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Review Article

Ocimum Tenuiflorum (Tulsi): Phytochemical Diversity, Therapeutic Applications, And Future Perspectives in Drug Discovery

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ABSTRACT

Ocimum tenuiflorum L. c ommonly known as Tulsi or Holy Basil is a sacred and medicinally important herb of the family Lamiaceae, widely used in traditional systems of medicine across Asia. Its remarkable phytochemical repertoire includes essential oils rich in eugenol and linalool, phenolic acids such as rosmarinic and caffeic acid, flavonoids, and triterpenoids including ursolic and oleanolic acid. These bioactive constituents underpin a wide range of pharmacological properties, including antimicrobial, anti-inflammatory, antioxidant, anticancer, antidiabetic, and neuroprotective effects. Advances in analytical chemistry, metabolomics, and pharmacological assays have provided new insights into the molecular targets and mechanisms of action of Tulsi-derived compounds, highlighting their potential as leads for modern drug discovery. However, variability in chemotypes, limited pharmacokinetic and toxicological data, and insufficient clinical validation remain key challenges. This article consolidates current knowledge on the phytochemical diversity and therapeutic potential of O. tenuiflorum, critically evaluates existing evidence, and outlines future directions for its development as a source of novel bioactive molecules in drug discovery and development.

INTRODUCTION

Tulsi or Holy Basil is a perennial aromatic herb of the family Lamiaceae, revered for centuries in traditional medicine systems such as Ayurveda, Siddha, and Unani, and celebrated culturally as the "Queen of Herbs" for its spiritual and therapeutic significance. Traditionally used to treat respiratory ailments, fever, infections, stress, inflammation, and metabolic disorders, Tulsi has gained modern

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scientific attention due to its diverse phytochemical profile comprising essential oils (eugenol, linalool, methyl eugenol), phenolic acids (rosmarinic, caffeic, chlorogenic), flavonoids (apigenin, luteolin derivatives), triterpenoids (ursolic and oleanolic acids), sterols, and polysaccharides. These metabolites are associated with a broad range of pharmacological activities, including antimicrobial, antioxidant, anti-inflammatory, anticancer, antidiabetic, neuroprotective, and cardioprotective effects, making Tulsi a promising source of lead compounds for drug discovery. Advances in analytical chemistry and metabolomics have provided deeper insights into its chemotype variations and molecular mechanisms, yet challenges such as variability in phytochemical composition, limited pharmacokinetic and toxicological data, and a paucity of well-controlled clinical trials hinder its full translational potential. This review consolidates the current state of knowledge on the phytochemical diversity and therapeutic applications of *O. tenuiflorum*, while also highlighting future directions for its integration into modern drug discovery and development.



Importance In Herbal Medicine

As a "Rasayana" plant, Tulsi is prized for its restorative, adaptogenic, and illness-preventive qualities. Tulsi is used as a general health-promoting tonic and in traditional systems like Ayurveda, Siddha, Unani, and diverse folk practices to treat respiratory conditions, fever, cough, asthma, gastrointestinal issues, inflammation, and skin illnesses[1]. It is known as the "Queen of Herbs" due to its extensive use as decoctions, herbal teas, tinctures, powders, and poultices, which demonstrate its adaptability in both medicinal and preventive applications. Over the past century, phytochemical studies have uncovered a varied chemical profile that supports and broadens its conventional applications. Tulsi is a rich source of phenolic acids (rosmarinic, caffeic, and chlorogenic), flavonoids (apigenin, luteolin, orientin, and vicenin), triterpenoids (ursolic and oleanolic acids), sterols, immunomodulatory polysaccharides, and essential oils (eugenol, linalool, methyl eugenol, and β-caryophyllene). Tulsi is a good option for evidence-based herbal treatments because of the diverse range of pharmacological benefits that these ingredients provide, including antibacterial, antioxidant, anti-inflammatory, anticancer, antidiabetic, cardioprotective, neuroprotective, and adaptogenic action[2].Globally, Tulsi is gaining recognition as an ingredient in herbal teas, nutraceuticals, functional foods, cosmeceuticals, and standardized phytopharmaceutical formulations, reflecting its transition from traditional medicine into mainstream health applications.

