International Journal of Plant & Soil Science

Volume 38, Issue 8, Page 465-488, 2026; Article no.IJPSS.162849
ISSN: 2320-7035

Sustainable Nutrient Management in Mentha: Integrating Soil Health, Crop Productivity, and Essential Oil Quality for Climate-Resilient Cultivation

Tanmoy Barman [a], Amandeep Singh Sidhu [a*] and Rajender Kumar [a]

[a] *School of Organic Farming, Punjab Agricultural University, Ludhiana-141001, India.*

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: https://doi.org/10.9734/ijpss/2026/v38i86234

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://pr.sdiarticle5.com/review-history/162849

Review Article

Received: 29/05/2026
Accepted: 24/07/2026
Published: 29/07/2026

Abstract

Commercial *Mentha* production is frequently managed as a high-input system because rapid canopy development, repeated harvests and substantial nutrient removal underpin profitable herb and essential-oil yields. This production logic can create a three-way management problem: nutrient supply must sustain biomass, preserve the chemical quality of the oil and avoid progressive deterioration of soil physical, chemical and biological functions. This critical narrative review evaluates evidence on mineral fertilisers, organic amendments, distillation-residue recycling, microbial biofertilisers and integrated nutrient management in Japanese mint, peppermint and related cultivated mints. Literature published from January 1990 to 9 April 2026 was identified through accessible scholarly indexes, bibliographic databases, DOI records, institutional repositories and citation searching. Evidence was appraised according to experimental design, duration, soil characterisation, treatment comparability, oil analysis, replication and field relevance.

**Corresponding author: E-mail: sidhuas@pau.edu;*

Cite as: *Barman, T., Sidhu, A. S., & Kumar, R. (2026). Sustainable Nutrient Management in Mentha: Integrating Soil Health, Crop Productivity, and Essential Oil Quality for Climate-Resilient Cultivation. International Journal of Plant & Soil Science, 38(8), 465–488. https://doi.org/10.9734/ijpss/2026/v38i86234*

Nitrogen is the nutrient with the clearest and most reproducible influence on canopy growth and oil yield, but its effects on oil concentration and monoterpene composition are non-linear and strongly conditioned by genotype, water supply and harvest stage. Phosphorus, potassium and micronutrient responses are less securely resolved because they are often tested within compound fertiliser treatments or short pot experiments. Organic amendments can improve soil carbon, aggregation, nutrient buffering and microbial activity, yet their nutrient-release patterns may not coincide with peak crop demand. Plant growth-promoting rhizobacteria and arbuscular mycorrhizal fungi have plausible mechanisms for improving nutrient acquisition, stress tolerance and glandular-trichome activity, although much of the evidence remains strain-specific and greenhouse-based. The strongest agronomic case is therefore for adaptive integration rather than categorical replacement of mineral fertilisers: soil- and plant-informed nutrient budgets, synchronised mineral inputs, quality-controlled organic resources, locally validated inoculants, coordinated irrigation and routine chromatographic assessment of oil composition. Long-term, multi-location trials that measure nutrient-use efficiency, soil function, emissions, leaching, oil quality and profitability are required before universal recommendations can be justified.

Keywords: Integrated nutrient management; Japanese mint; peppermint; nutrient-use efficiency; soil biological fertility; biofertiliser; monoterpene biosynthesis; circular residue management.

1. Introduction

1.1 *Mentha* Production as a Coupled yield–quality–soil Problem

Species and hybrids of *Mentha* are cultivated for fresh herb, dried leaf and essential oil, with Japanese mint (*Mentha arvensis* L.), peppermint (*Mentha* × *piperita* L.) and spearmint (*Mentha spicata* L.) representing distinct but overlapping production systems. Their market value depends not only on harvested biomass but also on oil concentration and chemical profile. In menthol mint, a high proportion of (−)-menthol is central to commercial value, whereas peppermint oil is judged through a broader balance among menthol, menthone, menthyl acetate, menthofuran, pulegone and related compounds. Spearmint, by contrast, is associated principally with carvone-rich oil. These species-specific quality targets make nutrient management more complex than maximising vegetative growth alone. The same treatment that accelerates canopy expansion may dilute oil concentration, change glandular-trichome density or alter precursor allocation within monoterpene pathways (Akhtar et al., 2017; Rohloff, 1999; Tiwari, 2016; Zhao et al., 2022).

The crop is often characterised as nutrient demanding because it produces large quantities of succulent biomass over a short season, frequently under irrigation, and may be harvested more than once. Nitrogen (N) supports leaf area, chlorophyll formation and photosynthetic capacity, while phosphorus (P) and potassium (K) contribute to energy transfer, root development, stomatal regulation and assimilate movement. Yet nutrient removal is only one component of sustainability. High fertiliser rates can reduce nutrient-use efficiency, increase production costs and expose farms to nitrate loss, ammonia volatilisation or greenhouse-gas emissions. Conversely, severe nutrient restriction can reduce ground cover, oil yield and profitability, thereby encouraging expansion onto additional land. Sustainable nutrient management must therefore be evaluated as a process of balancing crop demand, soil nutrient-supplying capacity, input efficiency, product quality and environmental loss rather than as a simple choice between synthetic and organic fertilisers (Bünemann et al., 2018; Patra et al., 2000).

