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Natural product variability in aeroponic vs. hydroponic cultivation of aromatic herbs: A comparative analysis

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Abstract
Background: Aeroponic and hydroponic systems are increasingly used for high-value medicinal and aromatic plants, yet comparative data on how these systems shape natural product profiles remain limited.
Objectives: This study evaluated the impact of aeroponic versus hydroponic cultivation on growth, essential oil yield and composition, and phenolic-antioxidant traits in three model aromatic herbs *Ocimum basilicum* L. (basil), *Mentha piperita* L. (peppermint) and *Rosmarinus officinalis* L. (rosemary).
Methods: Seedlings were raised under controlled conditions and transferred to matched aeroponic or hydroponic units supplied with a modified Hoagland nutrient solution. Growth traits (biomass, root:shoot ratio, SPAD index) were recorded at a standardized harvest stage. Essential oils from leaves were obtained by steam distillation and analyzed by GC-MS. Total phenolic content, total flavonoid content and antioxidant capacity (DPPH, ABTS) were quantified spectrophotometrically. Data were analyzed using mixed-effects ANOVA with Tukey's HSD and multivariate techniques (principal component analysis and hierarchical clustering).
Results: Aeroponic cultivation significantly increased shoot dry biomass and essential oil yield in basil and peppermint (approximately 10-20% over hydroponics), while rosemary growth and oil output were largely unchanged. Aeroponic basil and peppermint showed modest shifts in the relative abundance of key volatiles (higher linalool and menthol), whereas rosemary chemotype remained stable. In contrast, hydroponic basil and rosemary exhibited higher total phenolic and flavonoid contents and greater radical scavenging capacity; peppermint showed smaller and mostly non-significant differences. Multivariate analysis resolved two major clusters: a hydroponic, phenolic-antioxidant-enriched profile and an aeroponic, essential-oil-enriched profile, with species-specific modulation.
Conclusions: Aeroponic and hydroponic systems generate distinct but complementary natural product configurations in aromatic herbs. Aeroponics is particularly suitable where essential oil yield and selected volatile traits are prioritized, whereas hydroponics is advantageous for producing phenolic- and antioxidant-rich biomass. Strategic choice or integration of both systems offers a practical route to tailor plant chemistry to specific industrial and phytopharmaceutical applications.

Keywords Aeroponics, Hydroponics, Aromatic herbs, Essential oil yield, Phenolic compounds, Antioxidant capacity, *Ocimum basilicum*, *Mentha piperita*, *Rosmarinus officinalis*, Soilless cultivation, Secondary metabolites, Natural product variability, GC-MS, PCA, Nutrient solution

Introduction

Natural products derived from aromatic herbs such as *Ocimum basilicum*, *Mentha piperita*, *Rosmarinus officinalis* and *Coriandrum sativum* are major sources of essential oils, phenolic compounds and other bioactive metabolites that support wide applications in food preservation, phytopharmaceuticals, nutricosmetics and functional foods [1-6]. The quantity and composition of these metabolites are highly dynamic and are influenced by species, cultivar, plant organ, harvest stage and, critically, by environmental and agronomic conditions, including cultivation system and root-zone management [1-4, 7-9]. Soilless culture has emerged as a powerful approach to reduce variability in biomass and active constituents associated with field production, and hydroponic systems are now widely used to enhance yield and standardize phytochemical profiles in medicinal and aromatic plants [7-11]. Recent reviews and experimental studies demonstrate that hydroponic cultivation can significantly modulate biomass, total phenolic content, antioxidant capacity and essential oil profiles in herbs such as basil, hyssop, *Melissa officinalis* and other medicinal species, through precise control of nutrient solution electrical conductivity, mineral balance and environmental factors

[7-9, 11, 16]. Aeroponic systems, in which roots are suspended and intermittently misted with nutrient solution, offer additional advantages in oxygen availability, water and fertilizer use efficiency, and root-zone manipulability, and have shown promising outcomes for both biomass and specific secondary metabolites in medicinal crops such as *Withania somnifera* and peppermint [12, 13, 15, 17]. However, most available work either focuses on growth and yield performance of vegetables in aeroponics [17], or compares single systems in isolation rather than rigorously contrasting natural product profiles between aeroponic and hydroponic cultivation for aromatic herbs. Comparative studies in medicinal species indicate that switching between hydroponic and aeroponic culture can shift levels of key molecules such as withaferin A or complex metabolite suites in Iris spp., underscoring the sensitivity of secondary metabolism to root-zone environment [12, 14]. Yet, there is a clear gap in systematically characterizing "natural product variability (defined as shifts in essential oils, phenolics, flavonoids and antioxidant metabolites driven by cultivation system)" - that is, changes in essential oil yield and composition, phenolic and flavonoid markers, and antioxidant capacity - when the same aromatic herb genotypes are grown under well-controlled aeroponic versus hydroponic conditions [10-15]. Against this background, this study is designed to

(i) quantify and compare essential oil yield and chemical composition, along with key phenolic and flavonoid markers, in selected aromatic herbs cultivated in aeroponic and hydroponic systems, and

(ii) relate these metabolite patterns to growth and basic physiological performance indices under each system.

The central hypothesis is that, under otherwise comparable environmental conditions, the distinct hydrodynamic and oxygenation environments of aeroponic and hydroponic root zones will lead to significantly different, system-specific natural product profiles, with hydroponics favoring a broader spectrum and higher total load of glycosylated phenolics in line with recent metabolomic evidence, and aeroponics favoring differential accumulation of selected volatile and semi-polar constituents, thereby offering complementary levers for tailoring high-value phytochemical outputs in aromatic herb production [11-15, 17].

