiting the production of pro-inflammatory cytokines in dopaminergic neuronal subpopulations (Parhiz et al., 2015). Also, hesperetin has been implicated in preserving mitochondrial integrity and reducing the progression of alpha-synuclein aggregation - pathological hallmarks that are part of the evolution of Parkinsonian pathology (Russo et al., 2021; Rizaldy et al., 2022). Furthermore, citrus-derived flavonoids have demonstrated efficacy in improving motor coordination and overall behavioral functioning in experimentally induced Parkinsonian models (Rafique et al., 2020; Haida et al., 2022). All these findings support the suggestion that hesperetin is a promising natural neuroprotective agent in the management of Parkinson's disease (Singh et al., 2020; Yao et al., 2022).

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3.4. Antioxidant Activity

Citrus fruits and liquids are good sources of antioxidants, which include phenolic compounds, flavonoids, and ascorbic acid (Moosavy et al., 2017). Citrus fruits have the highest antioxidant activity of any food. Certain fruits contain large amounts of ascorbic acid, or vitamin C (Fig. 4), which has antioxidant properties. Furthermore, various enzyme systems, flavonoids, carotenoids, and glutathione are phytoconstituents that may contribute to antioxidant activity (Oikeh et al., 2016).

It has been demonstrated that hesperidin and hesperidin flavonoids from C. limon have antioxidant activity that extends beyond free-radical scavenging; they also strengthen cellular antioxidant defenses by activating the ERK/Nrf2 signaling pathway, as shown in Table 5 (Parhiz et al., 2015).

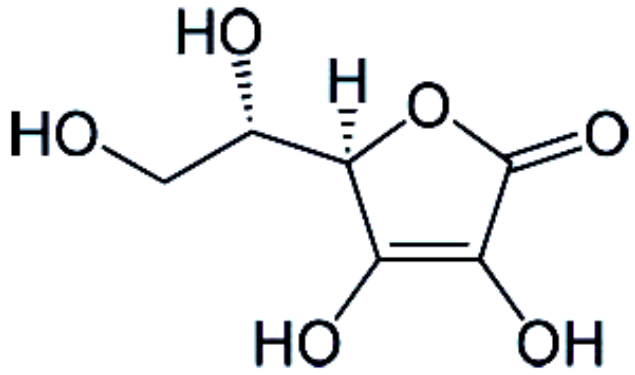

Fig. 4: Structure of Vitamin C (Elnour et al., 2018).

3.5. Antimicrobien Activity

Citrus limon juice contains flavonoids, alkaloids, steroids, saponins, terpenoids, reducing sugars, and cardiac glycosides (Oikeh et al., 2016). We recently showed that lemon Integra pectin, made from leftover lemon peels using hydrodynamic cavitation, exhibits significant in vitro efficacy against the indicator strain of *Staphylococcus aureus* (Presentato et al., 2020). The main culprit behind infections linked to prosthetic implants and infective endocarditis is the opportunistic bacterial pathogen Staphylococcus aureus. This bacterial strain has a significant global mortality rate and is also a cause of bacteremia and skin and soft-tissue infections (Tong et al., 2015).

Fruits of *C. limon* were used to extract ethanol and acetone, which showed activity against *Candida glabrata* (Otang & Afolayan, 2016). Conversely, components found in *C. limon* essential oil, such as D-limonene, β-pinene, and citral, have demonstrated inhibitory efficacy against *Candida parapsilosis, Saccharomyces cerevisiae* and *Aspergillus niger* (Lamine et al., 2020).

3.6. Anti-diabetic Activity

Citrus fruits are the primary source of Naringenin; grapefruit has relatively high levels, orange juice has lower levels, and lemon juice has much lower levels (Gattuso et al., 2007). Although naringenin is found at a relative low concentration in lemon juice, it has become the subject of a great deal of scientific interest due to its strong antidiabetic and metabolic regulation properties (Rafique et al., 2020; Rizaldy et al., 2022). It has been shown that naringenin enhances glucose homeostasis by increasing insulin sensitivity, decreasing hepatic glucose production, and regulating carbohydrate-metabolizing enzymes (Singh et al., 2020; Haida et al., 2022).

Fig. 5 shows the pharmacological effects of Naringenin, including its anti-inflammatory, immunomodulatory, hepatoprotective, nephroprotective, neuroprotective, anticancer, antiatherosclerotic, and antidiabetic properties, which have been investigated by Gattuso et al. (2007). The most recent experimental data suggest that naringenin can be used as an antidiabetic agent by alleviating oxidative stress, inhibiting chronic low-grade inflammation, and modulating key signaling pathways involved in glucose and lipid metabolism (Rafique et al., 2020; Russo et al., 2021). Additionally, polyphenol- and flavonoid-enriched citrus peel extracts were found to significantly lower blood glucose levels, improve lipid profiles, and mitigate insulin resistance in diabetic animal models (Rizaldy et al., 2022; Haida et al., 2022). Overall, these findings indicate that bioactive compounds derived by *Citrus limon* have good potential in the design of functional food and nutraceuticals to manage diabetes (Singh et al., 2020; Russo et al., 2021).

