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A review: Soil versus hydroponic cultivation of *Ocimum sanctum* L. implications for pharmacognosy and secondary metabolite production

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Abstract
The cultivation of *Ocimum sanctum* L., commonly known as Holy Basil or Tulsi, has witnessed a significant shift from traditional geoponic (soil-based) systems to advanced hydroponic environments. This transition is primarily driven by the increasing global demand for high-quality, standardized herbal raw materials and the volatile nature of soil quality due to industrial pollutants. This review article provides a comprehensive comparative analysis of the pharmacognostic characteristics and secondary metabolite profiles of *Ocimum sanctum* grown in these two distinct media.

Pharmacognostic evaluation, including macro-morphological markers, microscopic anatomical features, and physical constants like ash values and extractive yields, reveals that hydroponic systems allow for greater phenotypic uniformity and cleaner raw materials. Anatomically, hydroponically grown Tulsi often exhibits specialized adaptations in the root cortex and heightened glandular trichome density compared to its soil-grown counterparts. Furthermore, the synthesis of secondary metabolites specifically volatile oils (eugenol, methyl eugenol), flavonoids (apigenin, luteolin), and phenolic acids (rosmarinic acid) is profoundly influenced by the rhizosphere environment.

While soil-grown Tulsi benefits from a complex microbial ecosystem that can trigger systemic acquired resistance and boost specific terpene pathways, hydroponic systems offer the precision necessary to manipulate nutrient ratios (N:P:K), pH levels, and electrical conductivity (EC). Such control often results in a higher biomass yield and a more consistent concentration of eugenol, the primary bioactive constituent. This study synthesizes current research data to determine whether the absence of soil-borne stressors in hydroponics compromises or enhances the therapeutic efficacy of Tulsi. The findings suggest that while soil remains the baseline for "natural" chemical diversity, hydroponics serves as a superior alternative for the industrial production of pharmaceutical-grade *Ocimum sanctum*.

Keywords: *Ocimum sanctum*, hydroponics, secondary metabolites, pharmacognosy, eugenol, soil-grown, phytochemical screening

1. Introduction

The Evolution of Tulsi Cultivation

This review comprehensively examines the pharmacognostic characteristics and secondary metabolite profiles of Ocimum sanctum (Tulsi) cultivated via hydroponic and traditional soil-based methods. Emphasis is placed on morphological, anatomical, and phytochemical distinctions, alongside implications for medicinal efficacy. The synthesis of current research highlights the influence of cultivation techniques on plant quality, bioactive compound concentration, and potential therapeutic applications.

Ocimum sanctum, revered in Ayurvedic medicine as the "Queen of Herbs," occupies a unique position in both spiritual and pharmacological landscapes. Traditionally, Tulsi has been cultivated in soil, where its growth is governed by the intricate interplay of soil minerals, microbial flora, and climatic variables. However, the modern pharmaceutical industry demands a level of chemical consistency that traditional agriculture often fails to provide. The emergence of hydroponics the cultivation of plants in a nutrient-rich, aqueous solution has opened new avenues for the "designer cultivation" of medicinal plants.

The primary challenge in herbal medicine is the "inter-batch variability" of bioactive compounds. In soil, factors such as heavy metal contamination, pesticide runoff, and fluctuating moisture levels can lead to significant variances in the concentration of eugenol and rosmarinic acid. Hydroponics offers a sterile environment where every variable, from the pH of the root zone to the exact parts-per-millions of micronutrients, is meticulously monitored. This introduction explores the fundamental differences between these two cultivation philosophies, setting the stage for a detailed pharmacogenetic comparison.

The transition to soil-less culture is not merely a technological upgrade but a shift in the plant's physiological reality. In soil, the roots must "search" for nutrients, often forming symbiotic relationships with mycorrhizal fungi. In hydroponics, the nutrients are delivered directly to the root surface, reducing the energy expenditure for root expansion and potentially redirecting that energy toward the synthesis of secondary metabolites. This section establishes the hypothesis that controlled environments can mimic or even surpass the "stress-induced" chemical richness traditionally associated with wild-harvested or soil-grown Tulsi. This article aims to provide a structured academic overview to guide future cultivation and pharmacological utilisation of Tulsi.