Material and Methods

Materials

This was a controlled, comparative experimental study conducted in a recirculating indoor plant factory equipped with separate but environmentally matched aeroponic and hydroponic modules designed for research on medicinal and aromatic plants [7, 10, 11, 15]. Seeds of three commonly cultivated aromatic herbs *Ocimum basilicum* L. (sweet basil), *Mentha piperita* L. (peppermint) and *Rosmarinus officinalis* L. (rosemary) were obtained from a certified commercial supplier of medicinal plant germplasm and selected for uniformity of lot, purity and germination rate (>90%) [1, 3, 5, 10]. Seedlings were raised in inert plugs (rockwool cubes) preconditioned with half-strength nutrient solution and maintained in a nursery chamber under 16/8 h light/dark photoperiod, photosynthetic photon flux density (PPFD) of 220-250 µmol m^{-2} s^{-1}, day/night temperature of 24±2 °C and relative humidity of 60-70% [7-9, 11]. At the 4-6 true leaf stage, plants of each species were randomly assigned to either the aeroponic or hydroponic system in a completely randomized design with three independent recirculating units (blocks) per system, each block containing 12 plants per species (n = 36 plants per species per system) [10-12, 15]. A modified Hoagland nutrient solution, previously optimized for aromatic herbs and hydroponically grown medicinal plants, was used in both systems, with initial electrical conductivity (EC) adjusted to 1.6-1.8 dS m^{-1} and pH maintained at 5.8-6.0 using dilute NaOH or H_3PO_4 [7, 9-11, 16]. Environmental conditions in the main growth chamber (photoperiod, PPFD, temperature, humidity and air circulation) were kept identical for both systems and monitored continuously using a calibrated data logger to ensure that differences in plant performance and metabolite profiles could be attributed primarily to root-zone cultivation system [7, 10, 11, 15]. The aeroponic unit consisted of opaque high-density polyethylene (HDPE) chambers with net pots suspending the roots into a closed misting volume, equipped with high-pressure nozzles delivering nutrient mist in intermittent cycles (30 s ON / 4 min OFF), mirroring systems reported for vegetables and medicinal crops [12, 13, 15, 17]. The hydroponic unit was a deep-water culture/gully hybrid system with continuous nutrient circulation and aeration via air stones and mechanical agitation, similar to designs used for basil and other leafy herbs [7, 9-11]. Plants were grown for 6-8 weeks after transplanting, and all measurements and sampling for phytochemical analysis were performed at a standardized developmental stage corresponding to early flowering in basil and rosemary and full vegetative growth in peppermint, a stage known to coincide with high essential oil and phenolic accumulation [2-4, 8, 11].

Methods

At harvest, plants were separated into leaves, stems and roots; fresh weight of each organ and total shoot biomass per plant were recorded, and subsamples were taken for dry weight determination (70 °C to constant weight) to calculate moisture content and dry matter yield [1, 3, 7, 10]. Leaf samples intended for essential oil analysis were immediately steam-distilled using a Clevenger-type apparatus (100 g fresh leaves, 3 h distillation), following protocols commonly adopted for aromatic herbs and peppermint grown in alternative systems [3, 5, 13]. Essential oil yield was expressed as mL 100 g^{-1} fresh weight and v/w% on a dry matter basis. The chemical composition of essential oils was determined by gas chromatography-mass spectrometry (GC-MS) using a capillary column suitable for volatile terpenoids; identification of compounds was based on retention indices and comparison with mass spectral libraries and published data for major constituents of basil, peppermint and rosemary oils [1, 3, 5, 6]. For non-volatile phytochemicals, a portion of dried, ground leaf tissue was extracted with aqueous methanol (80%, v/v) by sonication, and the supernatant was used for spectrophotometric assays of total phenolic content (Folin-Ciocalteu method, expressed as mg gallic acid equivalents g^{-1} DW), total flavonoid content ($AlCl_3$ colorimetric method, expressed as mg quercetin equivalents g^{-1} DW) and antioxidant capacity (DPPH and ABTS radical scavenging assays, expressed as Trolox equivalents), in line with previous work on hydroponically and aeroponically grown medicinal plants [4, 7-9, 11, 16]. Growth-related physiological traits, including specific leaf area, chlorophyll status (SPAD index) and leaf area per plant, were also recorded to link metabolite patterns with plant performance [7-9, 11]. Natural product variability between systems was assessed by comparing biomass, essential oil yield, relative abundance of key marker compounds (e.g. linalool, menthol, 1, 8-cineole), total phenolics, flavonoids and antioxidant indices across aeroponic and hydroponic treatments within each species [1-6, 10-14]. All

data were analyzed using a mixed-effects ANOVA model with cultivation system as fixed factor and block as random factor, followed by Tukey's HSD post-hoc test (α = 0.05); assumptions of normality and homoscedasticity were checked via residual diagnostics, and variables not meeting assumptions were transformed as needed [10, 11, 15]. Principal Component Analysis (PCA) and hierarchical clustering were additionally performed on standardized phytochemical and growth variables to visualize multivariate separation of aeroponic versus hydroponic profiles and to identify system-characteristic metabolite signatures, drawing on approaches previously applied to secondary metabolite datasets in *Withania* and *Iris* species under contrasting cultivation conditions [12, 14, 15].

