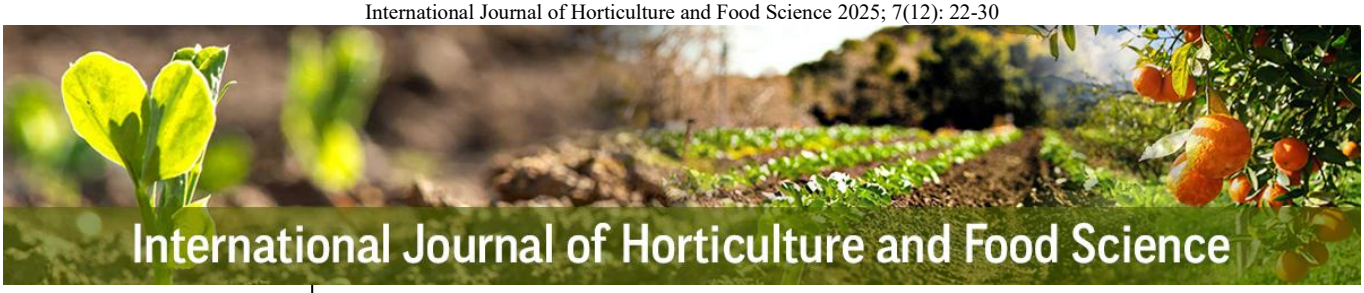

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Nutraceutical importance of onion leaf extracts: Phytochemicals and therapeutic applications

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Abstract
Onion (*Allium cepa*) is globally recognized not only as a culinary staple but also as a significant source of nutraceuticals and bioactive compounds. While the bulb has been extensively studied for its therapeutic properties, the green leaves remain underexplored despite their rich phytochemical profile. Onion leaves are a valuable reservoir of flavonoids, phenolic acids, saponins, organosulfur compounds, and essential vitamins and minerals, contributing to their remarkable antioxidant, antimicrobial, anti-inflammatory, and antidiabetic properties. This chapter highlights the nutraceutical potential of onion leaves by systematically analyzing their bioactive constituents, modes of action, and associated health benefits. Special emphasis is given to their role in reducing oxidative stress, modulating gut microbiota, regulating blood glucose levels, improving cardiovascular health, and enhancing immunity. Furthermore, the chapter explores their application in functional foods, herbal formulations, and pharmaceutical products, with an outlook on sustainable utilization of agricultural by-products. By integrating scientific evidence and practical insights, this work provides a comprehensive overview of onion leaves as a cost-effective, eco-friendly, and health-promoting resource. It also identifies research gaps and future perspectives to encourage innovative applications of *Allium cepa* leaves in nutraceutical and health industries.

Keywords: Onion leaves, *Allium cepa*, nutraceuticals, bioactive compounds, antioxidants, health benefits

1. Introduction
Onions (*Allium cepa* L.) are highly valued for their unique flavour, culinary versatility, and medicinal properties, making them one of the most extensively planted, oldest domesticated vegetable crops and consumed vegetables worldwide. The onion, or *Allium cepa*, is a perennial herb that grows from an underground bulb. Although some authors refer to onions as Alliaceae, they actually belong to the Liliaceae family. One or two leafless flower stalks on a common onion can grow to a height of 75-180 cm (2.5-6 feet) [1].

Since ancient times, onions (*Allium cepa*, L.) have been utilised as food and medicinal. Because of their taste and nutritional worth, onions are highly valued and preserved as pickles. Onion leaves are increasingly in demand as fresh edible vegetables in India, as seen by their frequent availability in supermarkets, local vegetable markets, and online marketplaces. Because of their mild flavour, freshness, and culinary variety, leaves are cheap, readily available, and commonly consumed in both urban and rural locations [1].

Onions and plants in the Allium genus have long been used as a herbal remedy for a variety of ailments due to their many pharmacological effects [2, 3]. About 90% of onions are water, and they also contain a lot of sugar and nutritious fiber. Scientists are becoming interested in onion leaves because of their high nutritional and phytochemical content. Organosulfur compounds (ACSOs), flavonoids (kaempferol, quercetin, and luteolin), phenolic acids (caffeic, p-coumaric and ferulic), vitamins, minerals, dietary fiber, and antioxidants are all abundant in them (Figure 1). Additionally, a number of flavonoids have been shown to possess antifungal and antibacterial qualities [1, 2].

Numerous health-promoting activites, such as antioxidant, antibacterial, anti-inflammatory, antidiabetic, cardioprotective, gut-health-modulating, and chemopreventive activities, are attributed to these bioactive substances (Figure 1) [2-4]. Thus, the goal of this study is to conduct a comprehensive evaluation of the literature that is currently accessible on the

chemical and morphological characteristics, pharmacological activity, and therapeutic potential of *A. cepa* leaves.