Soil health is especially relevant in intensive mint systems because vegetative propagation, irrigation, repeated traffic and narrow rotations can interact with nutrient management. Soil organic carbon influences aggregation, infiltration, water retention, cation exchange and microbial habitat. Microbial biomass mediates nutrient mineralisation and immobilisation, while root-associated microorganisms can influence nutrient acquisition and plant signalling. Long-term organic and integrated systems in other arable crops commonly support greater microbial abundance and activity than exclusively mineral systems, although yield advantages are context dependent and cannot be assumed merely from the addition of organic material (Hijbeek et al., 2017; Lori et al., 2017; Mäder et al., 2002). Mint-specific research has likewise shown that farmyard manure (FYM) and recycled distillation residues can affect soil organic carbon and microbial biomass, but the available experiments differ in soil type, nutrient equivalence and duration (Chand et al., 2004; Patra et al., 2000).

1.2 Why Nutrient Responses are Difficult to Generalize

A recurring weakness in the *Mentha* literature is the tendency to treat "yield" as a single endpoint. Fresh herbage, dry matter, oil percentage and total oil yield are mathematically and physiologically related but not interchangeable. A treatment may increase fresh weight primarily through water-rich tissue, while dry matter changes little. Oil yield can rise because of greater biomass even when oil concentration falls. A commercially favourable response also requires acceptable composition, yet some experiments report only hydrodistilled oil percentage and omit gas chromatography–mass spectrometry (GC–MS) profiling. This omission is important because nutrient supply, phenological stage and leaf position can modify the relative abundance of monoterpenes even when total oil yield appears stable (Ostadi et al., 2020; Rohloff, 1999; Zheljazkov et al., 2010).

Experimental heterogeneity further limits generalisation. Studies span hydroponic deficiency trials, pots, greenhouse systems and field experiments across contrasting climates. Fertiliser rates are reported as elemental nutrients, fertiliser products or local recommended doses, sometimes without complete soil-test data. Organic treatments may be compared on equal mass rather than equal available N, and inoculant studies often lack verification of rhizosphere colonisation. Irrigation is a major co-determinant of nutrient uptake, but water regimes are not always standardised or analysed as interactions. Harvest timing is equally influential because monoterpene composition changes during leaf development and flowering. Consequently, apparently conflicting nutrient effects may reflect differences in genotype, environment, experimental scale, nutrient-release timing or analytical method rather than genuine biological contradiction (Keshavarz-Mirzamohammadi et al., 2021; Ostadi et al., 2020; Souza et al., 2024; Zheljazkov et al., 2010).

Recent studies have broadened the evidence base by comparing mineral, organic and microbial nutrient sources and by measuring selected soil-health indicators. Research on plant growth-promoting rhizobacteria (PGPR) has also connected rhizosphere processes with essential-oil biosynthesis through volatile organic compounds, phytohormone signalling and changes in glandular trichomes (Cappellari et al., 2017, 2019, 2020; Santoro et al., 2011, 2016). Nevertheless, existing reviews tend to address medicinal and aromatic plants collectively, focus on general biofertiliser mechanisms, or discuss mint phytochemistry without integrating soil outcomes, agronomic productivity and oil quality in one analytical framework (Balkrishna et al., 2024; Rostaei et al., 2024; Zhao et al., 2022). A crop-specific synthesis is needed because responses derived from unrelated aromatic species cannot be transferred uncritically to *Mentha*, whose rapid vegetative growth and menthane monoterpene pathway create distinctive management trade-offs.

Recent field experiments further show that peppermint responses to organic and mineral fertiliser sources are conditioned by harvest sequence and water availability, with corresponding variation in biomass, nutrient status, soil properties and essential-oil characteristics (Asadi et al., 2023; Bghbani-Arani & Poureisa, 2024; Fallah et al., 2024).

1.3 Scope, Research Gap and Objectives

This review examines nutrient-management strategies for cultivated *Mentha*, with primary emphasis on Japanese mint and peppermint and selective inclusion of other mint species where they clarify mechanisms or quality responses. The scope covers mineral macronutrients and micronutrients, organic manures and composts, recycling of mint distillation residues, microbial biofertilisers and integrated nutrient management. Outcomes include soil physical, chemical and biological function; fresh and dry herb production; essential-oil concentration and yield; monoterpene composition; nutrient-use efficiency; and resilience under water or salinity stress. The central gap is the absence of a critical synthesis that treats these outcomes as interdependent rather than as separate agronomic, soil or phytochemical questions. The objectives are to evaluate the strength and limitations of current evidence, explain sources of inconsistent results, identify practices supported across multiple evidence types, and propose a decision framework and research priorities for productive, quality-conscious and soil-conserving mint cultivation. The review does not attempt a quantitative meta-analysis, establish universal fertiliser rates, or assess post-distillation processing and pharmacological efficacy except where these issues define oil-quality requirements.

2. Methods for Literature Selection

2.1 Review Design and Rationale

A critical narrative review was selected because the evidence is methodologically heterogeneous and includes field experiments, pot and greenhouse studies, hydroponic deficiency work, microbiological experiments, biochemical investigations and broader soil-health syntheses. The diversity of species, cultivars, nutrient formulations, soils, climates, harvest schedules and outcome measures precluded a defensible pooled effect estimate. The narrative approach was nevertheless conducted transparently, following the principle that narrative synthesis requires an explicit search logic, critical appraisal and traceable evidence–claim relationships rather than an informal selection of supportive studies (Ferrari, 2015). The purpose was analytical integration: to compare mechanisms and agronomic outcomes, test the consistency of commonly repeated claims and distinguish findings with field-level support from those based mainly on controlled environments.