Oral administration of *C. limon* peel ethanol extract was carried out for 12 days in diabetic rats that had been streptozotocin-induced diabetics. The study revealed decreased blood glucose, faster wound healing, higher collagen, protein, and hydroxyproline levels, and an increased rate of tissue development (Mohanapriya et al., 2013). Research has shown that polyphenols significantly reduce the development of hyperlipidemia, elevated blood glucose, insulin resistance, weight gain, and fat accumulation, all of which are distinct manifestations of obesity. Citrus peel contains several essential oils. Using these essential oils either kills the pathogenic germs or stops their growth. Citrus peels have antioxidant and diabetes-lowering properties because of its high total polyphenol content (Rafique et al., 2020).

3.7. Effects on the Digestive System

Lime has a delicious scent that hydrates the lips and supports basic digestion (saliva from digestion fills your mouth even before you taste it). After that, the acids in it finish the job. Flavonoids, which are substances present in

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fragrant oils made from limes, break down the macromolecules in food and promote peristaltic movement as illustrated in Table 5. Lemons also stimulate the digestive tract and boost the secretion of digestive juices, bile, and acids. For this reason, having lemon pickles with lunch and dinner is a long-standing custom in India and some of its neighboring nations (Jana et al., 2021).

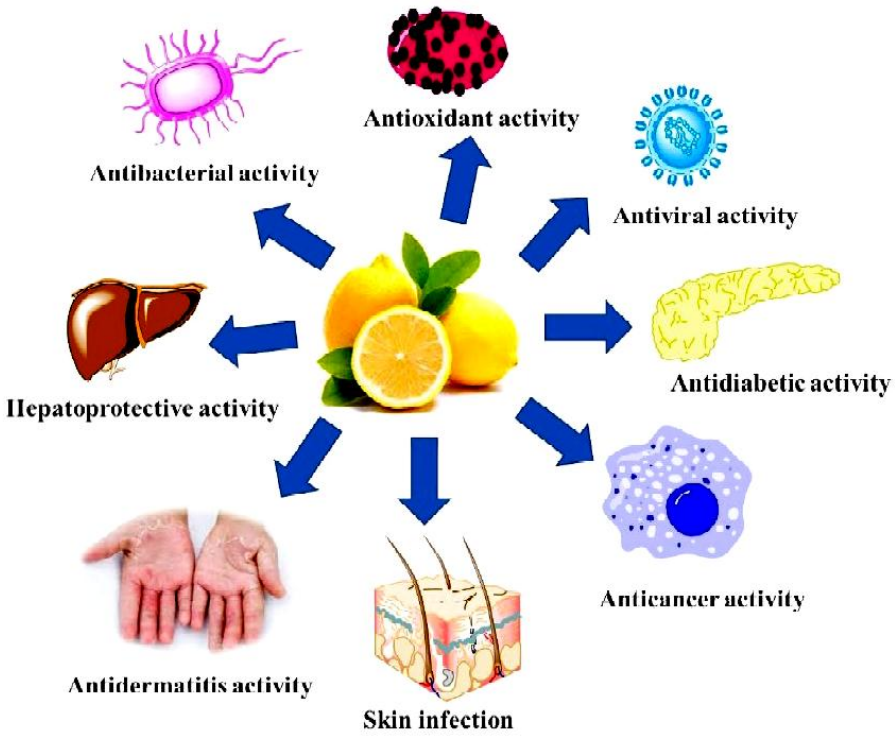

Fig. 5: Schematic illustrating pharmacological actions of *C. limon* (Khan et al., 2023).