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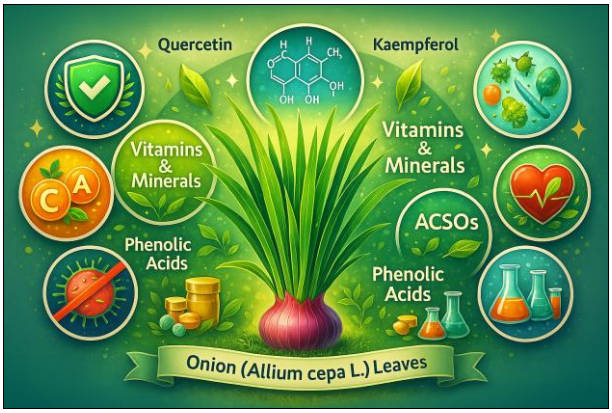

Fig 1: Health benefits and phytochemical composition of onion leaves

1.1 Morphological Characteristics

Allium cepa is a member of the Amaryllidaceae family. The slender stem of this perennial herb is encased in an underground bulb. The root system is adventitious and fibrous. Sheathing leaf bases with parallel venation emerge from a cluster of leaves to produce the cylindrical, fleshy bulb. The pedicels emerge from the peduncle's apex and are all the same length. The blooms are often protandrous, hypogynous, actinomorphic, trimerous, bracteate but ebracteolate, and tiny. Six white tepals with valvate aestivation are grouped in two whorls of three, joined (syntepalous). The flower features two whorls of six epitepalous stamens opposite the tepals, with dithecous, basifixed, introrse anthers that dehisce longitudinally [1].

With a superior trilocular ovary and two ovules per locule on axile placentation, the gynoecium is tricarpellary and syncarpous. The style has a thin stigma and is straightforward. The seeds are endospermous, and the fruit is a loculicidal capsule. They can be eaten raw, boiled, pickled, or powdered, and they can be red, white, or yellow. Onion plants have one or two leafless stalks that can grow to a height of 75-180 cm and yield white or purple blooms. The edible bulb is formed by the subsurface swelling of the concentric leaf bases. Onions are often grown from seeds, although they can also be grown from transplants or tiny bulbs. They are resistant plants that can withstand a variety of growing circumstances. The size, shape, colour, and pungency of the bulbs vary according on the location; milder bulbs are produced in warmer climates [5-7].

2. Onion leaves in local vegetable markets

Onion leaves are currently one of the most important and popular vegetables. It has been acknowledged as a domestic crop for over 6,000 years. China, Iran, East Asia, India, and Persia were among the places where it was grown. Onion leaves, sometimes referred to as "spring onion" or "green onion," are commonly found in Indian supermarkets, vegetable markets, and online grocery stores. According to major Indian supermarket platforms like JioMart, spring onion bunches are frequently sold in the fresh vegetable category, indicating continued market demand. Similarly, BigBasket and Blinkit in the leafy-vegetable section offer spring onions in identical packaging to maintain freshness throughout storage and delivery [8, 9]. Every day, small farmers gather spring onions and transport them to local village markets, where they are sold at low costs in little bunches. Because of their freshness and mild flavour, onion leaves are frequently used in traditional dishes, salads, and curries in rural communities [9-11].

These fresh greens are frequently offered alongside other leafy vegetables including spinach, fenugreek, and coriander in short bunches or 100-250 g bundles. Overall, spring onions and onion leaves are still a readily available and reasonably priced fresh produce in many local rural marketplaces; wholesale prices are around ₹17-20 per kilogramme, but retail packs and bunches are inexpensive. Because of their widespread availability and nutritional benefits, they play a significant role in the rural food supply. Small vendors and producers in rural areas harvest, package, and sell spring onions, providing rural consumers with affordable access to fresh, nutrient-rich greens. (Figure 2) [9-11].

Fig 2: Onion leaves Selling in the market

3. Phytochemical profile of onion leaves

3.1 Flavonoids and phenolic compounds

Green onion tops, or onion (*Allium cepa* L.) leaves, are prized for their rich phytochemical profile in addition to their culinary use. Flavonoids and phenolic compounds are two of the most prominent bioactive components found in onion leaves, and they play a major role in their antioxidant and therapeutic properties. The main class of polyphenols found in onion leaves are flavonoids. Quercetin, which is mostly found in glycosylated forms like quercetin-3-glucoside and quercetin-4'-glucoside, is the most common and often studied flavonoid (Figure 3). These substances are well known for their potent antioxidant properties and capacity to eliminate free radicals. Quercetin reduces inflammation, protects human cells from oxidative damage, and may reduce the risk of chronic illnesses like heart disease and certain types of cancer [12, 13].

Onion leaves also contain derivatives of luteolin and kaempferol, among other flavonoids, in addition to quercetin. While luteolin-7-glucoside is well-known for its potent anti-inflammatory and protective properties, kaempferol-3-glucoside and kaempferol rutinoside

contribute to anti-inflammatory and anti-carcinogenic activity (Figure 3). Together, these flavonoids offer a number of health-promoting benefits and increase onion leaves' overall antioxidant capacity [12, 13].