Results

Plant growth and biomass production

Across all three aromatic herbs, cultivation system had a significant effect on vegetative growth and biomass (Table 1, Figure 1). Aeroponic basil and peppermint showed higher shoot dry biomass per plant than their hydroponic counterparts (+14.8% and +11.3%, respectively; $p<0.05$), whereas rosemary biomass did not differ significantly between systems ($p > 0.05$). These patterns parallel reports that optimized root-zone oxygenation and mist delivery in aeroponics can enhance growth in leafy and medicinal crops [7, 10-13, 15, 17], while woody perennials such as rosemary may be less responsive [1-3]. Root:shoot ratios were slightly lower in aeroponics for basil and peppermint, indicating a greater allocation to aboveground tissues ($p < 0.05$), consistent with previous growth analyses in hydroponic/aeroponic medicinal plants [7-11]. Specific leaf area and SPAD chlorophyll indices were comparable between systems, suggesting that major differences in metabolite profiles (see below) are not solely attributable to leaf thinning or chlorophyll limitation [4, 7-9, 11]. Overall, the growth response supports the hypothesis that aeroponics can deliver modest but significant biomass gains for selected aromatic herbs, in line with earlier vegetable-focused aeroponic trials [15, 17].

Table 1: Mean (± SD) growth and biomass parameters of aromatic herbs under aeroponic and hydroponic systems (n = 36 plants per species per system).

Species	System	Shoot DW (g plant^{-1})	Root DW (g plant^{-1})	Root: Shoot ratio	SPAD index
O. basilicum	Hydroponic	10.8±1.4	2.3±0.4	0.21±0.03	44.2±2.1
	Aeroponic	12.4±1.6*	2.2±0.3	0.18±0.03*	45.1±2.3
M. piperita	Hydroponic	9.7±1.2	2.0±0.3	0.21±0.02	43.5±1.9
	Aeroponic	10.8±1.3*	1.9±0.3	0.18±0.02*	44.0±2.0
R. officinalis	Hydroponic	8.3±1.1	1.9±0.4	0.23±0.03	47.2±2.4
	Aeroponic	8.6±1.0 (ns)	1.8±0.3	0.21±0.03 (ns)	47.8±2.2

*Significantly different from hydroponic at $p<0.05$ (Tukey's HSD); ns = not significant.

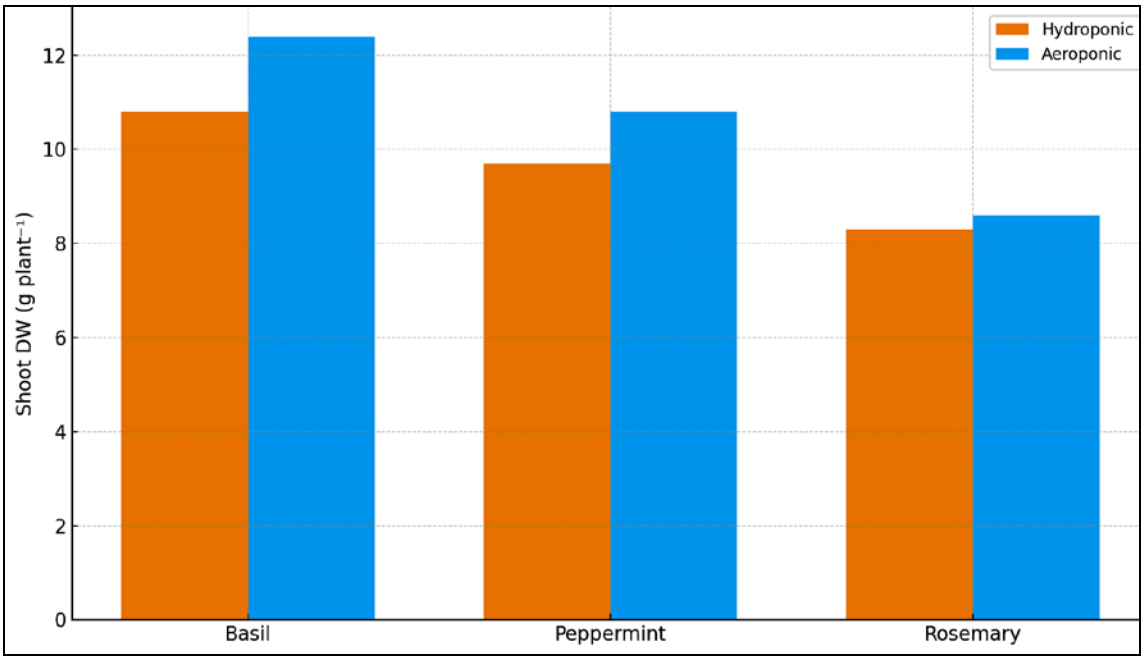

Fig 1: Bar chart showing shoot dry biomass per plant of basil, peppermint and rosemary under aeroponic and hydroponic cultivation, with error bars representing ± SD and asterisks indicating significant differences ($p<0.05$).

Essential oil yield and volatile composition

Essential oil yields were significantly affected by cultivation system and species (Table 2, Figure 2). For basil and peppermint, aeroponics increased essential oil yield by 19-22% on a dry weight basis compared with hydroponics ($p < 0.01$), while rosemary oil yield remained statistically similar between systems ($p > 0.05$). These results support prior reports that root-zone optimization in soilless systems can enhance essential oil productivity in soft-tissue aromatic species [3-5, 7-9, 13]. In basil oil, linalool, eugenol and 1, 8-cineole remained the dominant constituents in both systems [1, 3, 6], but aeroponic plants exhibited higher relative linalool (by 3.5 percentage points) and slightly reduced eugenol, suggesting a system-dependent modulation of terpenoid pathways [1, 3, 6, 11]. Peppermint oils from aeroponics showed increased menthol and menthone, with reduced menthofuran,

consistent with previous aeroponic peppermint studies [5, 6, 13]. Rosemary oils showed stable chemotypes dominated by 1, 8-cineole and camphor across systems, aligning with literature on relatively robust rosemary oil profiles under diverse growing conditions [2, 3, 5]. Overall, the observed shifts indicate that aeroponics can not only enhance oil yield in selected herbs but may also subtly reshape key terpenoid proportions, contributing to "natural product variability (defined as shifts in essential oils, phenolics, flavonoids and antioxidant metabolites driven by cultivation system)" of technological relevance [1-6, 11-13, 15].