2.2 Information Sources

Searches were conducted through PubMed/MEDLINE, the Directory of Open Access Journals, AGRIS, OpenAIRE Explore and broad scholarly web indexing. Bibliographic identities and DOI assignments were checked against DOI registry landing pages and official article records. Institutional repositories were used to confirm publication metadata or access accepted manuscripts where appropriate. Backward citation searching was undertaken from relevant reviews and high-value primary studies, and forward and related-article searching was used to identify subsequent field or mechanistic work. Searches for corrections, retractions and bibliographic inconsistencies were incorporated during reference verification. Direct, complete searches of subscription-only databases were not claimed because exported records were not available for this review.

2.3 Search Strategy and Search Period

The principal search period extended from January 1990 to 15 May 2026. This start date captured early deficiency and field nutrient studies that shaped contemporary mint fertilisation while allowing inclusion of later work on integrated nutrient management, soil biological indicators and rhizosphere engineering. Searches combined crop terms with nutrient-source, soil and product-quality concepts. A representative string was: ("*Mentha*" OR peppermint OR spearmint OR "Japanese mint" OR "menthol mint") AND (fertili* OR nutrient* OR nitrogen OR phosphorus OR potassium OR micronutrient* OR manure OR compost OR vermicompost OR biofertili* OR rhizobacteria OR PGPR OR mycorrhiz* OR "integrated nutrient management") AND ("essential oil" OR menthol OR menthone OR carvone OR biomass OR yield OR "soil organic carbon" OR "microbial biomass" OR "soil health" OR "nutrient use efficiency"). Supplementary searches paired individual species names with irrigation, drought, salinity, harvest stage, glandular trichomes, distillation waste, residue recycling, zinc, iron and oil composition. Search terms were adapted to the syntax and field limitations of each accessible source.

2.4 Eligibility Criteria

Eligible sources were peer-reviewed journal articles published in English that directly examined nutrient management in cultivated mint, investigated mechanisms relevant to nutrient-mediated oil biosynthesis, or provided high-quality evidence on soil responses to organic or integrated nutrient inputs. Primary studies were prioritised when they reported experimental design, treatment definition and measurable agronomic, soil or oil outcomes. Reviews were included selectively to establish broader soil-health concepts, medicinal-aromatic-plant responses or mint phytochemistry. Studies of unrelated aromatic crops were not used as direct evidence for mint performance, although a small number of broader syntheses informed interpretation of organic amendments. Conference abstracts, patents, commercial promotional material, unverifiable records and papers with incomplete bibliographic identity were excluded. Studies published after the search end date were not incorporated. Articles that measured only pharmacological properties of purchased oil, without agronomic relevance, were outside scope.

2.5 Screening, Duplicate Handling and Study Selection

Records were consolidated by DOI, title, authorship and publication year. Duplicate records arising from index pages, repositories and official article pages were merged, with corrected metadata retained from authoritative records. Titles and abstracts were assessed for relevance to nutrient source, soil function, crop productivity or oil quality. Full texts or sufficiently detailed official abstracts were then examined for design, treatment comparability and claim support. Inaccessible records were retained only when bibliographic identity and the specific information used in the synthesis could be confirmed from reliable records; otherwise, they were excluded. No screening counts are reported because the review was designed as a critical narrative synthesis rather than a systematic review with prospectively documented record-flow statistics.

2.6 Critical Appraisal and Evidence Synthesis

Evidence was appraised according to experimental scale, duration, replication, controls, baseline soil characterisation, nutrient-rate comparability, reporting of irrigation and harvest stage, measurement validity, oil-analysis method and relevance to commercial production. Multi-year field trials with defined nutrient budgets and soil outcomes were given greater agronomic weight than single-season pot studies. Controlled studies were valued for mechanistic inference but not treated as equivalent to field effectiveness. For microbial inoculants, attention was paid to strain identity, mode of application, colonisation evidence and the distinction between direct plant-growth promotion and indirect stress mitigation. Themes were developed around nutrient demand and oil biosynthesis, mineral fertilisation, organic-resource management, microbial biofertilisers, integrated decision-making and methodological limitations. Contradictory findings were interpreted in relation to species, genotype, soil fertility, climate, water regime, phenological stage and analytical method.

3. Nutrient Demand and the Biological Basis of Oil-Quality Responses

3.1 Biomass Formation, Nutrient Demand and the Meaning of Productivity

Mint productivity emerges from sequential processes: establishment of stolons or transplants, rapid leaf-area expansion, accumulation of dry matter, differentiation of glandular trichomes, synthesis and storage of volatile compounds, and recovery of oil during distillation. Nutrient management influences each process, but not necessarily in the same direction. Nitrogen deficiency restricts chlorophyll and canopy development, thereby limiting the photosynthetic carbon available for both structural growth and secondary metabolism. Adequate N normally raises leaf area and herbage yield. Yet a larger canopy can contain a lower proportional concentration of oil if vegetative expansion outpaces trichome formation or if carbon allocation favours proteins and structural growth. Total oil yield may still rise because the biomass effect exceeds the change in oil percentage. This distinction explains why field studies can report beneficial N effects on oil yield without a corresponding increase in oil concentration (Seif Sahandi et al., 2019; Zheljazkov et al., 2010).

Phosphorus supports energy transfer, nucleic-acid synthesis and root growth, while K is involved in osmotic control, enzyme activation and carbohydrate transport. Their specific contribution to oil quality is less clearly isolated because many studies apply NPK mixtures or compare complete fertiliser regimes with organic inputs. The resulting response cannot be assigned confidently to a single nutrient. Micronutrients such as iron (Fe) and zinc (Zn) operate within redox enzymes, chlorophyll formation and metabolic regulation, but the response curve can be narrow: deficiency impairs growth, while excess can create toxicity or antagonise other nutrients. The early Fe work in Japanese mint illustrates the value of controlled deficiency studies for identifying critical tissue concentrations, but its hydroponic conditions do not establish field rates across heterogeneous soils (Misra & Sharma, 1991).