The second greatest class of bioactive compounds found in onion leaves is phenolic acids. They fall into two main groups: hydroxybenzoic acids and hydroxycinnamic acids. Ferulic acid, p-coumaric acid, caffeic acid, and sinapic acid are examples of hydroxycinnamic acids that have been shown to have antibacterial and antioxidant properties. These substances contribute to the health benefits that users have noticed while also shielding the plant from environmental stress. Gallic acid, vanillic acid, and protocatechuic acid are examples of hydroxybenzoic acids that also contribute to antioxidant activity, metal chelation, and free-radical neutralisation [12, 13].

Onion leaves are routinely found to have higher levels of phenolic acids and flavonoids than onion bulbs. This is mostly due to the green leaves' increased exposure to sunlight, which promotes the synthesis of flavonoids. The precise amounts of these phytochemicals are influenced by a number of factors, including onion varietal, plant maturity, environment, and storage conditions. Onion leaves' total flavonoid content (TFC) is commonly represented in mg quercetin equivalents, whilst their total phenolic content (TPC) is typically assessed in mg gallic acid equivalents (GAE) per gramme [12, 13].

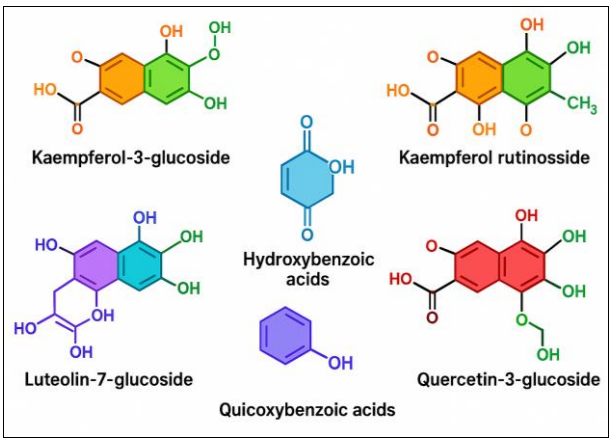

Fig 3: The chemical structures of the major phenolic and flavonoid compounds in onion leaves.

3.2 Organosulfur compounds

Similar to the bulb, onion leaves have a rich profile of organosulfur compounds (OSCs), which give them their distinct scent and many biological uses. The main source of these compounds is S-alk(en)yl-L-cysteine sulfoxides (ACSOs), which function as sulfur-storage molecules in Allium species. Methiin (S-methyl-L-cysteine sulfoxide), isoalliin (S-(1-propenyl)-L-cysteine sulfoxide), and propiin (S-propyl-L-cysteine sulfoxide) are the main ACSOs present in onion leaves. When the tissue is sliced or crushed, this enzyme converts these precursors into a variety of chemically reactive sulphur compounds, including trisulfides, sulphides, and thiosulfinates, which are all responsible for the potency and health advantages of onions [1, 15, 16].

Since most studies focus on entire green onions (leaf + stalk) or complete bulbs, specific amounts for onion leaves alone are scarce in terms of quantitative data. A study on Allium species found that thiosulfinate concentrations for green tissues varied from 22 to 35 mg/100 g fresh weight. The values, however, differ by species and may not be a true representation of onion leaves. Although leaf-specific data were not separated, a further analytical evaluation reveals that the total ACSO concentration in onion tissues typically ranges between 100 and 350 mg/100 g fresh weight [1, 14, 15].

However, it is generally known that OSCs are present in onion leaves and behave biochemically. Along with ACSOs, onion leaves also include sulphides, thiosulfinates, sulfenic acids, and a special sulfur-containing substance known as Onionin A, which has been shown to have anti-inflammatory properties [15].

Overall, the pungency, medicinal qualities, and antioxidant activity of onion leaves are attributed to a variety of organosulfur compounds that are produced from cysteine-sulfoxide precursors. Analytical techniques, ambient factors, onion variety, and ripeness all affect their concentrations.

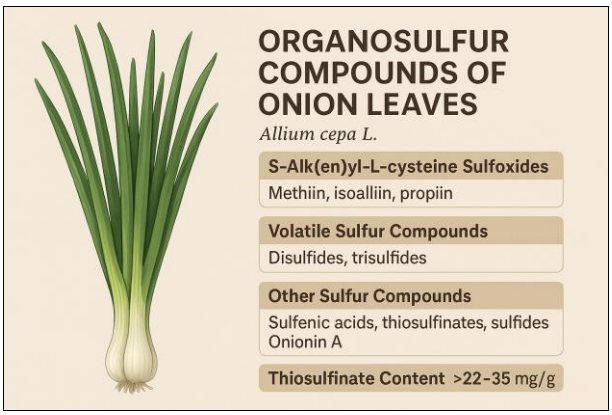

Fig 4: Organosulfur profile of onion leaves showing ACSOs, volatile sulfur compounds, and other sulfur derivatives.