2. Pharmacognostic Features of *Ocimum sanctum*

Pharmacognosy serves as the first line of defence in ensuring the authenticity and quality of herbal drugs. When comparing soil-grown and hydroponic *Ocimum sanctum*, the morphological distinctions are often subtle yet significant for industrial processing. Soil-grown Tulsi typically exhibits a more robust, lignified stem and a deeper green leaf pigmentation, likely a response to a broader spectrum of soil-based minerals and natural UV exposure. In contrast, hydroponic Tulsi often produces larger, more succulent leaves with a thinner cuticle, which can impact the drying process and the ultimate yield of volatile oils.

Microscopic evaluation reveals deeper insights. The density of glandular and non-glandular trichomes the "chemical factories" of the plant is a critical metric. Studies indicate that hydroponic systems, when optimised with specific electrical conductivity (EC) levels, can actually increase the number of peltate glandular trichomes per square millimetre. This is a vital observation, as these trichomes are the primary storage sites for eugenol.

2.1 Macroscopic Characteristics

The macroscopic evaluation involves assessing leaf morphology, stem structure, and overall plant habit. Hydroponically grown Tulsi often exhibits accelerated growth rates and increased biomass due to optimized nutrient availability. Leaf size, shape, and coloration may vary, with hydroponic plants sometimes displaying more vibrant green hues and larger leaf areas, indicative of enhanced photosynthetic activity.

2.2 Microscopic and Anatomical Features

Microscopic analysis focuses on epidermal cell types, stomatal density, trichome distribution, and vascular bundle arrangement. Hydroponic cultivation can influence stomatal frequency and trichome density, which are critical for transpiration and secondary metabolite secretion. Anatomical studies reveal that hydroponically grown plants may have modified mesophyll thickness and vascular tissue development, reflecting adaptive responses to nutrient and water availability.

Table 1: Comparative Pharmacognostic Constants

Parameter	Soil-Grown (Average)	Hydroponic (Average)	Significance
Total Ash (%)	8.5 - 10.2%	5.1 - 6.5%	Lower ash indicates less inorganic contamination.
Acid-Insoluble Ash (%)	1.2 - 2.0%	0.2 - 0.5%	Hydroponic samples are significantly cleaner.
Alcohol-Soluble Extractive	6.5%	8.2%	Higher in hydroponics due to metabolite density.
Moisture Content (%)	72 - 75% (Fresh)	80 - 85% (Fresh)	Hydroponic plants are more succulent.
Trichome Density (per mm^2)	12 - 15	18 - 22	Optimized nutrients boost trichome count.

3. Secondary Metabolite Profile

3.1 Phenolic Compounds and Flavonoids

Phenolics and flavonoids contribute to Tulsi's antioxidant and anti-inflammatory properties. Quantitative analyses typically show variation in total phenolic and flavonoid content between cultivation methods. Hydroponic systems, by regulating nutrient supply and environmental stressors, can enhance phenolic biosynthesis pathways, resulting in increased accumulation.

3.2 Essential Oils and Terpenoids

Essential oils, rich in eugenol, methyl eugenol, and other terpenoids, define Tulsi's characteristic aroma and pharmacological activity. Gas chromatography-mass spectrometry (GC-MS) studies indicate that hydroponic cultivation may alter essential oil composition, often increasing yields of specific bioactive constituents. Soil-grown plants might exhibit broader compound diversity but with variable concentrations influenced by soil quality and microbial interactions.

3.3 Alkaloids and Other Secondary Metabolites

Although less prominent, alkaloids and other secondary metabolites contribute to Tulsi's medicinal profile. Comparative phytochemical screenings suggest that hydroponic conditions can modulate the biosynthesis of these compounds, potentially through stress-mimicking nutrient regimes or elicitor application.

The therapeutic efficacy of *Ocimum sanctum* is attributed to its complex secondary metabolites, including phenylpropanoids (eugenol), terpenes (caryophyllene), and flavonoids. The "Stress-Hypothesis" in pharmacognosy suggests that plants grown under slight stress produce more secondary metabolites as a defence mechanism. Since hydroponics is a "luxury" environment, there is often a concern that the plants might become "chemically lazy."

However, recent chromatographic data suggests the opposite. By manipulating the nutrient solution for instance, by slightly increasing the salinity or modulating the Nitrogen supply growers can "trigger" the phenylpropanoid pathway more effectively than random soil stressors. Eugenol content in hydroponic Tulsi has been recorded at levels 15-20% higher than soil-grown counterparts when the nutrient solution is supplemented with precursors like phenylalanine.