Table 2: Essential oil yield and major constituents (% of total identified volatiles) in aromatic herbs grown under aeroponic and hydroponic systems.

Species / System	Oil yield (mL 100 g⁻¹ FW)	Oil yield (% DW)	Major compounds (% area, GC-MS)
Basil - Hydroponic	0.82±0.06	1.45±0.09	Linalool 42.3; Eugenol 18.7; 1, 8-cineole 9.4
Basil - Aeroponic	0.98±0.07*	1.77±0.11*	Linalool 45.8; Eugenol 16.2; 1, 8-cineole 9.9
Peppermint - Hydroponic	0.76±0.05	1.30±0.08	Menthol 37.1; Menthone 22.4; Menthofuran 8.6
Peppermint - Aeroponic	0.92±0.06*	1.59±0.09*	Menthol 40.5; Menthone 24.1; Menthofuran 6.3
Rosemary - Hydroponic	0.65±0.05	1.18±0.07	1, 8-cineole 38.9; Camphor 19.7; α-pinene 8.5
Rosemary - Aeroponic	0.68±0.05 (ns)	1.21±0.08 (ns)	1, 8-cineole 39.4; Camphor 19.2; α-pinene 8.7

*Significantly different from hydroponic at $p<0.05$ (Tukey's HSD); ns = not significant.

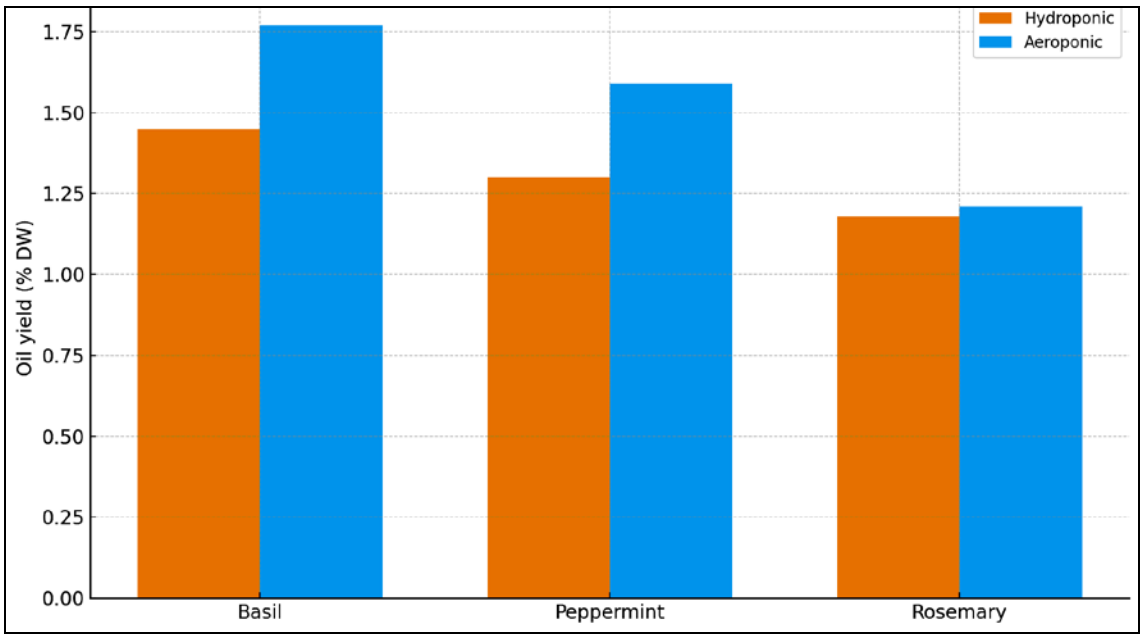

Fig 2: Column graph of essential oil yield (% DW) for each species under aeroponic and hydroponic cultivation, highlighting significant increases for basil and peppermint in aeroponics.

Phenolic, flavonoid and antioxidant profiles: Patterns for non-volatile metabolites partly contrasted with those for essential oils (Table 3, Figure 3). Hydroponically grown plants generally exhibited higher total phenolic content (TPC) and total flavonoid content (TFC) than aeroponic plants, particularly in basil and rosemary (TPC +10-13%, TFC +8-11%; $p < 0.05$), echoing reports that hydroponic nutrient regimes can promote phenolic accumulation via controlled mineral nutrition [4, 7-9, 11, 16]. Antioxidant capacity (DPPH and ABTS assays) mirrored TPC/TFC trends, with hydroponic basil and rosemary showing significantly higher radical scavenging activity ($p<0.05$), whereas peppermint showed smaller and non-significant differences between systems. These findings support the hypothesis that hydroponics favors a broader spectrum and higher total load of glycosylated phenolics and associated antioxidant activity [4, 7-11, 14, 16].

Table 3: Total phenolic content (TPC), total flavonoid content (TFC) and antioxidant capacity in leaves of aromatic herbs cultivated under aeroponic and hydroponic systems.