Description

Growing between 30 and 90 cm in height, Tulsi is a perennial aromatic shrub belonging to the Lamiaceae family. It has highly branching morphology and hairy, quadrangular stems. The plant's distinctive scent comes from the abundance of glandular trichomes on its opposing, elliptical, serrated leaves which is usually 2–5 cm long,

which release essential oils. There are two primary types that are known to exist which are purple-leaved (Krishna Tulsi) and green-leaved (Sri Tulsi). The plant produces racemes of tiny, purple to reddish flowers with four Lamiaceae-typical stamens and a bilabiate corolla. Fruits are little brown nutlets with a prolonged calyx around them. Tulsi is widely grown for its culinary, medicinal, and religious uses in India and Southeast Asia. It requires well-drained soils and grows well in tropical and subtropical climes[3].

Phytochemical Diversity

The secondary metabolite profile of the chemically abundant medicinal plant *Ocimum tenuiflorum* (Tulsi) includes phenolic acids, flavonoids, triterpenoids, sterols, polysaccharides, volatile essential oils, and a number of other minor compounds. This chemo diversity is influenced by genetics (chemotypes), environment (soil, season, climate), plant component, and extraction/analysis techniques. It manifests itself in both qualitative composition (which classes of compounds are present) and quantitative variability (relative amounts of certain compounds). Tulsi's reputation as a versatile phytochemical reservoir is confirmed by recent thorough studies and metabolomic surveys, which makes it appealing for both conventional applications and current drug-discovery initiatives[4,5].

- One of the most unique and extensively researched facets of Tulsi chemistry is the volatile fraction, or essential oil. Though their relative proportions differ greatly throughout chemotypes, the oils are generally rich in phenylpropanoids and terpenoids, most notably eugenol, methyl eugenol, linalool, β-caryophyllene, and 1,8-cineole.

- Eugenol-rich, linalool-rich, or methyl-eugenol-rich chemotypes are frequently used to classify tulsi populations; reports show that some accessions have eugenol levels ranging from about 20% to over 70%. Harvest period, plant age, and distillation technique all have a significant impact on essential oil yield and composition, which is crucial when relating oil composition to bioactivity[6].

- Another significant bioactive component is made up of non-volatile phenolic chemicals. Other prevalent phenolic acids include caffeic, chlorogenic, and ferulic acids; rosmarinic acid is extensively employed as an analytical/standardization marker and is often described as a dominating phenolic in tulsi. According to mechanistic and in vivo research, these polyphenols are principally in charge of Tulsi's antioxidant and anti-inflammatory properties through metal chelation, radical scavenging, and regulation of signalling pathways like NF-κB and MAPKs[7].Among water-soluble phenolics, rosmarinic acid frequently exhibits the highest quantities, while the quantitative amounts reported in the literature vary depending on the extraction solvent and plant origin.

- Tulsi leaves are rich in flavonoids and flavone glycosides, which support the plant's antibacterial and cytoprotective properties. Apigenin, luteolin, orientin, vicenin, and other quercetin glycosides are examples of representative molecules; many of them occur as O-glycosides that impact solubility and bioavailability. In cell and animal models, these flavonoids have been connected to anti-proliferative, anti-inflammatory, and neuroprotective properties. They frequently work in tandem with phenolic acids to provide antioxidant capacity. These flavonoid profiles have been mapped across cultivars with the aid

of high-performance LC and NMR-based metabolomics studies[8,9,10,11].