Productivity should therefore be reported through at least four separate variables: fresh herbage yield, dry-matter yield, oil concentration on a defined moisture basis and oil yield per unit land. Nutrient uptake and recovery efficiency are also required to judge whether a yield increment represents efficient capture or simply greater input. Few mint studies provide complete nutrient balances. This omission matters in perennial or sequential systems because residual nutrients can benefit the following crop or be lost between harvests. Patra et al. (2000) addressed this system dimension by evaluating mint within a mint–mustard sequence and measuring residual soil effects, whereas many later studies remain confined to a single crop cycle.

3.2 Glandular Trichomes and Monoterpene Biosynthesis

Essential oils in mint are synthesised and stored primarily in peltate glandular trichomes. Their density, developmental state and enzymatic activity influence both oil concentration and composition. The menthane monoterpene pathway converts geranyl diphosphate through limonene and a sequence of oxidation and reduction reactions to products including menthone and menthol. Comparative transcriptomic evidence indicates that differential expression of pathway genes helps explain why mint species vary in menthol accumulation (Akhtar et al., 2017). Nutrient effects on oil quality are therefore mediated not only through general biomass but also through developmental and regulatory processes in secretory tissues.

This mechanism creates two interpretive cautions. First, oil composition changes naturally with leaf age and position. Rohloff (1999) showed that peppermint monoterpene profiles differ by leaf position, demonstrating that sampling design can confound treatment comparisons. Second, harvest stage alters the balance among monoterpenes. Nitrogen and harvest timing interacted in field work on peppermint, and the agronomically highest oil yield did not automatically correspond to the most desirable composition for every market (Zheljazkov et al., 2010). Studies that harvest treatments on a single calendar date, despite differences in phenological development, may therefore compare plants at unequal physiological stages.

PGPR research adds a signalling dimension. Inoculation or exposure to bacterial volatile organic compounds has increased peppermint growth, phenolic metabolism and essential-oil production in controlled studies (Cappellari et al., 2017; Santoro et al., 2011, 2016). Cappellari et al. (2019) linked bacterial induction of oil production with higher jasmonate and salicylate levels and greater glandular-trichome density. This provides mechanistic support for the proposition that the rhizosphere can influence secondary metabolism above ground. The evidence is persuasive as proof of biological possibility, but most experiments used selected strains under controlled conditions. It does not yet establish that commercial inoculants will reproduce the response across soils, climates and resident microbial communities.

3.3 Species, Genotype, Environment and Management Interactions

The term “mint” can obscure large biological differences. Japanese mint is commonly managed for menthol-rich oil and rapid biomass production in subtropical systems. Peppermint oil quality depends on a characteristic mixture rather than menthol alone, and elevated menthofuran or pulegone can be undesirable. Spearmint quality is centred on carvone. A nutrient treatment that shifts carbon flux towards menthol may be advantageous in one crop but irrelevant or adverse in another. Even within a species, cultivars differ in growth habit, oil concentration and enzyme expression. Tiwari (2016) emphasised the importance of trichome biology and biosynthetic regulation in *M. arvensis*, while Akhtar et al. (2017) demonstrated species-level transcriptional differences. Fertiliser recommendations that omit cultivar identity therefore have limited transferability.

Environment modifies these genetic responses. Temperature, photoperiod, radiation and water availability influence growth and volatile metabolism. Seasonal work on peppermint has shown that transplanting and harvest season alter oil production and composition (Souza et al., 2024). Irrigation can modify nutrient mobility and uptake, while water deficit changes stomatal conductance, biomass and secondary metabolism. Keshavarz-Mirzamohammadi et al. (2021) explicitly linked fertiliser treatments, irrigation regimes, agronomic traits, soil properties and oil profile, illustrating why single-factor recommendations are incomplete. The apparent effect of a nutrient source may reflect its interaction with soil moisture, especially where organic amendments alter water retention or microbial mineralisation.

Table 1 summarises the principal outcome domains and the interpretive risks that arise when they are measured in isolation. The central implication is that a sustainable treatment cannot be identified from a single endpoint. A credible assessment needs an outcome set spanning crop production, oil chemistry, soil function and resource efficiency.

Table 1. Outcome domains and interpretive risks in *Mentha* nutrient-management research

Outcome domain	Preferred indicators	Common but incomplete proxies	Principal interpretive risks	Supporting references
Crop productivity	Fresh and dry herbage yield, leaf-to-stem ratio, harvest frequency, stand persistence	Plant height or fresh mass alone	Water-rich tissue may inflate apparent yield; phenology and plant density may confound treatment effects	Ostadi et al. (2020); Zheljazkov et al. (2010)
Essential-oil productivity	Oil concentration on a defined basis and oil yield per unit land	Oil percentage without biomass, or biomass without oil recovery	A lower oil percentage can coexist with higher total oil yield; distillation method affects recovery	Tepecik et al. (2022); Verma et al. (2016)

Outcome domain	Preferred indicators	Common but incomplete proxies	Principal interpretive risks	Supporting references
Oil quality	GC–MS profile, market-relevant marker compounds and undesirable constituents	Total oil or menthol alone	Species and market standards differ; leaf age, harvest stage and storage can alter composition	Akhtar et al. (2017); Rohloff (1999); Zhao et al. (2022)
Nutrient efficiency	Uptake, partial factor productivity, recovery efficiency, residual nutrient status	Applied rate or tissue concentration alone	High uptake may reflect luxury consumption; residual nutrients and losses are often unmeasured	Patra et al. (2000); Kumar et al. (2025)
Soil health	Soil organic carbon, aggregation, bulk density, available nutrients, microbial biomass/activity and biological function	A single chemical indicator	Short-term changes may not represent durable function; values depend on soil type and sampling time	Bünemann et al. (2018); Chand et al. (2004)
Environmental performance	Nitrate loss, gaseous N emissions, nutrient balance, energy use and residue fate	Reduced mineral-fertiliser rate	Substitution does not guarantee lower impacts if nutrient availability and application timing are poorly matched	Hijbeek et al. (2017); Rostaei et al. (2024)

Note. GC–MS = gas chromatography–mass spectrometry.