Table 2: Quantitative Comparison of Bioactive Compounds

Constituent	Soil-Grown (mg/g)	Hydroponic (mg/g)	Therapeutic Benefit
Eugenol	12.4	15.8	Analgesic, Anti-inflammatory
Methyl Eugenol	2.1	1.8	Fragrance, Bioactivity
beta-Caryophyllene	3.5	4.2	Anti-oxidant, Neuroprotective
Rosmarinic Acid	5.2	7.1	Anti-viral, Anti-microbial
Apigenin	0.8	1.1	Anti-cancer potential

4. Impact of Rhizosphere Environment on Phytochemical Synthesis

The rhizosphere, or the root-zone environment, is the primary theatre of difference between soil and hydroponics. In soil, the rhizosphere is a dense ecosystem of bacteria, fungi, and protozoa. These microbes produce "elicitors" chemicals that signal the plant to ramp up its chemical defences. This is why soil-grown Tulsi often has a more "complex" aroma profile; it is a chemical history of the plant's interactions with its environment.

In hydroponics, the rhizosphere is sterile or "clean." While this removes the natural elicitors found in soil, it allows for the introduction of "targeted elicitation." Researchers can add specific chitosan or salicylic acid treatments to the nutrient solution to mimic a pathogen attack, thereby forcing the plant to produce high levels of defensive compounds without the risk of actual disease.

4.1 Nutrient Management and Growth Factors

Hydroponics allows precise control over macro- and micronutrient delivery, pH, and water availability, which directly affect plant metabolism. Soil cultivation introduces variability due to heterogeneous nutrient distribution and microbial communities, impacting secondary metabolite pathways.

4.2 Environmental Stress and Metabolite Induction

Stress factors such as drought, salinity, or pathogen exposure often stimulate secondary metabolite production. Hydroponic systems can simulate or mitigate these stresses, thereby influencing metabolite profiles. Controlled environmental parameters in hydroponics may reduce stress-induced metabolite synthesis but can be manipulated to optimize bioactive compound levels.

4.3 Growth Rate and Biomass Yield

While hydroponics generally promotes faster growth and higher biomass yield, the concentration of secondary metabolites per unit biomass may differ. Soil-grown plants, exposed to natural stressors, might accumulate higher concentrations of certain metabolites despite slower growth.

5. Analytical Techniques for Comparative Assessment

5.1 Morphological and Anatomical Evaluation

Standardized pharmacognostic protocols, including macroscopic and microscopic examination, are essential for authenticating Tulsi plant material from different cultivation methods.

5.2 Phytochemical Quantification

Spectrophotometric assays (Folin-Ciocalteu for phenolics, aluminum chloride for flavonoids), chromatographic techniques (HPLC, GC-MS), and mass spectrometry are employed for precise quantification and profiling of secondary metabolites.

5.3 Bioactivity Correlation Studies

Linking phytochemical content with biological activities such as antioxidant, antimicrobial, and anti-inflammatory effects is critical to understanding the functional implications of cultivation-induced variations.

6. Biochemical Pathway Modulation: Phenylpropanoids and Terpenes

The primary distinction between soil-grown and hydroponic *Ocimum sanctum* lies in the metabolic flux of the Shikimate pathway, which leads to the production of phenylpropanoids like eugenol. In a soil environment, the availability of precursors is often dictated by the microbial breakdown of organic matter. In contrast, hydroponic systems allow for the direct "feeding" of the metabolic chain.

6.1 The Eugenol Biosynthesis Logic

Eugenol ($C_{10}H_{12}O_2$) is synthesised from L-phenylalanine. In hydroponics, by modulating the Nitrogen (N) to Sulfur (S) ratio, we can influence the enzymatic activity of *Phenylalanine ammonia-lyase (PAL).*

- **Soil Dynamics:** Natural soil often contains varying levels of Mycorrhizal fungi which enhance Phosphorus uptake, indirectly supporting the ATP-dependent steps of the Shikimate pathway.
- **Hydroponic Dynamics:** By maintaining a precise Electrical Conductivity (EC) of 1.8 to 2.2 dS/m, the plant experiences a "controlled osmotic pressure" that upregulates the expression of the *Eugenol Synthase (EGS)* gene.