- A third significant non-volatile group of interest for drug discovery consists of sterols and triterpenoids. Tulsi leaf extracts have been shown to include pentacyclic triterpenoids, such as ursolic acid and oleanolic acid, which have been shown to have multi-target pharmacology, including hepatoprotective, anti-inflammatory, anticancer, and metabolic regulating properties. Additionally present are sterols that have lipid-modulating and cardiovascular effects, such as stigmasterol and β-sitosterol. Triterpenoids are typically identified by organic solvent extraction, chromatographic isolation, and $^{13}C/^{1}H$-NMR confirmation because they are very nonpolar and frequently present in dried leaves at low percentage levels.

- In addition to the main classes, Tulsi contains fatty acids, coumarins, physiologically significant polysaccharides, and trace alkaloid-like substances[12,13,14]. While coumarins (including scopoletin) and specific fatty acids contribute to antioxidant and cell-membrane effects, polysaccharide fractions have been demonstrated to have immunomodulatory activity both in vitro and in vivo. Although these minor or high molecular weight components are not as well understood, they may be crucial to the overall pharmacology of whole plant extracts.

Major Phytochemicals

Compound	Class	Plant Part	Concentration	Bioactivities
Eugenol	Phenylpropanoid (volatile oil)	Leaves, flowers	20–70% of essential oil (chemotype-dependent)	Antimicrobial, analgesic, anti-inflammatory
Linalool	Monoterpene alcohol	Leaves	up to 30% of essential oil	Sedative, antimicrobial
Methyl eugenol	Phenylpropanoid	Leaves	variable, chemotype-dependent	Insect repellent, antimicrobial
β-Caryophyllene	Sesquiterpene	Leaves	5–10% of essential oil	Anti-inflammatory, analgesic
Rosmarinic acid	Phenolic acid	Leaves	0.5–2% dry weight	Antioxidant, anti-inflammatory
Apigenin	Flavonoid	Leaves	trace–0.1%	Anticancer, antioxidant
Ursolic acid	Triterpenoid	Leaves	0.2–0.6% dry weight	Anticancer, hepatoprotective, anti-inflammatory
Oleanolic acid	Triterpenoid	Leaves	~0.1–0.3%	Antioxidant, hepatoprotective
β-Sitosterol	Sterol	Leaves	Variable	Anti-hyperlipidemic, anti-inflammatory

Antimicrobial activity

Broad-spectrum antibacterial qualities against viruses, fungi, and bacteria are demonstrated by tulsi. Essential oil compounds including β-caryophyllene, linalool, and eugenol break down microbial membranes and allow cell contents to seep out[15]. Staphylococcus aureus, Escherichia coli, Klebsiella pneumoniae, and Candida albicans have all been demonstrated to be inhibited by

extracts. Preliminary research has also shown antiviral activity against SARS-CoV-2, herpes simplex, and influenza. Combination studies indicate that Tulsi may lessen germ resistance and increase the effectiveness of antibiotics[16].

Anti-inflammatory and Immunomodulary Effects

Both volatile and non-volatile components of Tulsi exhibit potent anti-inflammatory properties[17]. By inhibiting pro-inflammatory enzymes including cyclooxygenase (COX) and lipoxygenase (LOX), ursolic acid and eugenol lower the production of prostaglandins and leukotrienes. Rosmarinic acid reduces pro-inflammatory cytokines such IL-1β, TNF-α, and IL-6 by modulating the NF-κB and MAPK signalling pathways [18,19].Tulsi extracts considerably lessen formalin-induced arthritis and carrageenan-induced paw oedema in rats when administered in vivo. Phagocytic activity is increased by polysaccharide fractions, confirming its historical function as an immunomodulator and adaptogen.

Antioxidant activity

Strong radical-scavenging capabilities are provided by polyphenols such apigenin, caffeic acid, and rosmarinic acid. Tulsi extracts, both aqueous and ethanolic, show strong activity in the DPPH, ABTS, and FRAP tests[20]. Additionally, these chemicals defend against damage caused by oxidative stress by upregulating endogenous antioxidant defences such as glutathione, catalase, and superoxide dismutase. Numerous therapeutic properties of Tulsi, such as neuroprotection, hepatoprotection, and anticancer activity, are supported by antioxidant processes[21].