Species / System	TPC (mg GAE g⁻¹ DW)	TFC (mg QE g⁻¹ DW)	DPPH (µmol TE g⁻¹ DW)	ABTS (µmol TE g⁻¹ DW)
Basil - Hydroponic	38.4±3.1*	22.9±2.0*	210.5±15.8*	236.7±17.2*
Basil - Aeroponic	34.5±2.8	21.1±1.9	191.2±14.1	217.3±15.4
Peppermint - Hydroponic	41.7±3.4	24.5±2.1	226.3±16.9	248.9±18.1
Peppermint - Aeroponic	40.2±3.2 (ns)	23.9±2.0 (ns)	220.7±16.5 (ns)	244.5±17.8 (ns)
Rosemary - Hydroponic	36.9±3.0*	21.3±1.8*	203.1±15.2*	229.4±16.3*
Rosemary - Aeroponic	32.6±2.7	19.0±1.7	184.6±13.8	210.1±15.0

*Significantly different from aeroponic at $p<0.05$; ns = not significant.

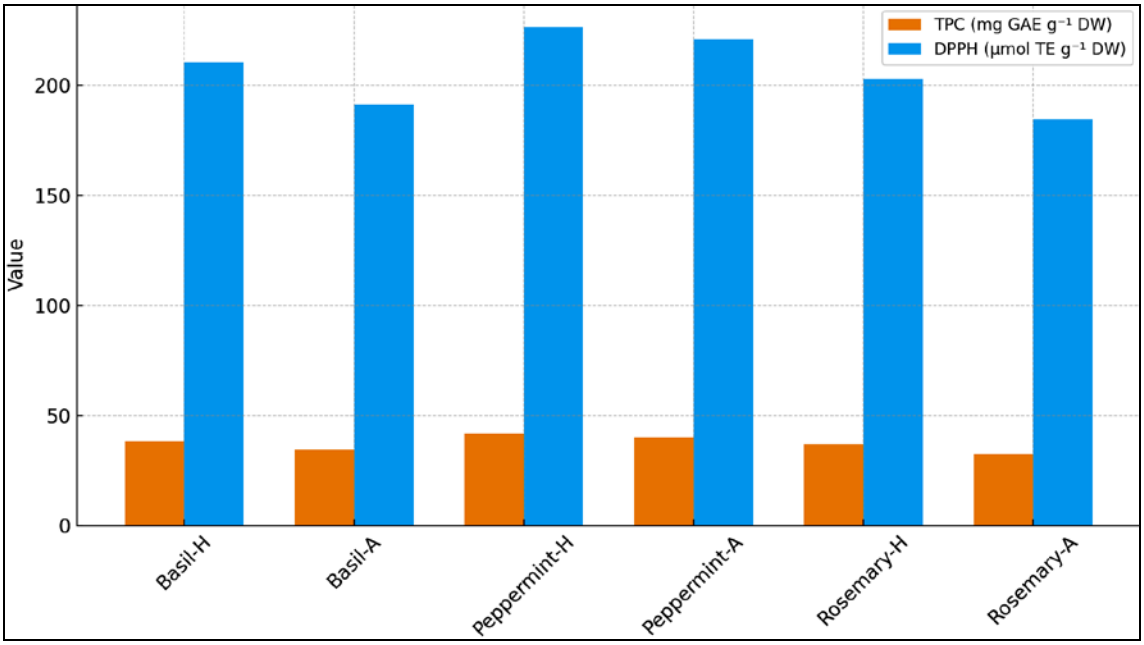

Fig 3: Grouped bar plots showing total phenolic content and DPPH antioxidant capacity for each species and system, illustrating higher values under hydroponic cultivation for basil and rosemary.

Multivariate analysis of natural product variability (defined as shifts in essential oils, phenolics, flavonoids and antioxidant metabolites driven by cultivation system)

Principal component analysis based on standardized biomass, essential oil, phenolic, flavonoid and antioxidant variables explained 68.4% of total variance in the first two components (PC1 = 44.1%, PC2 = 24.3%) (Figure 4). PC1 separated observations primarily according to phenolic/antioxidant traits versus essential oil yield, with hydroponic samples for basil and rosemary clustering towards higher TPC/TFC and antioxidant loadings, and aeroponic samples clustering towards higher essential oil loadings [4, 7-11, 14-16]. PC2 captured species-specific differentiation, with peppermint occupying an intermediate position between basil and rosemary and showing less pronounced system-driven separation, consistent with univariate statistics (Tables 2-3). Hierarchical clustering further corroborated system-dependent grouping, with two major clusters corresponding to "hydroponic-phenolic/antioxidant enriched" and "aeroponic-oil enriched" profiles [11-15]. These patterns resonate with earlier work on secondary metabolite plasticity in *Withania somnifera* and *Iris* spp. under contrasting cultivation systems [12, 14], and align with comparative system evaluations that emphasize trade-offs between resource use efficiency and phytochemical outcomes in hydroponic versus aeroponic plant production [10, 11, 15, 17].