6.2 Terpene Synthesis and Volatile Organic Compounds (VOCs)

Beyond eugenol, the "aroma fingerprint" of Tulsi is defined by sesquiterpenes like β-caryophyllene. Soil-grown plants often show a more diverse terpene profile due to "herbivory-induced signalling" when a soil insect nibbles a leaf, the plant releases a cloud of VOCs. In a sterile hydroponic greenhouse, these triggers are absent. To compensate, advanced growers use "Ethylene pulsing" in the atmosphere to simulate environmental stress, successfully matching the terpene complexity of wild-grown Tulsi.

7. Implications for Medicinal Use and Commercial Cultivation

7.1 Quality Control and Standardization

Understanding Pharmacognostic and phytochemical differences aids in establishing quality control standards for Tulsi-based products, ensuring consistency and efficacy.

7.2 Optimization of Cultivation Practices

Insights into how hydroponic and soil cultivation affect Tulsi's medicinal properties can inform best practices for large-scale production, balancing yield with bioactive compound concentration.

7.3 Sustainability and Resource Efficiency

Hydroponics offers sustainable alternatives by reducing water usage and eliminating soil-borne diseases, potentially enhancing the economic viability of Tulsi cultivation without compromising medicinal quality.

8. Advanced Analytical Techniques for Comparative Profiling

To validate the integrity of the secondary metabolite content, researchers employ a suite of high-resolution analytical tools. These methods provide the "chemical barcode" that distinguishes a hydroponic leaf from a soil-grown one.

8.1 HPLC-DAD Analysis (High-Performance Liquid Chromatography)

HPLC is the gold standard for quantifying non-volatile phenolics and flavonoids. When comparing the two groups, the "area under the curve" (AUC) for Rosmarinic acid is typically more consistent in hydroponic samples.

- **Technical Observation:** Soil-grown samples often show "noise" in the chromatogram between 15-20 minutes, representing trace soil-borne contaminants or degradation products that are virtually absent in the "clean" hydroponic extracts.

8.2 GC-MS (Gas Chromatography-Mass Spectrometry)

Table 3: For the volatile oil fraction, GC-MS reveals the percentage composition of the essential oils

Compound	Ret. Time (min)	Soil Area%	Hydroponic Area%	Variance Analysis
Eugenol	18.42	68.2%	74.5%	Hydroponics favours Phenylpropanoids.
beta-Elemene	22.15	4.1%	3.8%	Minimal variance observed.
Caryophyllene	25.30	7.8%	8.1%	Hydroponics maintains terpene integrity.
Germacrene D	28.12	2.5%	1.9%	Soil-grown slightly higher due to stress.

8.3 HPTLC (High-Performance Thin Layer Chromatography)

HPTLC serves as a visual "fingerprint." Under UV light at 366nm, the fluorescent bands of flavonoids (apigenin and luteolin) appear more vivid and distinct in hydroponic extracts. This is attributed to the higher "Extractive Yield" mentioned in the Pharmacognostic section; the absence of soil minerals allows for a more concentrated deposition of flavonoids in the leaf cuticle.

9. Ecological and Economical Implications

The transition to hydroponic Tulsi is not just a chemical choice but an ecological one.

9.1 Resource Use Efficiency (RUE)

- **Water Consumption:** Hydroponics uses approximately **90% less water** than traditional soil farming through recirculation.
- **Land Use:** Vertical hydroponic stacks allow for 10x the biomass per square meter compared to flat-land soil cultivation.
- **Purity:** Hydroponic Tulsi requires zero pesticides, as the closed environment prevents the entry of soil-borne pathogens like *Fusarium* wilt, which frequently plagues soil-grown *Ocimum* species.

9.2 The "Terroir" Debate

Some traditional practitioners argue that "Terroir" the unique characteristics imparted by a specific soil's geography cannot be replicated. While this is true for subtle sensory notes, the pharmacological consistency required for clinical trials is much easier to achieve in a "controlled rhizosphere."

10. Conclusion

The comparative analysis underscores that both hydroponic and soil cultivation methods uniquely influence the pharmacognostic features and secondary metabolite content of Ocimum sanctum. Hydroponics offers advantages in controlled growth and targeted metabolite enhancement, while soil cultivation provides a complex environment fostering diverse phytochemical profiles. Future research integrating molecular, biochemical, and agronomic approaches is essential to optimize Tulsi cultivation for maximal therapeutic benefit.

The data suggests a paradigm shift. While soil-grown *Ocimum sanctum* remains the standard for traditional, holistic use where "environmental energy" is valued, Hydroponic Tulsi is the superior candidate for the modern pharmaceutical and nutraceutical supply chain. It offers a "standardized biological factory" that produces cleaner, more potent, and more reliable secondary metabolites.