Anticancer potential

Tulsi's main anticancer components are the triterpenoids ursolic acid and oleanolic acid. By suppressing VEGF, they prevent angiogenesis, alter PI3K/Akt and MAPK signalling, and trigger apoptosis through mitochondrial pathways (upregulation of Bax, caspase activation)[22].

Additional cytotoxic and chemo preventive actions are provided by flavonoids including orientin and apigenin . In animal models of skin and lung carcinogenesis, Tulsi extracts decrease tumor incidence and suppress the growth of breast, colon, and pancreatic cancer cell lines. Despite the strength of preclinical evidence, there is still a lack of clinical validation[23].

Antidiabetic and metabolic effects

Tulsi extracts increase insulin secretion, block α-glucosidase and α-amylase, and encourage peripheral glucose absorption. Studies on animals show better lipid profiles and decreased fasting blood glucose. HbA1c, postprandial, and fasting glucose levels are shown to decrease in type 2 diabetic patients in small-scale clinical trials. Flavonoid glycosides, rosmarinic acid, and ursolic acid are primarily responsible for these actions[24,25].

Neuroprotective and stress modulating effects

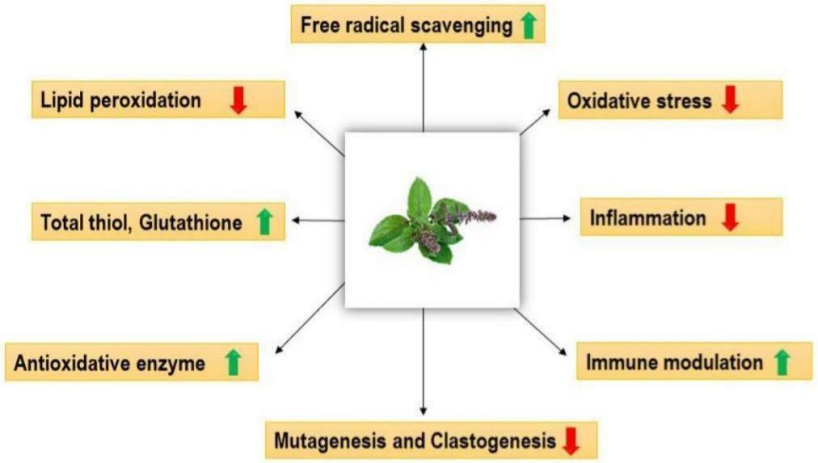
Tulsi, which is traditionally considered a Rasayana, has neuroprotective and adaptogenic properties. Eugenol has anxiolytic and antidepressant-like effects, whereas the flavonoids orientin and vicenin shield neurons from oxidative stress and excitotoxicity . Tulsi has been shown in animal models to enhance memory retention, prevent neurodegenerative alterations, and lower stress-induced cortisol rise. These results provide credence to its long-standing applications in stress reduction and cognitive improvement[26].

Cardioprotective and hepatoprotective effects

Triterpenoids and sterols (β-sitosterol) found in Tulsi have hepatoprotective, antihypertensive, and lipid-lowering properties. Extracts raise HDL cholesterol, lower triglycerides and blood cholesterol, and stop the development of atherosclerotic plaque[27]. Tulsi extracts, mostly through antioxidant and anti-inflammatory mechanisms, reduce transaminase levels and arrest histological alterations brought on by CCl_4 and paracetamol in hepatotoxicity models[28].

Wound healing and Dermatological applications

In animal studies, topical Tulsi administration speeds up collagen synthesis, wound contraction, and epithelialization . Its antibacterial and anti-inflammatory qualities aid in the healing process even more. Formulations containing essential oils are used to treat inflammatory skin disorders, acne, and cutaneous fungal infections[29].