3.3 Vitamins, minerals, and other nutrients:

Onion leaves are rich in many important vitamins. Vitamin A, which is primarily found as β-carotene, is one of the most important. A substantial quantity of vitamin K is present. Vitamin C is another essential vitamin that can be found in onion leaves. Onion leaves also contain B-complex vitamins, including thiamine (B1), pyridoxine (B6), riboflavin (B2) and folate (B9). Onion leaves offer a variety of micronutrients in terms of minerals. Calcium and potassium are present in these leaves. Iron is essential for the transportation of oxygen and the synthesis of hemoglobin, which helps avoid iron-deficiency anemia [16, 17]. About 32 kcal, 1.8 g of protein, 7.3 g of carbs, and 2.6 g of dietary fibre are found in 100 g of onion leaves. Phosphorus, Potassium (276 mg), Calcium (72 mg), magnesium (20 mg) and iron (1.5 mg) are important minerals. They also have powerful antibacterial and anti-inflammatory qualities due to the presence of chlorophyll, antioxidants, and sulphur compounds. All things considered, onion leaves are nutrient-rich and promote bone health, digestion, and immunity [16, 17].

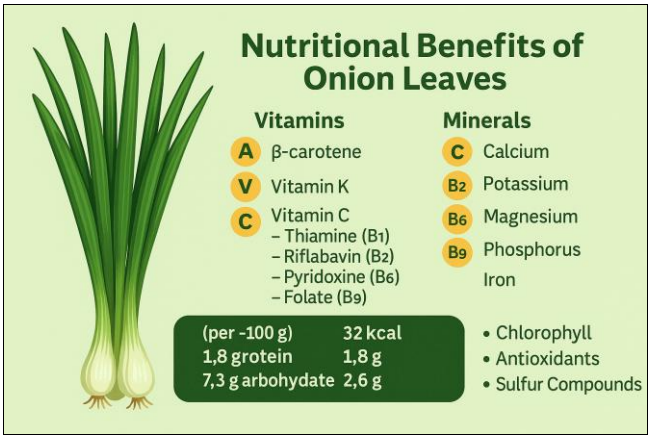

Fig 5: Vitamins, minerals, and nutrients present in onion leaves.

4. Nutraceutical properties

Rich in flavonoids (quercetin, kaempferol), phenolic acids, vitamins, minerals, and organosulfur compounds (ACSOs), onion leaves are an underappreciated, nutrient-dense resource. Strong immunomodulatory, antioxidant, antimicrobial, anti-inflammatory, antidiabetic, antifungal, cardioprotective, gut-microbiome-modulating, and chemopreventive actions are supported by these bioactives [17-19].

4.1 Antioxidant activity

Overall, onion leaves are a potent natural source of antioxidants due to their high flavonoid and phenolic content. Because of these compounds' anti-inflammatory, antibacterial, and protective properties, onion leaves are not only nutrient-dense but also help to maintain long-term health. Their strong antioxidant activity highlights their importance in nutritional and medicinal applications. As a strong antioxidant, vitamin K aids in wound healing, collagen production, immunological defence, and iron absorption. By donating hydrogen atoms, neutralising reactive oxygen species (ROS), and preventing lipid peroxidation, phenolic acids-such as caffeic acid, ferulic acid, p-coumaric acid, and gallic acid-further increase the antioxidant potential. Onion leaves contain vitamin C, which boosts cellular defence mechanisms and regenerates other antioxidants to offer more protection [18, 19].

The antioxidant capacity is also influenced by other flavonoids, such as derivatives of luteolin and kaempferol. Quercetin-3-glucoside and quercetin-4'-glucoside are very good in preventing oxidative stress and scavenging free radicals. According to a thorough analysis of Allium species, including onion leaves, green tissues have significant antioxidant activity because of their high phenolic and flavonoid content [18]. Quercetin and related flavonoids in onion leaves and bulbs have potent anti-inflammatory and antioxidant properties, according to another analysis of onion phytochemistry [19].

The antioxidant capacity of fresh onion leaves was investigated using conventional assays in a significant work named "Taste features, volatile elements, sensory properties, and antioxidant activity of fresh onion leaves." The researchers found an ORAC value of 805.78 ± 100.32 µmol Trolox equivalents/100 g and a DPPH free-radical scavenge activity of 406.70 ± 63.64 µmol Trolox equivalents/100 g, indicating strong antioxidant efficacy [20, 21].