4. Mineral Nutrient Management: Productivity Gains and Quality Trade-offs

4.1 Nitrogen as the Dominant but Non-linear Driver

Among mineral nutrients, N has the strongest experimental basis in mint. It reliably supports canopy formation and often increases fresh and dry herbage yield where baseline soil N is limiting. In peppermint, Zheljazkov et al. (2010) found that productivity and oil composition responded to N in conjunction with growth stage and harvest timing. Seif Sahandi et al. (2019) similarly reported changes in essential-oil content and composition under N application. These studies support a broad conclusion that N is necessary for profitable production but do not justify a universal optimum. Response curves depend on soil mineralisation, previous crop, irrigation, cultivar and harvest strategy.

The relation between N rate and oil quality is particularly conditional. Adequate N can increase leaf area and the absolute number of oil-bearing trichomes, but excessive vegetative growth may reduce oil concentration or delay maturation. Nitrogen can also alter the relative abundance of menthol, menthone and precursor compounds through developmental effects on the pathway. Because harvest stage itself changes composition, a fertilised crop harvested at the same chronological date as a low-N crop may be physiologically younger. This confounding is rarely resolved through repeated compositional sampling. Consequently, the strongest inference is not that more N improves or worsens quality, but that N must be optimised jointly with phenology and harvest objectives.

Split application is biologically attractive because it can align available N with crop demand and reduce the period during which nitrate is exposed to loss. Mint establishes rapidly and may require a basal supply followed by top-dressing during canopy expansion or after cutting. Yet comparative evidence on split schedules, controlled-release products and fertigation remains thin relative to rate experiments. Many studies report a single seasonal rate without evaluating recovery efficiency. Future recommendations should therefore distinguish between total N requirement and delivery strategy. A lower, synchronised rate may outperform a larger one-time dose, but this proposition requires direct field testing.

4.2 Phosphorus, Potassium and Nutrient Balance

Evidence for P and K is less definitive because they are frequently applied as components of NPK treatments. In high-P soils, additional P may produce little response, whereas low-P soils or cool conditions can restrict root acquisition. Arbuscular mycorrhizal fungi (AMF) may improve P access, but the benefit is expected to diminish when soluble P is abundant. Potassium can support turgor regulation and carbohydrate transport, making it relevant under high evaporative demand, yet K effects on mint oil composition are not consistently isolated from N or irrigation. Tepecik et al. (2022) showed that fertiliser treatments altered nutrient status, essential oils and yield in peppermint, but such multi-nutrient comparisons are more useful for evaluating complete regimes than for assigning causality to one nutrient.

Balanced nutrition is therefore preferable to N-centric management. Increasing N without sufficient P, K or micronutrients can create stoichiometric imbalance, restrict response and reduce apparent N-use efficiency. Conversely, routine application of P and K without soil testing can accumulate nutrients beyond crop demand. Sustainability requires a budget that accounts for soil-test supply, organic inputs, irrigation water, previous residues and expected removal. This is especially important where FYM or compost contributes P and K over several seasons. Treating organic N substitution as the only calculation can unintentionally over-apply P.

The literature also seldom addresses sulphur, calcium and magnesium explicitly, despite their roles in protein synthesis, membrane function and photosynthesis. Their omission does not prove that they are unimportant; rather, it indicates that deficiency risk should be diagnosed rather than assumed. Site-specific soil and tissue testing is more defensible than importing a complete fertiliser formula from another region. Where local calibrations are absent, small diagnostic strips or omission plots can identify the nutrients constraining response.

4.3 Micronutrients: Correction of Deficiency Versus Speculative Stimulation

Micronutrient research in mint spans classical deficiency diagnosis, foliar salts and newer formulations. Misra and Sharma (1991) established a critical Fe relationship with oil yield and quality in Japanese mint under controlled conditions. The study demonstrates that micronutrient deficiency can impair both biomass and secondary metabolism. Its agronomic translation, however, requires information on soil pH, carbonate content, root-zone redox conditions and Fe availability. A tissue threshold derived from solution culture should not be converted directly into a field application rate.

Foliar micronutrients can bypass soil fixation and supply small quantities during rapid growth. Prasad et al. (2014) reported that metallic-salt sprays altered yield, oil composition, whitefly population and rhizosphere properties in menthol mint. The broad range of outcomes is intriguing but also creates multiple-testing and mechanism questions. A foliar nutrient may influence plant physiology directly, modify pest behaviour or reach soil through wash-off. Replication across environments is needed before such treatments are treated as routine quality-management tools.

A recent review of aromatic crops concluded that micronutrients can improve yield and essential-oil quality when deficiency or responsive conditions are present, while also highlighting variation among species and application methods (Kumar et al., 2022). The evidence base is weaker for nano-chelated or nanoparticle forms. Potential advantages in delivery do not remove the need to evaluate dose, persistence, worker exposure, soil accumulation and non-target effects. Sustainable micronutrient management should therefore begin with diagnosis and conventional correction. Claims of biostimulant effects beyond deficiency correction require stronger field evidence.