Uses Of Tulsi Plant

Tulsi, or *Ocimum tenuiflorum*, is a Rasayana herb that is valued for fostering longevity, fortitude, and general health in Ayurvedic, Siddha, and Unani medicine. Tulsi has long been used to treat a variety of illnesses, including worm infestations, diarrhoea, and indigestion; feverish conditions like dengue and malaria; and respiratory disorders including cough, cold, bronchitis, and asthma. While leaf pastes and oils are frequently used to treat wounds, skin diseases, and insect bites, decoctions, leaf juices, and herbal teas (kadha) made with Tulsi are used as home remedies. Chewing leaves is advised for stress reduction and dental hygiene, and seeds are utilized as a cooling agent in urinary diseases. In ritual and cultural contexts, Tulsi is considered a sacred plant believed to purify the environment and protect against illness[30,31]. Since Tulsi's essential oils (eugenol, linalool), phenolics (rosmarinic acid, caffeic acid), flavonoids (orientin, vicenin), and triterpenoids (ursolic, oleanolic acids) have shown antimicrobial, anti-inflammatory, antioxidant, adaptogenic, and wound-healing qualities, these traditional uses closely align with pharmacological findings. Tulsi's function as a "bridge plant" connecting traditional methods to scientifically supported treatments is highlighted by the intersection between ethnomedicine and contemporary pharmacology.

Applications Of Tulsi

The food and nutraceutical industries are using tulsi more and more because of its potent scent, bioactive ingredients, and health-promoting qualities. Because of its antibacterial, adaptogenic, and antioxidant properties, Tulsi leaves are used in herbal teas, functional drinks, and flavoured water. As natural flavorings and preservatives, leaf extracts are added to dairy products, confections, and baked goods to prolong their shelf life by preventing microbiological growth. Because of its antibacterial properties, tulsi essential oil, which is high in eugenol and linalool, is used in food packing and preservation. Tulsi extracts and powders are sold as dietary supplements for improving immunity, reducing stress, and maintaining metabolic health in functional meals. It is also useful for lowering lipid oxidation in processed foods due to its natural antioxidant properties, which enhances both quality and safety[32].

Therapeutic Applications

Antimicrobial, anti-inflammatory, antioxidant, antidiabetic, anticancer, cardioprotective, hepatoprotective, neuroprotective, and wound-healing properties are just a few of the many therapeutic benefits that make tulsi (Ocimum tenuiflorum) valuable. Together, its phenolics (rosmarinic acid), flavonoids (orientin, vicenin), essential oils (eugenol, linalool), and triterpenoids (ursolic and oleanolic acids) combat infections, control oxidative stress, boost immunity, safeguard key organs, and promote metabolic health[33]. Tulsi is one of the most significant medicinal plants that connects traditional medicine with contemporary therapeutic uses since it is also regarded as an adaptogen, which lowers stress and increases general resilience.

Future Perspectives in Drug Discovery

1. **Lead compounds as drug scaffolds:** Tulsi's phytochemical diversity offers a special resource for the development of novel medicinal compounds. Ursolic acid, oleanolic acid, rosmarinic acid, eugenol, and other flavonoids are examples of compounds with multi-target pharmacology that alter pathways linked to infection, oxidative stress, inflammation, the development of cancer, and metabolic diseases. Tulsi-derived phytochemicals frequently work via a network pharmacology method, in contrast to single-target synthetic medications. This makes them promising candidates for the treatment of complicated, multifactorial diseases like diabetes, cancer, and neurodegenerative disorders. This implies that systems biology and network-based drug design techniques employing Tulsi phytoconstituents as lead compounds may prove advantageous in future drug development.

2. **Omics-based approaches:** The discovery of bioactive substances and their molecular targets is anticipated to be sped up by developments in omics technologies, such as metabolomics, transcriptomics, and proteomics. Tulsi phytochemical binding affinities with disease-relevant proteins can be predicted using high-throughput screening and in silico techniques like molecular docking and dynamic simulations. In order to improve potency and selectivity, these methods will aid in the establishment of precise mechanism of action routes and direct logical changes of natural scaffolds. By using extensive datasets from experimental investigations conducted in Tulsi, artificial intelligence and machine learning algorithms have the potential to enhance predictive drug discovery pipelines.