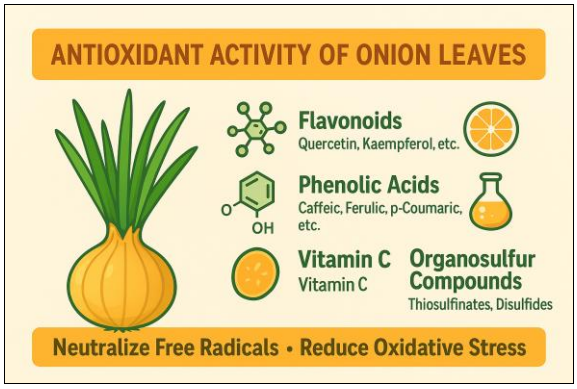

Fig 6: Antioxidant activity of onion (*Allium cepa L.*) leaves

4.2 Antimicrobial and antifungal potential

Similar to the bulb, onion leaves (*Allium cepa* L.) have strong antibacterial and antifungal properties because of their abundance of flavonoids, phenolic acids, and organosulfur compounds. By damaging cell membranes, interfering with enzyme systems, and causing oxidative stress in microbial cells, these bioactive components inhibit a variety of harmful bacteria and fungi.

Sulfur-containing substances such thiosulfinates, disulphides, and S-alk(en)yl-L-cysteine sulfoxides (ACSOs) were found to have strong antibacterial action against common infections in a study assessing fresh onion leaves [20]. These substances are known to impede the synthesis of DNA, proteins, and lipids as well as harm microbial cell walls.

Variants of luteolin, kaempferol, and quercetin are among the flavonoids found in onion leaves that contribute to their antibacterial activity. It has been shown that quercetin inhibits both Gram-negative and Gram-positive bacteria by preventing the synthesis of nucleic acids and interfering with cytoplasmic membrane activities. Phenolic acids including ferulic acid, caffeic acid, and p-coumaric acid further enhance antibacterial properties by inducing oxidative damage and protein denaturation in microbial cells [20, 22].

In terms of antifungal activity, Allium species, such as green onion leaves, have shown inhibitory effects against Penicillium species, *Aspergillus niger*, *Candida albicans*, and *Fusarium oxysporum*. Sulphur compounds, which hinder ergosterol synthesis and jeopardise fungal membrane integrity, are principally responsible for the antifungal effect. Due in major part to their higher sulphur and phenolic content, onion leaf extracts demonstrated greater antibacterial and antifungal action in comparison to a number of other edible green vegetables [20].

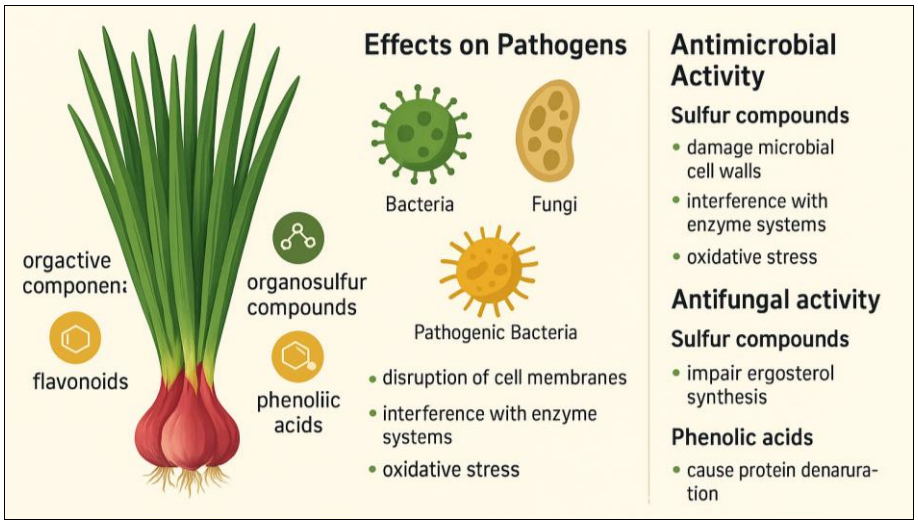

Fig 7: Antimicrobial and antifungal potential activity of onion (*Allium cepa L.*) leaves

4.3 Anti-inflammatory and immunomodulatory effects:

Due to their abundance of flavonoids, phenolic acids, vitamin C, and organosulfur compounds, onion leaves, like the bulb, have strong anti-inflammatory and immunomodulatory properties. These bioactive ingredients boost immunity and lessen inflammation via a variety of biochemical processes [18, 20].

Quercetin, a significant flavonoid found in onion leaves, has been demonstrated to have anti-inflammatory qualities. It reduces pro-inflammatory cytokines like TNF-α, IL-1β, and IL-6 while inhibiting inflammatory enzymes like lipoxygenase (LOX) and cyclooxygenase-2 (COX-2). Flavonoids like kaempferol and luteolin derivatives also help reduce oxidative stress by neutralizing free radicals, preventing lipid peroxidation, and stabilizing cell membranes. Phenolic acids, especially ferulic, p-coumaric acids and caffeic improve these effects by reducing oxidative tissue damage and inhibiting the production of nitric oxide (NO) [18].

Onion leaves contain organosulfur compounds that have additional anti-inflammatory properties, such as thiosulfinates, sulfoxides, and disulphides. By suppressing inflammatory mediators and blocking the NF-κB pathway, a crucial inflammatory regulator, these substances alter immunological signalling [20].