Table 5: Therapeutic Properties of *Citrus limon*

Activity	Action Mechanism	References
Antioxidant	• Cellular defenses against oxidative stress are strengthened through the ERK/Nrf2 pathway.	(Parhiz et al., 2015; Xavier et al., 2007; Singh et al., 2020; Rizaldy et al., 2022)
Antiviral	• Inhibiting *Herpes simplex* from replicating.	(Minami et al., 2003; Russo et al., 2021; Rizaldy et al., 2022; Singh et al., 2020)
Anticaries	• Glucosyltransferase transcription and enzymatic activity are inhibited. • *Streptococcus mutant's* growth and adherence to enamel are inhibited.	(Liu et al., 2013; Singh et al., 2020; Russo et al., 2021; Rafique et al., 2020)
Anti-obesity	• D-limonene has the following effects: - Blood sugar equalization • Regeneration of degenerative alterations in the liver and pancreas. • Reduction of cholesterol and fat deposits.	(Jing et al., 2013; Rafique et al., 2020; Russo et al., 2021; Haida et al., 2022)
Treatment of menstrual irregularities	• In cases with irregular menstrual cycles, period induction.	(Bhatia et al., 2015; Russo et al., 2021; Rizaldy et al., 2022)
Effects on the nervous system	• Its activity on pain receptors is similar to that of indomethacin and hyoscine (D-limonene). • It works by activating serotonin and dopamine receptors, which have a sedative and anxiolytic effect.	(Komiya et al., 2006; Yao et al., 2022; Haida et al., 2022)
Effect on the digestive system	• D-limonene has the following effects • Neutralization of stomach acids • Reduction of nausea and increased gastric motility • Relief of gastric reflux • A rise in bile flow.	(Komiya et al., 2006; Alkanat & Alkanat, 2025; Komolafe et al., 2025)

3.8. The Essence of *Citrus limon*

Numerous useful natural products can be characterized as combinations of oxygenated hydrocarbons made up of essential oils substances as well as non-volatile leftovers. Terpenes, sesquiterpenes, alcohols, esters, sterols, and

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aldehydes are among them (Ben Hsouna et al., 2017). Citrus species are emphasized for their abundance of essential oils, which are highly adaptable and frequently used as flavorings in a variety of products, including drinks, soaps, cosmetics, and household items. Since essential oils have antimicrobial, antifungal, antibacterial, and antiparasitic properties, they are also widely used in medical treatments. According to Fig. 6, demand for natural aroma compounds and essential oil-based products is increasing across the culinary, pharmaceutical, cosmetic, and perfume industries (Swamy et al., 2016). The main cause of the waste of fragrant lemons was the industry's requirement for a specific range of fruit sizes, particularly for fruit tea. The primary source of perfume lemon leaves was the trimming of perfume lemon trees, which was often discarded as waste and had negative ecological and environmental repercussions. Therefore, recycling abandoned perfume, lemon and leaf trash not only helps to fully use natural resources but also has the potential to turn waste into treasure and raise the added value of the agricultural process as shown in Fig. 6 (Wu et al., 2021).

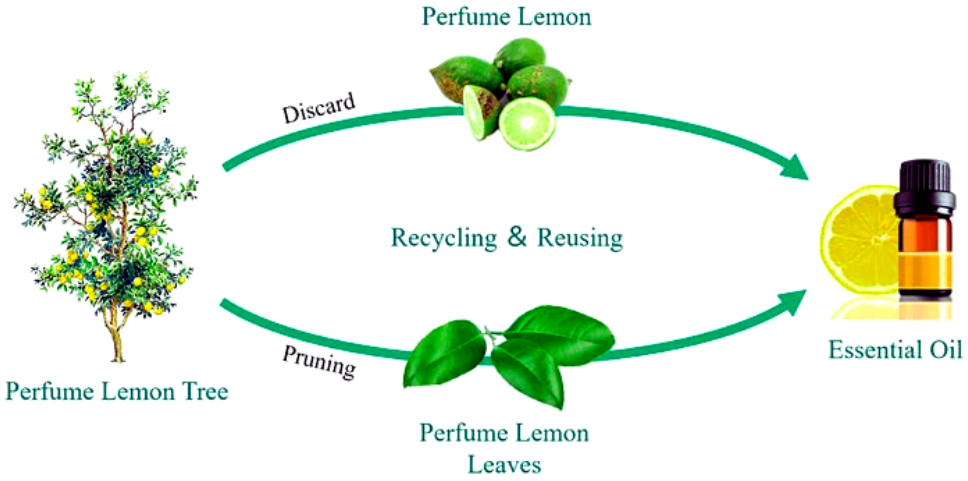

Fig. 6: Reusing and recycling the leftover scented lemons and foliage.

4. CONCLUSION

Lemons and other citrus fruits are widely grown around the world because of their broad appeal and numerous culinary uses. Due to this extensive cultivation, considerable amounts of by-products, such as peels, pulp, and seeds, are produced that are high in bioactive compounds. These substances, particularly naturally occurring antioxidants such as phenolic acids and flavonoids, are essential for food preservation and health promotion. For example, citrus peels are prized not only for their flavor in food preparation but also for their ability to extend the shelf life and nutritional content of food products. Citrus by-products are increasingly recognized for their medicinal potential, which extends beyond their culinary appeal and supports the development of functional foods and nutritional supplements to enhance health outcomes. Citrus is therefore used holistically, from fruit to by-product, highlighting its importance in the global nutrition and health sectors as well as in cuisine.

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