3. **Nanotechnology formulations:** Poor pharmacokinetics and bioavailability of chemicals obtained from plants present another significant obstacle in the development of herbal drugs. Despite compelling preclinical evidence, ursolic acid and rosmarinic acid have a high rate of metabolism and poor water solubility. Formulations based on nanotechnology, such as solid lipid nanoparticles, polymeric nanoparticles, liposomes, and nanoemulsions, hold promise for the future since they can increase systemic circulation, improve oral absorption, and deliver drugs precisely where they are needed. By limiting off-target effects, such delivery techniques may lessen toxicity in addition to increasing efficacy. Therefore, traditional herbal medicines can be transformed into clinically viable phytopharmaceuticals by combining Tulsi-derived bioactives with sophisticated formulation techniques.

4. **Synergistic use:** Additionally, there is a lot of room for formulations that work well together. Future drug discovery can investigate polyherbal formulations and multi-herb synergistic effects, as Tulsi has historically been utilized in Ayurvedic medicine in conjunction with other herbs. In fields where combination mechanisms are more effective than single molecules, such as immunomodulation, metabolic regulation, and stress adaptability, this could be very helpful. In a similar vein, the creation of functional foods, nutraceuticals, and fortified beverages that contain Tulsi extracts may supplement conventional treatment while offering preventive health advantages.

5. **Standardization:** Regulatory validation and standardization continue to be major obstacles to the widespread use of treatments based on tulsi. Differences in phytochemical concentration and efficacy are caused by variations in chemotypes, geographic origin, harvesting season, and extraction methods. Standardized cultivation methods, verified extraction techniques, and marker-based quality control—using rosmarinic acid, ursolic acid, and eugenol as reference compounds—must be the main focus of future research. To guarantee reproducibility and international market acceptance, pharmacopeial monographs must be established and Good Manufacturing Practices (GMP) and Good Agricultural and Collection Practices (GACP) must be followed.

6. **Clinical validation:** Lastly, the requirement for carefully planned clinical trials is critical. The majority of current research on Tulsi is restricted to small-scale human trials with methodological flaws or preclinical models. It is necessary to conduct extensive, double-blind, randomized, placebo-controlled clinical trials to verify safety and effectiveness in certain disease areas. To convert lab results into evidence-based phytopharmaceuticals, cooperation between ethnopharmacologists, clinical researchers, and the pharmaceutical industry will be crucial.

7. **Drug discovery reservoir:** With its diverse phytochemistry, Tulsi holds promise for developing next-generation treatments for metabolic, inflammatory, infectious, and neurodegenerative diseases.

CONCLUSION

One of the most significant medicinal plants is Tulsi, which connects traditional wisdom with contemporary scientific verification. Numerous therapeutic uses, including

antimicrobial, anti-inflammatory, antioxidant, anticancer, antidiabetic, cardioprotective, neuroprotective, and wound-healing properties, are supported by its diverse phytochemical profile, which includes essential oils, phenolic acids, flavonoids, triterpenoids, and sterols. Emerging pharmacological research supports the traditional use of Tulsi in Ayurveda and other medical systems, emphasizing its value as a preventative and curative agent. There are still issues with standardization, chemotype variability, and the absence of extensive human trials, despite encouraging preclinical and limited clinical results. To transform Tulsi from a culturally valued herb into evidence-based phytopharmaceuticals, future studies concentrating on bioactive lead optimization, formulations based on nanotechnology, pharmacokinetics, and thorough clinical validation will be essential. With its unique combination of cultural significance and scientific potential, Tulsi represents not only a cornerstone of herbal medicine but also a valuable reservoir for next-generation drug discovery.

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