Additionally, onion leaves have immunomodulatory properties. White blood cell function is supported by vitamin C, which also improves phagocytosis and shields immune cells from oxidative damage. By enhancing macrophage activity, encouraging lymphocyte proliferation, and regulating Th1/Th2 responses, flavonoids influence both innate and adaptive immunity. Additionally, organosulfur compounds have antibacterial properties that indirectly boost immunity by lowering the pathogen load [18].

5. Health benefits of onion leaves

5.1 Cardiovascular health

Another essential mineral that aids in controlling blood pressure, muscle contraction, and fluid balance is potassium. Rich in flavonoids, phenolic acids, vitamin C, fibre, and organosulfur compounds, onion leaves play a major role in protecting the heart. Quercetin, kaempferol, caffeic acid, and S-alk(en)yl-L-cysteine sulfoxides, which promote heart health via antioxidant, anti-inflammatory, lipid-lowering, and antihypertensive processes, are primarily responsible for their effects.

Quercetin, a flavonoid that lowers oxidative stress and inflammation-two primary causes of cardiovascular disease-is one of the most significant substances found in onion leaves. According to Griffiths *et al*. (2002), quercetin from *Allium cepa* enhances endothelial function and lessens blood vessel oxidative damage [23-26].

Additionally, organosulfur compounds found in onion leaves have been shown to have antithrombotic and cholesterol-lowering properties. According to Bordia *et al*. (1996), onions' sulphur compounds lower blood lipid levels and platelet aggregation, which lowers the risk of atherosclerosis. These substances aid in improving blood flow and preventing the formation ofclots. Vitamin C, flavonoids, and phenolics are antioxidants found in onion leaves that prevent LDL cholesterol from oxidising, which is a major contributing factor to the development of plaque. The dietary fiber in the leaves also improves lipid metabolism and aids in cholesterol regulation. Onion leaves contain two anti-inflammatory compounds that reduce vascular inflammation, which is strongly linked to hypertension and coronary artery disease: quercetin and ferulic acid. Combining these strategies lowers the risk of cardiovascular disease, increases vascular flexibility, and promotes normal blood pressure. Overall, because they minimize oxidative stress, enhance lipid profiles, promote vasodilation, and lower inflammation, onion leaves are an important dietary component that protects the heart [24-27].

5.2 Antidiabetic potential

Due to their high concentration of flavonoids, phenolic acids, organosulfur compounds, dietary fibre, and antioxidants, onion leaves have a considerable potential to prevent diabetes. Enhancing insulin sensitivity, decreasing glucose absorption, boosting antioxidant defence, and modifying important enzymes involved in carbohydrate metabolism are just a few of the ways these bioactive compounds work. Quercetin, a flavonoid that enhances glucose absorption and controls insulin signalling pathways, is one of the main antidiabetic ingredients in onion leaves. Quercetin helps reduce blood glucose levels by improving insulin sensitivity and increasing AMPK activation [27]. Additionally, kaempferol and luteolin derivatives found in onion leaves slow down the digestion of carbohydrates and

lessen postprandial blood sugar rises by inhibiting the enzymes α-glucosidase and α-amylase. [28].

By increasing pancreatic β-cell function and lowering oxidative stress, organosulfur compounds like S-methyl-L-cysteine sulfoxide (SMCS) and thiosulfinates contribute to antidiabetic benefits. SMCS from *Allium cepa* dramatically reduces fasting blood glucose and improves lipid profiles in diabetic animals, as Augusti and Sheela (1996) showed [27, 28].

5.3 Role in gut health and microbiome modulation

As onion leaves (*Allium cepa* L.) are rich in dietary fibre, prebiotic fructans, flavonoids, and organosulfur compounds, they have a significant role in promoting gut health and modifying the intestinal flora. These bioactive ingredients support good gut flora, strengthen mucosal immunity, facilitate better digestion, and lessen gastrointestinal tract irritation.

The prebiotic fructooligosaccharides (FOS) and inulin-type carbohydrates found in onion tissues-which are also found in the green leaves-are important for intestinal health. Prebiotic fibres specifically promote the growth of Lactobacillus and Bifidobacterium species, which are beneficial microorganisms. These microorganisms create short-chain fatty acids (SCFAs), enhance intestinal barrier function, and lower dangerous bacterial populations [29].

Onion leaves' dietary fibre also promotes regular bowel movements, increases the volume of stool, and improves digestive health in general. SCFAs like butyrate, which are produced by fibre fermentation in the colon, support colonocytes and lower the risk of inflammatory bowel disorders [30, 31]. Onion leaves are rich in flavonoids like quercetin, kaempferol, and luteolin derivatives, which have anti-inflammatory and antioxidant properties that further support intestinal health. By preventing harmful species and promoting the growth of good bacteria, these substances alter the microbial makeup. In particular, quercetin has been demonstrated to lessen intestinal oxidative stress and enhance the integrity of the gut barrier. Onion leaves' organosulfur compounds also have antibacterial properties against pathogenic gut bacteria, assisting in the preservation of microbial equilibrium without upsetting helpful microorganisms [18, 32, 33].