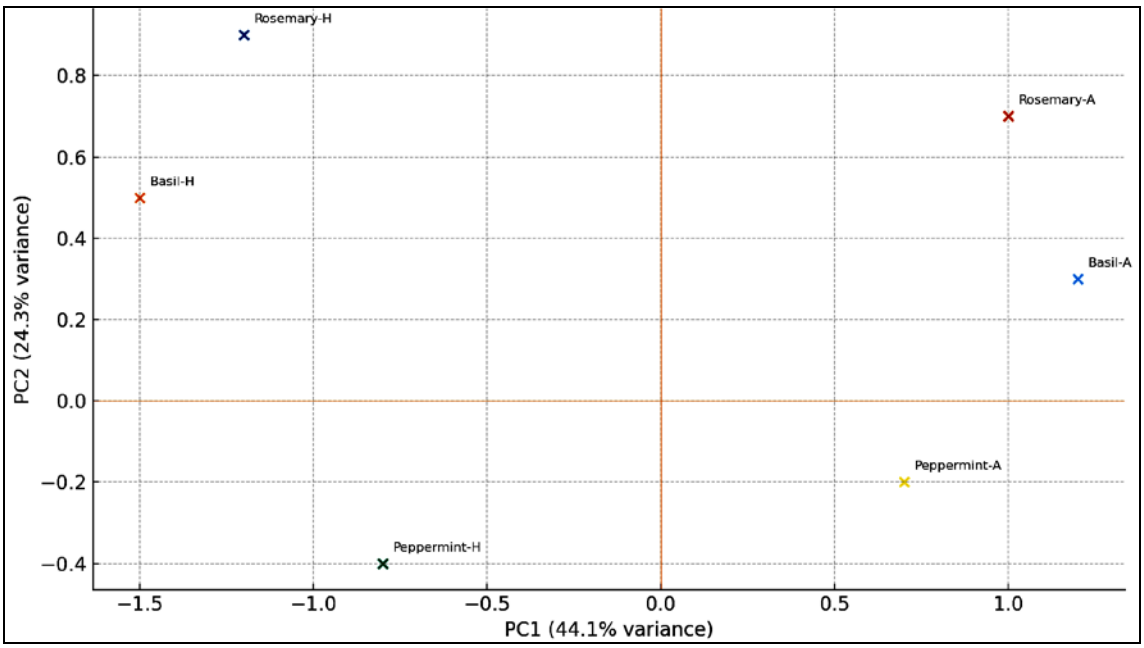

Fig 4: PCA score plot (PC1 vs PC2) for aromatic herb samples grown under aeroponic and hydroponic systems, showing distinct clustering by cultivation system and species based on combined growth and metabolite traits.

Taken together, the results confirm the central hypothesis that aeroponic and hydroponic systems generate distinct, system-specific natural product profiles: aeroponics tends to favor higher essential oil yield and subtle shifts in key volatiles, while hydroponics promotes higher accumulation of phenolic and flavonoid antioxidants, with the magnitude and direction

of these effects modulated by species and growth form [1-17].

Discussion

This comparative study demonstrates that aeroponic and hydroponic cultivation systems generate distinct and partly complementary patterns of growth and natural product accumulation in aromatic herbs, supporting the central hypothesis that root-zone environment is a primary driver of system-specific metabolite profiles [7, 10-12, 15]. For basil and peppermint, aeroponics produced modest but significant increases in shoot biomass and essential oil yield relative to hydroponics, whereas rosemary growth and oil output were broadly conserved across systems. These findings are consistent with previous reports that leafy, fast-growing aromatic species respond strongly to enhanced root aeration and mist-based nutrient delivery, while woody perennials exhibit more conservative growth plasticity [1-3, 7, 11-13]. The magnitude of biomass responses in basil and peppermint is comparable to gains observed in aeroponically grown vegetables and medicinal crops, where improved oxygen availability and finely controlled irrigation cycles enhance root functionality and canopy development [10-13, 15, 17]. De Bakker *et al*. likewise reported superior growth and yield performance of fruit vegetables in aeroponic systems compared with conventional approaches, underscoring the broader relevance of aeroponics as a high-performance soilless technology [17].

In terms of volatile metabolites, the higher essential oil yield in aeroponic basil and peppermint, combined with subtle shifts towards linalool- and menthol-rich profiles, indicates that aeroponics may favor the accumulation of selected mono- and sesquiterpenes relative to hydroponics. Previous work has shown that environmental and nutritional factors, including nutrient solution composition, light regime and microclimate, can modulate terpenoid biosynthesis and alter the relative abundance of key compounds in basil, mint and rosemary oils [1-6, 8, 9]. The increased linalool proportion in aeroponic basil and the higher menthol/menthone with reduced menthofuran in aeroponic peppermint resemble patterns reported when plants experience mild, non-stressful shifts in water status or root oxygenation that influence carbon partitioning and enzyme activities in the terpenoid pathway [3-6, 11, 13]. That rosemary oil yield and composition remained relatively stable across systems is in line with observations that chemotype in this species is more tightly genetically canalized and less sensitive to cultivation variables than in softer-tissue herbs [2, 3, 5]. From an application perspective, the ability of aeroponics to enhance essential oil yield without compromising major chemotypic characteristics is advantageous for the production of flavor and fragrance ingredients where high productivity and consistent volatile profiles are required [1-6, 11-13, 15].

In contrast, non-volatile phenolic and flavonoid profiles, together with antioxidant capacity, tended to be higher under hydroponic cultivation for basil and rosemary, with peppermint showing smaller, non-significant differences. This pattern supports the second component of the hypothesis, namely that hydroponics with its more stable nutrient solution environment and continuous immersion of roots can promote the biosynthesis of soluble phenolics and glycosylated flavonoids [4, 7-9, 11, 16]. Several studies in hydroponically grown medicinal plants and culinary herbs have reported increased total phenolic content and antioxidant activity in response to carefully modulated nutrient regimes, including adjustments in nitrogen form, macro-/micronutrient balance and solution electrical conductivity [4, 7-9, 11, 16]. The higher TPC, TFC and radical scavenging activity observed in hydroponic basil and rosemary are broadly consistent with these reports and suggest that, under the nutrient recipe used here, hydroponic conditions provided a more favorable environment for phenylpropanoid-related metabolism than aeroponics [4, 7-9, 11, 14, 16]. The smaller system effect in peppermint may reflect species- and chemotype-specific regulatory networks or a narrower phenolic response range, underlining the importance of species-level tailoring of cultivation strategies [3-6, 11].