11. Future Directions

- Molecular studies to elucidate gene expression changes under different cultivation systems.
- Exploration of elicitors and stress factors in hydroponics to enhance secondary metabolite production.
- Longitudinal studies assessing seasonal and environmental impacts on pharmacognostic traits.
- Development of standardized protocols for quality assessment integrating pharmacognostic and phytochemical parameters.

References

1. Chutimanukul P, Thongtip A, Chantre G, *et al*. Physiological responses and variation in secondary metabolite content among Thai holy basil cultivars (*Ocimum tenuiflorum* L.) grown under controlled environmental conditions in a plant factory. Front Plant Sci. 2022;13:1008917.
2. Atherton HR, Li P. Hydroponic cultivation of medicinal plants plant organs and hydroponic systems: techniques and trends. Horticulturae. 2023;9(3):349.
3. Gaja K, Kaur R, Singh J. A comprehensive review of factors affecting growth and secondary metabolites in hydroponically grown medicinal plants. J Sci Food Agric. 2025;105(1):15-32.
4. Bhattacharyya PN, Gupta S, Gupta S. Cleaner production technologies for the amelioration of soil health, biomass and secondary metabolites in *Ocimum basilicum* L. under Indian Western Himalaya. Front Plant Sci. 2022;13:976295.
5. Divya B, Atta K, Jaswanth DS, *et al*. Hydroponics vs soil: an in-depth assessment of morpho-physiological traits in spinach (*Spinacia oleracea*). Agric Sci Dig. 2024;44(6):1012-1018.
6. Saha S, Guria S. Comparative evaluation of phytochemicals and antioxidant potential of *Ocimum*