4.4 Harvest Timing and Nutrient Management cannot be Separated

Ostadi et al. (2020) demonstrated that fertiliser source and harvest time jointly influenced growth, nutrient uptake, oil productivity and composition in peppermint. This interaction is central to interpretation. A nutrient regime changes the rate of canopy development, so the biologically comparable harvest stage may occur on different dates. Conversely, harvesting all treatments at the same stage may require different calendar dates and expose plants to different weather. Robust experiments should report both chronological and phenological timing, analyse oil from comparable leaf fractions and, where possible, sample composition across more than one stage.

Oil-quality targets should also guide the harvest decision. Maximum herbage yield may occur after the oil has shifted away from a preferred profile. In peppermint, menthol and menthone proportions evolve as leaves mature, while undesirable compounds can respond differently. Zheljazkov et al. (2010) showed that N, growth stage and harvest timing together shaped productivity and composition. Nutrient recommendations divorced from harvest strategy therefore risk optimising the wrong endpoint.

Table 2 compares representative mineral-nutrient evidence and its principal limits. Across these studies, N has the greatest field support, whereas P, K and micronutrient conclusions remain more conditional. The practical lesson is to use soil- and tissue-based diagnosis, evaluate oil composition and avoid transferring response rates across soils or species.

Table 2. Representative evidence on mineral nutrient management in cultivated mint

Nutrient or management factor	Species and context	Main indication	Critical limitation	Supporting references
Nitrogen rate	Field-grown peppermint	N can increase biomass and oil yield, but composition depends on growth stage and harvest timing	Site-specific response; limited direct evidence on losses and recovery efficiency	Zheljazkov et al. (2010)
Nitrogen supply	Peppermint under controlled field management	Oil content and monoterpene composition respond to N, but not necessarily in parallel with biomass	Single-environment response and potential phenological confounding	Seif Sahandi et al. (2019)
Complete fertiliser regimes	Peppermint	Fertiliser source changes tissue nutrients, yield and essential-oil attributes	Nutrient effects are difficult to separate within multi-element treatments	Tepecik et al. (2022)
Fertiliser source × harvest time	Peppermint field experiment	Nutrient uptake, growth, oil productivity and composition are jointly regulated by source and harvest	Generalisability depends on cultivar, climate and baseline soil fertility	Ostadi et al. (2020)
Iron nutrition	Japanese mint in controlled culture	Fe deficiency has identifiable critical relationships with oil yield and quality	Hydroponic thresholds do not directly specify field application rates	Misra and Sharma (1991)
Foliar metallic salts	Menthol mint field study	Foliar salts can modify crop, oil and pest-related outcomes	Mechanisms and environmental reproducibility remain uncertain	Prasad et al. (2014)
Micronutrient interventions	Review across aromatic crops	Correcting micronutrient limitations can improve oil yield or composition	Cross-species synthesis; responsive conditions and safe rates require local validation	Kumar et al. (2022)

5. Organic Amendments, Residue Recycling and Soil Health

5.1 Organic inputs as nutrient sources and soil conditioners

Organic amendments differ fundamentally from soluble mineral fertilisers. Their nutrients are embedded in materials that also supply carbon and influence physical structure, microbial activity and water relations. FYM, compost and vermicompost can increase soil organic carbon, aggregation and nutrient-buffering capacity, but the magnitude and timing of benefits depend on feedstock, maturity, carbon-to-nitrogen ratio, application rate and climate. Mineralisation is biologically mediated and may not coincide with the rapid nutrient demand of a mint canopy. A treatment labelled "100% organic N" can therefore supply a different quantity of plant-available N during the season than an equal nominal rate of mineral N.

Long-term comparisons outside mint show that organic systems often increase soil microbial abundance and activity, yet yield outcomes are variable. Lori et al. (2017) found a general microbial advantage for organic farming in meta-analysis, while Hijbeek et al. (2017) showed that organic inputs do not automatically produce additional yield when nutrient supply is otherwise adequate. Mäder et al. (2002) demonstrated sustained fertility and biodiversity benefits in a long-term organic comparison, but the relevance of such results to short-duration mint trials must be calibrated. The broader evidence supports soil-function benefits, not a guarantee that any organic material at any rate will maximise mint yield.

Mint-specific field research provides a stronger basis for integration. Patra et al. (2000) compared organic manures and mineral fertilisers in a Japanese mint–mustard sequence at two locations. The study is important because it evaluated productivity, nutrient accumulation and residual soil properties rather than a single-season biomass response. Chand et al. (2004) subsequently showed that integrated inputs and mint distillation waste affected soil organic carbon and microbial biomass in the sequence. These studies support the proposition that crop residues and manures can contribute to soil restoration while maintaining production, but their results reflect particular soils, climate and management in northern India.

5.2 Farmyard Manure, Compost and Vermicompost

FYM is widely available in mixed farming systems, but its quality varies with animal diet, bedding, storage and decomposition. Fresh or poorly matured manure can immobilise nutrients, introduce weed seeds or pathogens, and create uneven nutrient release. Well-characterised compost is more stable but may contain less immediately available N. Vermicompost can provide fine organic matter, microbial metabolites and plant-available nutrients, yet production quality and application economics vary. Reviews of medicinal and aromatic plants generally report positive effects of organic manures on biomass, essential-oil yield or antioxidant attributes, although the evidence combines diverse species and often includes pot experiments with high amendment proportions (Rostaei et al., 2024).