5.4 Anticancer and chemopreventive properties

Due to their abundance of flavonoids, phenolic acids, organosulfur compounds, antioxidants, and vitamins, onion leaves (*Allium cepa* L.) have strong chemopreventive and anticancer effects. These bioactive substances work in a variety of ways, such as preventing the growth of tumours, triggering apoptosis, reducing inflammation, and shielding cells from oxidative damage [28, 34, 33].

Quercetin, a powerful flavonoid that inhibits the growth of cancer cells, is the most researched anticancer ingredient found in onion leaves. By triggering caspase pathways, inhibiting anti-apoptotic proteins, and preventing cell-cycle progression, quercetin causes apoptosis, or programmed cell death [34]. It works well against lung, liver, colon, and breast cancers, among other types of cancer. Onion leaves also contain derivatives of kaempferol and luteolin, which have comparable effects by inhibiting angiogenesis (the growth of new blood vessels in tumours) and downregulating signalling pathways like PI3K/Akt and MAPK [33].

Additionally, Onion leaves contain phenolic acids, such as ferulic and caffeic acids, which reduce DNA damage and neutralize free radicals, delaying the onset of cancer. One of the main causes of cancer is oxidative stress, which is prevented by these antioxidants. Organosulfur compounds, including S-methyl-L-cysteine sulfoxide and thiosulfinates, have demonstrated strong chemopreventive activity. According to Lanzotti (2006), sulfur compounds from Allium species inhibit the growth of tumors by altering detoxification enzymes, boosting glutathione activity, and stopping the production of nitrosamines. By reducing chronic inflammation, which is strongly linked to the development of tumors, onion leaves' anti-inflammatory phytochemicals aid in the prevention of cancer. By inhibiting COX-2, NF-κB, and pro-inflammatory cytokines, these compounds reduce the environment that promotes tumor growth [28].

6. Applications in functional foods and pharmaceuticals

6.1 Food fortification and supplements

Green onion leaves may be processed into powders, extracts, and functional components for use in fortified foods, according to research. Fresh onion leaf extracts have significant amounts of phenolics, flavonoids, and antioxidants, which makes them appropriate for use in formulations that promote health [20]. Onion leaves can be added to flour, soups, sauces, baked goods, and herbal blends because they retain a significant portion of their micronutrient and antioxidant profile when dried and powdered. To increase the amount of fibre, minerals, and antioxidants in cereal-based diets, onion leaf powder has been investigated as a fortifying ingredient. Because flavonoids like quercetin are stable during mild heat processing, they can be added to fortified foods and drinks [35, 36].

Onion leaves can be utilised as supplements in tinctures, pills, capsules, and functional teas. Their organosulfur compounds have been shown to have antidiabetic, antibacterial, and cholesterol-lowering properties, particularly S-methyl-L-cysteine sulfoxide. This validates their application in nutraceutical compositions targeted at immunological support, cardiovascular protection, and metabolic health. Onion leaf-based supplements are beneficial for digestive health because the prebiotic fibres and flavonoids in onion leaves also support the balance of the gut bacteria [29, 37, 38].

6.2 Herbal and nutraceutical formulations

Rich in vitamins, flavonoids, phenolic acids, minerals, chlorophyll, dietary fibre, and organosulfur compounds, onion leaves have great potential for use in herbal and nutraceutical formulations. They are appropriate for health-promoting products because of their varied bioactive profile, which promotes antioxidant, antibacterial, anti-inflammatory, antidiabetic, cardioprotective, and immunomodulatory actions [20, 29].

Powders, extracts, tinctures, capsules, and functional drinks can all be made from onion leaves. According to studies, green onion leaf extracts maintain high concentrations of sulphur compounds, ferulic acid, caffeic acid, kaempferol, and quercetin, all of which have therapeutic advantages. Herbal compositions that address oxidative stress, inflammation, digestive issues, and metabolic diseases include these extracts [20, 39].

Due to their high fibre and antioxidant content, herbal

powders prepared from dried onion leaves are frequently employed in traditional medicines to promote digestion and strengthen immunity. They are also appropriate for herbal teas and polyherbal blends used for detoxification and respiratory support because of their high quercetin content. Onion leaf extract contains high flavonoids and sulphur compounds linked to antidiabetic benefits in nutraceutical capsules and tablets. Augusti & Sheela (1996) shown that sulphur compounds produced from onions considerably improve lipid metabolism and lower blood glucose, which supports their usage in supplements for metabolic health. Onion leaves can be combined with prebiotic fibres like fructooligosaccharides (FOS) to create gut-health nutraceuticals that support a healthy microbiome. Furthermore, they are appropriate for cardioprotective and anti-aging compositions due to their potent antioxidant action [29].