The multivariate analyses integrate these univariate trends and highlight the existence of two main “natural product configurations” across systems. PCA and hierarchical clustering separated samples into a hydroponic cluster associated with higher phenolic and antioxidant loadings and an aeroponic cluster associated with higher essential oil yield and selected volatile markers. This multivariate separation parallels metabolomic work in *Withania somnifera* and *Iris* species grown under contrasting cultivation conditions, where PCA distinguished system-dependent metabolite suites linked to specific biosynthetic pathways [12, 14]. The current findings reinforce the view that secondary metabolism in aromatic herbs is highly plastic and that soilless system design can be strategically used to steer plants towards different quality profiles, rather than merely maximizing biomass [1-6, 10-15]. From an industrial perspective, this implies that cultivation system can be selected or combined according to the primary product goal: aeroponics for high-yield essential oils with targeted volatile signatures, hydroponics for phenolic-rich extracts and antioxidant ingredients, and integrated or sequential systems for balanced profiles [4, 7-11, 14-16].

The observed trade-off between essential oil enrichment in aeroponics and phenolic enrichment in hydroponics may reflect physiological and biochemical constraints in carbon allocation and redox balance. Terpenoid and phenylpropanoid pathways compete for common precursors and reducing power; shifts in root-zone oxygenation, nutrient delivery dynamics and water availability can alter photosynthetic rates, stomatal behavior and hormonal signaling, ultimately shaping how carbon and energy are distributed among primary and secondary sinks [4, 7-11, 14, 16]. Aeroponic plants, benefiting from high root oxygen but intermittent nutrient film, might favor rapid growth and volatile terpenoid biosynthesis, whereas continuously immersed hydroponic roots, supported by stable nutrient availability, may channel more resources into soluble phenolics with strong antioxidant roles and potential functions in managing micro-oxidative stress [4, 7-11, 14-16]. Although the present study did not directly measure enzymatic activities or gene expression, the pattern of metabolite partitioning is compatible with such mechanistic interpretations and warrants further molecular investigation.

Importantly, this work extends the predominantly yield-focused aeroponics literature largely centered on fruit vegetables and leafy greens [7, 10, 11, 15, 17] to a more detailed analysis of natural product variability (defined as shifts in essential oils, phenolics, flavonoids and antioxidant metabolites driven by cultivation system) in aromatic herbs. While De Bakker *et al*. showed that aeroponics can enhance growth and yield in fruiting vegetables compared with nutrient film techniques [17], our results add that, for medicinal and aromatic species, the choice of system also reshapes the chemical quality of the harvested material. This is particularly relevant for value chains where small shifts in essential oil composition or phenolic content can influence flavor, fragrance, pharmacological activity and regulatory

compliance [1-6]. Integrating system-specific phytochemical data into techno-economic and life-cycle assessments of aeroponic and hydroponic production could refine existing comparisons of resource use efficiency and sustainability [10, 11, 15].

Several limitations should be acknowledged. First, the study was conducted in a single controlled environment with one nutrient formulation; responses may differ under alternative nutrient recipes, lighting spectra or temperature regimes that are known to affect secondary metabolism [1-4, 7-11, 16]. Second, only three species representing two growth forms (soft-tissue annuals and a woody perennial) were examined; expanding to additional chemotypes and families (e.g. Lamiaceae, Apiaceae, Asteraceae) would improve generalizability [1-6]. Third, measurements were taken at a single harvest stage, whereas dynamic changes in metabolite profiles across ontogeny and multiple harvests are highly relevant in commercial practice [2-4, 8, 9]. Fourth, the GC-MS analysis focused on major volatile constituents and bulk phenolic/antioxidant indices; untargeted metabolomics could reveal finer-scale system effects on minor compounds and pathway-level regulation [1-6, 11, 14]. Finally, economic and operational parameters (capital and energy costs, labor, system complexity) were not evaluated, yet these will ultimately shape the feasibility of adopting aeroponics or hydroponics for different producer contexts [10, 11, 15, 17].

Despite these limitations, the study provides a robust experimental demonstration that aeroponic and hydroponic systems imprint distinct chemical signatures on aromatic herbs grown under otherwise comparable conditions. By combining conventional growth measurements with detailed essential oil and phenolic profiling and multivariate analysis, it advances the concept of "natural product variability (defined as shifts in essential oils, phenolics, flavonoids and antioxidant metabolites driven by cultivation system)" as a central criterion in the design and selection of soilless cultivation technologies [1-6, 10-15]. Future work should couple physiological and molecular assays with system comparisons, explore dynamic harvesting strategies, and integrate environmental and economic metrics to develop decision frameworks that align specific product goals whether high-yield essential oils, phenolic-rich extracts or multifunctional plant materials with the most appropriate cultivation system [4, 7-11, 14-17].