In Japanese mint, Kumar et al. (2025) compared mineral recommendations, FYM-derived N and biofertiliser treatments over three seasons. The combined FYM and biofertiliser treatment performed strongly for growth, herbage yield, oil outcomes and selected soil properties. Its multi-year field design and four replications increase its relevance. Nevertheless, the result should not be interpreted as proof that complete mineral-N replacement will succeed universally. The experiment was conducted at one site under a defined management system, and treatment performance may reflect local manure quality, inoculant compatibility, irrigation and baseline soil fertility. Nutrient recovery, gaseous losses and full life-cycle burdens were not the central endpoints.

Dehghani et al. (2025) compared rose-waste compost, animal manure and chemical fertiliser for mint growth and biochemical characteristics. The work broadens circular-resource options by testing a crop-residue compost, but its transferability depends on compost composition and experimental scale. Organic materials from aromatic industries can contain residual phenolics, salts or volatile compounds that influence decomposition and plant response. Product-specific characterisation is therefore essential; "compost" is not a chemically uniform treatment.

Al-Amri (2021) found that organic and biofertiliser agents influenced peppermint growth, essential-oil composition, endogenous hormones and microbial activity. The concurrent changes are consistent with both nutritional and signalling mechanisms. Yet combined treatments make it difficult to separate improved nutrient supply from microbial or hormonal effects. This is a recurring design problem: studies often compare complex packages against a mineral control, producing a useful practical contrast but limited mechanistic attribution.

5.3 Distillation Waste and Circular Nutrient Flows

Mint distillation generates large quantities of spent biomass. Returning this material to soil could reduce disposal burdens, recycle nutrients and add carbon. The field evidence from Patra et al. (2000) and Chand et al.

(2004) indicates that distillation waste can participate in integrated nutrient supply and increase soil microbial biomass. This creates a circular-economy opportunity that is particularly attractive where distillation units are close to farms and transport distances are short.

Circularity should not be equated automatically with safety or agronomic value. Fresh spent material may have a high moisture content, uneven decomposition and residual volatile or phenolic compounds. Large surface applications can temporarily immobilise N or alter soil oxygen. If the biomass is contaminated by processing water, lubricants or mixed wastes, direct return may be inappropriate. Composting or co-composting can stabilise the material, but the process loses some carbon and N and requires space, time and moisture management. Balkrishna et al. (2024) reviewed medicinal and aromatic plant wastes with particular attention to vermicomposting, highlighting their potential but also the need for feedstock-specific management.

A defensible residue-recycling programme should quantify dry matter, total and mineral N, P, K, carbon-to-nitrogen ratio, pH, electrical conductivity and maturity. Application should be based on nutrient content rather than wet mass. The residual value for subsequent crops should be included in the farm nutrient budget. These basic controls are seldom reported in mint experiments, limiting comparison among studies and making it difficult to calculate true fertiliser substitution.

5.4 Soil Biological Responses and their Interpretation

Soil microbial biomass is a sensitive indicator of organic substrate supply, but it is not a direct measure of all soil-health functions. Chand et al. (2004) found that integrated nutrient supply and distillation waste influenced microbial biomass more strongly than inorganic NPK alone. This is biologically plausible because organic carbon provides energy and habitat. Nevertheless, higher microbial biomass can represent beneficial nutrient cycling, temporary nutrient immobilisation or simply a response to recent substrate addition. Sampling time relative to amendment and harvest is therefore critical.

A robust soil-health assessment should combine biological indicators with physical and chemical measures. Bünemann et al. (2018) emphasised that soil quality is context dependent and cannot be reduced to a universal single index. For mint systems, relevant measurements include soil organic carbon, aggregate stability, bulk density, infiltration, available nutrients, pH, electrical conductivity, microbial biomass, enzyme activity and potentially disease-suppressive function. Their interpretation requires baseline values and repeated sampling. Short trials can detect available nutrients or respiration but may be too brief to demonstrate durable changes in structure or carbon stocks.

Organic amendments can also alter water relations. Improved aggregation and water retention may indirectly enhance nutrient uptake, especially in light-textured soils or under intermittent water stress. This interaction complicates attribution: a yield increase may arise from nutrient release, better moisture supply or both. Keshavarz-Mirzamohammadi et al. (2021) showed that soil properties, irrigation and fertiliser treatments were related to peppermint agronomic traits and oil profile. Future experiments should therefore measure soil water and nutrient dynamics together rather than treating irrigation as a fixed background factor.

Table 3 compares organic and integrated strategies. The evidence is strongest for improvements in soil carbon-related and biological indicators and for maintaining or increasing yield in responsive settings. It is weaker for universal replacement ratios and long-term environmental performance.

Table 3. Organic and integrated nutrient strategies in *Mentha* systems

Strategy	Expected soil functions	Evidence for crop or oil response	Main evidence constraint	Supporting references
FYM combined with mineral NPK	Adds carbon and slow-release nutrients while mineral inputs meet immediate demand	Multi-location sequence work supports productivity and residual fertility	Historic regional trials; nutrient equivalence and loss pathways need modern reassessment	Patra et al. (2000)
Mint distillation	Returns carbon and nutrients; stimulates	Supports circular nutrient supply and	Feedstock maturity, salinity, residual	Chand et al. (2004);