6.3 Industrial prospects and sustainability

Onion leaves can be processed into powders, extracts, functional ingredients, and supplements for use in the culinary and nutraceutical industries. They can be used to create herbal drinks, fortified foods, anti-inflammatory blends, and gut-health products due to their strong antibacterial and antioxidant properties [20]. Additionally, their phytochemicals and natural colours can be used as clean-label ingredients in functional meals and drinks. Bioactive substances including quercetin, kaempferol, and sulphur derivatives have anti-inflammatory, anti-aging, and antibacterial properties in the pharmaceutical and cosmeceutical industries. These substances promote skin health, lessen oxidative stress, and aid in wound-healing formulas, according to studies. Thus, onion leaf extracts can be utilised in topical herbal treatments, gels, and lotions [28].

From the standpoint of sustainability and the circular economy, onion leaves offer a sustainable way to value trash. When onions are harvested and marketed, a lot of green leaves are thrown away. Utilising these leaves to make value-added goods promotes sustainable agriculture, minimises waste, and lessens pollution in the environment. Because of their organic matter and vitamin content, their conversion into compost or biofertilizers improves soil health [18, 40].

7. Challenges and future prospects

Although a number of limitations restrict their full utilisation, onion leaves (*Allium cepa* L.) are important for industrial applications, herbal medicine, and nutrition. One significant issue is that onion leaves are typically considered agricultural waste, which results in significant losses after harvest. Their high moisture content makes processing, storage, and transportation difficult since it speeds up nutritional loss, microbial development, and breakdown [20].

Additionally, producers do not follow recognised protocols for drying, cleaning, or extracting bioactive compounds from leaves, which leads to inconsistent powder and extract quality.

Another challenge is that businesses and consumers are ignorant of the practical and nutritional advantages of onion leaves. Leaves are given less scientific attention than bulbs, which results in less commercial products such vitamins, fortified foods, or medicinal formulations. Furthermore, variations in phytochemical content-which are impacted by variety, age, habitat, and agricultural practices-make standardisation for pharmaceutical and nutraceutical applications difficult [28].

The prospects for onion leaves in the future are very promising despite these challenges. Opportunities for producing functional foods, nutraceutical supplements, natural preservatives, cosmeceuticals, and herbal medicines are presented by their rich profile of phenolic acids, flavonoids (quercetin, kaempferol), minerals, vitamins, and organosulfur compounds. As interest in plant-based health products grows globally, onion leaf extracts can be helpful ingredients in formulations for gut health, anti-inflammatory, antidiabetic, and antioxidant properties [18].

Onion leaf powder can be added to snacks, soups, baked goods, noodles, and spice mixes in the food sector to increase nutritional value and decrease food waste. The stability and bioavailability of onion leaf bioactives will be further improved by developments in drying technology, microencapsulation, and green extraction methods. From a sustainability standpoint, using onion leaves promotes circular economy models by turning agricultural waste into valuable goods including natural colourants, animal feed additives, biofertilizers, and biodegradable packaging. Commercialisation can be accelerated through increased financing for research, industry partnerships, and consumer education [41-43].

8. Conclusion

Traditionally ignored and frequently thrown away as agricultural waste, onion leaves (*Allium cepa* L.) have become a remarkable source of bioactive chemicals and nutraceuticals with significant promise for improving health. The amazing quantity of flavonoids, phenolic acids, organosulfur compounds, vitamins, minerals, dietary fibre, and antioxidants in these green leaves-all of which promote a range of biological processes-is highlighted in this chapter. Their potent antibacterial, antioxidant, antifungal, antidiabetic, anti-inflammatory, cardioprotective, immunomodulatory, gut-health-promoting, and chemopreventive qualities are supported by scientific data. Onion leaves are a crucial component of contemporary diets and natural healthcare systems due to their numerous therapeutic benefits.

Onion leaves have great potential for use in functional meals, nutritional supplements, herbal formulations, and medicinal treatments in addition to their health benefits. When added to food items including soups, baked goods, snacks, spice blends, and nutraceutical drinks, they can enhance nutritional value and support sustainable food systems. Furthermore, by reducing post-harvest waste and facilitating the creation of environmentally beneficial products like natural preservatives, biofertilizers, biodegradable packaging, and cosmetic formulations, the valorisation of onion leaves aligns with the principles of the circular economy.

Notwithstanding these encouraging uses, there are still issues, such as low consumer knowledge, a lack of industrial processing standards, and inconsistent phytochemical content. To fully realise the economic potential of onion leaves, it will be essential to close these gaps through improved drying technologies, enhanced extraction techniques, better storage procedures, and more funding for research. In conclusion, onion leaves are an underutilised but extremely important bioresource that presents prospects for cost-effectiveness, sustainability, and health

enhancement in the food, pharmaceutical, and nutraceutical industries. Their significance in advancing human health and sustainable development will be strengthened by ongoing research and innovation, which will also broaden their applications.

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10. Conflict of interest
The author declares no conflict of interest.

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