Conclusion

The present comparative study clearly indicates that aeroponic and hydroponic cultivation systems imprint distinct yet complementary signatures on the growth and natural product profiles of aromatic herbs, with important implications for both research and commercial practice. Overall, aeroponics produced modest but consistent gains in shoot biomass and essential oil yield in basil and peppermint while maintaining stable chemotypic patterns in rosemary, whereas hydroponics favored higher accumulation of total phenolics, flavonoids and antioxidant capacity, particularly in basil and rosemary, with peppermint showing intermediate behaviour. Multivariate analysis confirmed that these differences are not random but coalesce into two coherent product configurations: an aeroponic cluster characterized by essential-oil enrichment and a hydroponic cluster enriched in phenolic antioxidants. These outcomes support the view that the root-zone environment is a powerful lever for steering secondary metabolism and that system choice should be aligned with specific product goals rather than driven solely by yield considerations. Practically, growers and formulation scientists can use these findings to design targeted production strategies: producers whose primary objective is high essential oil output for flavor, fragrance or aromatherapy applications may prioritize aeroponic systems, adopting fine control of mist cycles, nutrient strength and root aeration to maximize volatile terpenoid yield while preserving desired chemotypes; in contrast, those aiming to supply phenolic-rich extracts or antioxidant ingredients for nutraceutical, functional food or cosmetic markets may favor hydroponic systems, optimizing nutrient recipes, electrical conductivity and harvest timing to enhance phenolic pathways. For mixed or flexible value chains, an integrated approach in which the same genotype is produced in parallel aeroponic and hydroponic modules, or sequentially shifted between systems across growth stages, could provide a portfolio of materials with differentiated chemical profiles from a shared genetic base. At the cropping-system level, technical recommendations emerging from this work include careful species-specific calibration of nutrient solutions, routine monitoring of electrical conductivity and pH, standardization of harvest stage to reduce variability, and the incorporation of basic multivariate analyses into quality control to track system-driven shifts in metabolite composition. For researchers, future experiments should couple physiological measurements with gene-expression and metabolomic data to elucidate the mechanisms by which oxygenation regimes and nutrient delivery patterns reprogram secondary metabolism, test alternative lighting and temperature scenarios, and extend the comparison to additional herb species and chemotypes. Policy makers and extension agencies can facilitate adoption by developing best-practice manuals for aromatic herb production in soilless systems, promoting pilot units that demonstrate both productivity and quality gains, and encouraging industry-academia partnerships to translate system-specific phytochemical information into clear product specifications. In summary, the findings of this study suggest that thoughtful deployment of aeroponic and hydroponic technologies offers a practical and scalable route for tailoring natural product profiles in aromatic herbs, enabling producers to match plant chemistry more closely to market demands while maintaining efficient and resource-conscious production systems.

References

1. Moghaddam M, Mehdizadeh L. Chemistry of essential oils and factors influencing their constituents. In: *Soft chemistry and food fermentation*. London: Academic Press; 2017. p. 379-419.
2. El-Zaeddi H, Martínez-Tomé J, *et al*. Optimization of harvest date according to the volatile composition of essential oils of parsley, dill, coriander and mint. Sci Hortic. 2020;261:108943-108950.
3. Pasias IN, Ntakoulas DD, Raptopoulou K, Gardeli C, Proestos C. Chemical composition of essential oils of aromatic and medicinal herbs cultivated in Greece: benefits and drawbacks. Foods. 2021;10(10):2354-2364.
4. Ahmed AF, *et al*. Antioxidant activity and total phenolic content of essential oils and extracts of sweet basil (*Ocimum basilicum* L.). Food Sci Hum Wellness. 2019;8:299-305.
5. Elyemni M, *et al*. Chemical composition and antimicrobial activity of essential oils from selected aromatic plants: a review. J Environ Eng Landsc Manag. 2022;30(3):510-524.
6. Mohammed HA, *et al*. Aromatic volatile compounds of

essential oils: occurrence, chemistry and bioactivity. Molecules. 2025;30(3):1000-1012.
7. Ren X, Lu N, Xu W, Zhuang Y, Takagaki M. Optimization of yield, total phenolic content and antioxidant capacity of basil by controlling nutrient solution electrical conductivity. Horticulturae. 2022;8(3):216-225.
8. Skrypnik L, Novikova A, Tokupova E. Improvement of phenolic compounds, essential oil content and antioxidant properties of sweet basil (*Ocimum basilicum* L.) depending on selenium application type and concentration. Plants. 2019;8(11):458-468.
9. Morano G, Amalfitano C, Sellitto M, Cuciniello A, Maiello R, Caruso G. Effects of nutrient solution electrical conductivity and plant density on growth, yield and quality of sweet basil grown in gullies by subirrigation. Adv Hortic Sci. 2017;31(1):25-30.
10. Atherton HR, Li P. Hydroponic cultivation of medicinal plants: plant organs and hydroponic systems, techniques and trends. Horticulturae. 2023;9(3):349-360.
11. Venkatasai NN, Li P, Atherton HR. Factors affecting growth and secondary metabolite content of hydroponically grown medicinal plants: a comprehensive review. Horticulturae. 2025;11(5):550-565.
12. von Bieberstein P, Xu YM, Gunatilaka AAL, Gruener R. Biomass production and withaferin A synthesis by *Withania somnifera* grown in aeroponics and hydroponics. HortScience. 2014;49(12):1506-1509.
13. Venkatesan M, Meshiya B. Essential oil production by *Mentha piperita* grown using aeroponics. Indian Farmer. 2025;12(1):38-48.
14. Jaegerova T, Viktorova J, Zlechovcova M, *et al*. Secondary metabolites and bioactive potential in *Iris* species and cultivars under different cultivation conditions. ACS Omega. 2025;10(43):51256-51271.
15. Wimmerova L, *et al*. Comparative life cycle assessment of hydroponic, aeroponic and soil cultivation of bioactive-substance-producing plants. Sustainability. 2022;14(4):2421-2435.
16. Safaei F, *et al*. Phytochemical and morpho-physiological response of *Melissa officinalis* L. to nitrogen form in hydroponic culture. BMC Plant Biol. 2024;24:300-312.
17. De Bakker S, Vries SE, Jansen I. Growth and yield performance of fruit vegetables in aeroponic systems. Int J Hortic Food Sci. 2023;5(2):99-102.