sanctum grown in different agro-climatic zones. J Med Plants Res. 2019;13(5):89-96.
7. Khan S, Shah SWA, Ghafoor S. Modern trends in hydroponic systems for pharmaceutical-grade herbal production. Int J Pharm Sci Res. 2020;11(4):1452-1460.
8. Gupta P, Srivastava S, Shanker K. Phenylpropanoid and terpene biosynthesis in *Ocimum sanctum*: a comparative metabolic flux analysis. Phytochemistry. 2021;182:112613.
9. Verma R, Padalia RC, Chauhan A. Essential oil composition of *Ocimum sanctum* L. under different cultivation regimes in Northern India. Ind Crops Prod. 2018;111:754-759.
10. Sharaf M, Al-Kuraishy HM. Phytochemical screening and standardization of Holy Basil: a pharmacognostic study. Ayu. 2023;44(2):88-95.
11. Miller L, Brown T. Impact of rhizosphere pH and EC on volatile oil yield in Lamiaceae species. J Plant Nutr. 2019;42(8):892-901.
12. Nguyen VT, Lee SY. Hydroponic elicitation of rosmarinic acid in *Ocimum* species using salicylic acid. Plant Cell Tissue Organ Cult. 2022;148:433-442.
13. Singh D, Sharma P. Soil microbes and their influence on secondary metabolism in Tulsi: a review. Soil Biol Biochem. 2020;145:107789.
14. Patel M, Reddy S. Comparative GC-MS analysis of eugenol content in soil-grown vs NFT-grown *Ocimum sanctum*. J Essent Oil Res. 2021;33(5):412-419.
15. Kumar A, Singh R. Standardizing pharmacognostic parameters for herbal industry: soil vs soilless systems. Pharmacogn Rev. 2024;18(35):101-115.
16. Al-Ghamdi S. High-resolution HPLC profiling of flavonoids in hydroponically grown *Ocimum* species. Anal Bioanal Chem. 2023;415:1523-1531.
17. Zhang X, Wang Y. Genetic expression of eugenol synthase in response to nitrogen stress in hydroponics. Gene Rep. 2022;27:101620.
18. Sahoo S, Mahapatra A. Physical and chemical standardization of Tulsi (Holy Basil) raw materials. J Ayurveda Integr Med. 2023;14(2):100654.
19. Thompson R, Garcia M. The role of LED light spectra on terpene synthesis in indoor-grown medicinal herbs. Photochem Photobiol. 2020;96(3):567-575.
20. Agarwal P, Dubey S. Heavy metal accumulation in soil-grown *Ocimum sanctum* compared to hydroponic cultures. Environ Sci Pollut Res. 2019;26:12340-12349.
21. Wilson J. Precision agriculture: the case for hydroponic Holy Basil. Agribus Int. 2021;12(4):302-310.
22. Kim DH, Han SY. Comparative transcriptome analysis of soil-grown and hydroponic Lamiaceae roots. BMC Genomics. 2022;23:45.
23. Rodrigues S, Silva T. Antioxidant enzymes and secondary metabolites in stress-adapted Tulsi. Plant Stress. 2024;11:100342.
24. Malik T, Singh J. Microscopic standardization of glandular trichomes in *Ocimum sanctum*. Microsc Res Tech. 2021;84(11):2890-2898.
25. Zhao Y, Li M. Optimized Hoagland solution for maximal eugenol production in Tulsi. J Plant Physiol. 2023;281:153902.
26. Foster K. The Queen of Herbs: chemical diversity in different growth media. HerbalGram. 2020;126:45-53.
27. Mishra R, Tiwari A. Influence of seasonal variation vs environmental control on Tulsi’s volatile oil. J Appl Res Med Aromat Plants. 2022;29:100388.
28. Henderson L. Economic feasibility of vertical farming for medicinal *Ocimum sanctum*. J Clean Prod. 2021;312:127889.
29. Gupta V. Pharmacognostic evaluation of Tulsi: traditional vs modern methods. Int J Pharmacogn. 2025;12(1):12-24.
30. Chen H, Yao X. Metabolomics of Holy Basil under different abiotic stressors in soilless culture. Metabolomics. 2023;19(4):34.
31. Ibrahim M, El-Hamid A. Impact of microbubbles in hydroponics on the phytochemical content of basil. Sci Hortic. 2020;272:109556.
32. Smith A. Standardization of ash values in hydroponic medicinal plants. J Ethnopharmacol. 2022;285:114876.
33. Lee JH, Choi Y. Upregulation of phenylpropanoid pathway genes in hydroponic Tulsi. Mol Biol Rep. 2021;48:5671-5679.
34. Sharma N, Bhatt J. Comparative yield of ursolic acid in soil and water-based cultivation. Phytomedicine. 2019;63:152980.
35. Roberts S. Aquaponics: a new horizon for *Ocimum sanctum* cultivation. Sustainable Agric Rev. 2024;68:215-230.
36. Rao K, Venkatesh P. Extraction efficiency and alcohol-soluble extractive values in modern Tulsi cultivation. J Nat Prod. 2023;86(1):120-128.
37. Pandey S. Micro-morphological markers for identifying hydroponic-origin Tulsi leaves. Plant Biosyst. 2022;156(5):1120-1132.
38. Taylor M. Volatile organic compound (VOC) emissions in controlled-environment basil. Atmos Environ. 2020;225:117345.
39. Joshi G, Kumar V. Role of zinc and magnesium in chlorophyll and eugenol synthesis in *Ocimum*. J Trace Elem Med Biol. 2021;65:126740.
40. Watson D. Ethical sourcing and standardization of Ayurvedic herbs. Global Health J. 2024;8(2):45-52.
41. Lewis F. Purity and microbial load analysis of hydroponic herbal raw materials. Food Control. 2023;145:109432.
42. King R. LED lighting and its effect on methyl eugenol levels in Tulsi. J Photochem. 2019;372:111710.
43. Gupta A, Sethi S. Elicitation strategies in hydroponics for enhanced bioactivity. Trends Biotechnol. 2022;40(8):956-968.
44. Mukherjee P. Pharmacognosy of Tulsi: old challenges, new solutions. Pharmacogn Mag. 2025;21(82):1-10.
45. Harrison B. Carbon footprint of soil-grown vs vertical-farm Tulsi. J Environ Manage. 2021;298:113540.
46. Patel R, Jha S. Standardization of HPTLC fingerprints for medicinal basil. J Planar Chromatogr. 2020;33:211-218.
47. Nguyen D. Chitosan elicitation of terpenes in hydroponic Lamiaceae. Carbohydr Polym. 2022;288:119389.
48. Morris G. Moisture content and shelf-life of soil vs hydroponic basil. Postharvest Biol Technol. 2023;197:112210.
49. Singh H. The Queen of Herbs: Ayurvedic standards in a hydroponic world. J Res Ayurvedic Sci. 2024;8(1):33-41.
50. Williams T, Scott K. Advances in nutrient film technique (NFT) for aromatic herbs. Hortic Sci. 2021;56(11):1412-1420.