Strategy	Expected soil functions	Evidence for crop or oil response	Main evidence constraint	Supporting references
waste recycling	microbial biomass	soil biological activity	volatiles and transport economics are rarely quantified	Balkrishna et al. (2024)
FYM plus biofertiliser	Couples organic nutrient release with microbial nutrient mobilisation	Three-season Japanese mint field study reported strong yield, oil and soil responses	Single-site evidence; strain performance and nutrient balance may vary	Kumar et al. (2025)
Crop-residue compost or animal manure	Improves organic matter and supplies multiple nutrients	Mint growth and biochemical traits can respond positively	Compost composition and experimental scale limit direct rate transfer	Dehghani et al. (2025)
Organic and microbial agents	Potentially modifies nutrient supply, microbial activity and plant hormones	Peppermint growth and oil composition responded to combined treatments	Complex packages prevent separation of nutritional and signalling effects	Al-Amri (2021)
Organic manures across medicinal and aromatic plants	Generally improve soil condition and may support biomass and oil production	Broad review indicates frequent positive responses	Cross-species heterogeneity and publication bias limit mint-specific certainty	Rostaei et al. (2024)

6. Biofertilisers and Rhizosphere Engineering

6.1 Plant Growth-promoting Rhizobacteria: Mechanisms and Evidence Hierarchy

PGPR can influence plant nutrition through N fixation, phosphate solubilisation, siderophore production, phytohormone modulation and changes in root architecture. They may also produce volatile organic compounds that alter plant metabolism without direct physical contact. These mechanisms are relevant to mint because oil synthesis occurs in aerial secretory tissues but responds to whole-plant carbon balance and signalling. The controlled evidence is unusually detailed compared with many biofertiliser claims.

Santoro et al. (2011) showed that rhizobacterial volatile organic compounds increased peppermint growth parameters and essential-oil biosynthesis. Santoro et al. (2015) evaluated native *Pseudomonas* strains and demonstrated plant-growth-promoting effects in vitro. A subsequent analysis linked fluorescent *Pseudomonas* strains and their volatiles to changes in peppermint essential-oil composition (Santoro et al., 2016). These studies establish strain-specific biological activity and help move interpretation beyond the vague claim that "beneficial bacteria improve growth". They do not, however, demonstrate consistent field performance because volatile exposure, inoculum density, root-zone competition and environmental stability differ outside controlled systems.

Cappellari et al. (2017) found that PGPR inoculation induced phenolic production and volatile emissions in peppermint. Cappellari et al. (2019) then associated increased essential-oil production with higher jasmonate and salicylate levels and greater glandular-trichome density. This sequence of studies provides a coherent mechanistic chain from rhizobacterial exposure to hormonal signalling, secretory structure and oil output. Confidence in the mechanism is stronger than confidence in agronomic scalability. Field soils contain complex microbial communities, and inoculated strains may fail to establish, be displaced or act differently under nutrient-rich conditions.

6.2 Stress Mitigation and Nutrient Acquisition

Microbial inoculants may be most valuable where stress limits nutrient acquisition. Bharti et al. (2014) reported that PGPR alleviated salinity-induced reductions in growth, oil content and physiological status in Japanese mint. Cappellari et al. (2020) showed that bacterial volatiles improved secondary metabolites and antioxidant status in peppermint under salt stress. Ozhuner (2025) found that PGPR enhanced essential-oil production and antioxidant activity under water deficit. These studies support a role for rhizobacteria in stress buffering, potentially through improved root growth, osmotic adjustment, antioxidant defence and hormonal regulation.

Stress-mitigation evidence should be interpreted carefully. A treatment that reduces the severity of an imposed stress is not necessarily superior under non-stress field conditions. Controlled salinity or water-deficit experiments may use uniform stress levels that do not reflect spatially variable farms. The magnitude of benefit can also depend on the susceptibility of the control cultivar. Field validation should include both stressed and adequately supplied conditions, quantify soil salinity or water status and test whether inoculation remains effective over repeated harvests.

Biofertilisers are sometimes presented as substitutes for fertiliser, but many PGPR primarily increase access to existing nutrients or alter plant physiology. They cannot create P or K, and non-symbiotic N fixation may supply only part of the N required by a high-yielding crop. Their performance therefore depends on the soil nutrient pool and compatible organic or mineral inputs. Kumar et al. (2025) provides field evidence that a biofertiliser can function effectively with FYM in Japanese mint, but the product, strains, application method and local context should be specified before extrapolation.

6.3 Arbuscular Mycorrhizal Fungi

AMF extend the effective root absorptive network and can improve acquisition of relatively immobile P and micronutrients. They may also alter water relations and secondary metabolism. Heydarizadeh et al. (2013) examined mycorrhizal infection, essential-oil content and morpho-phenological variability in three mint species, showing that species identity influences the response. This variation is expected because host dependence, root architecture and compatibility with fungal taxa differ.

The benefit of AMF is likely to be greatest in low- to moderate-P soils and may be suppressed by high soluble-P fertilisation. Field inoculation must also compete with indigenous mycorrhizal communities. A commercial inoculum can appear effective in sterilised or low-microbial substrates but add little in a biologically active field soil. Trials should verify colonisation and include a native-community control. Without colonisation data, a non-response cannot distinguish biological inefficacy from failed establishment.

AMF effects on oil composition remain insufficiently resolved. Changes may arise from improved P nutrition, altered water status, stress signalling or shifts in phenology. Experiments should measure tissue nutrients, root colonisation, biomass, trichome traits and complete oil composition. Testing AMF as one component of an integrated programme is more realistic than assuming it can replace balanced fertilisation.

6.4 From Promising Strains to Reliable Farm Inputs

Four translational barriers recur across microbial studies. The first is strain specificity: results from one *Pseudomonas* isolate cannot be generalised to all PGPR. The second is formulation and shelf life. Laboratory cultures may not survive storage, transport or application. The third is ecological establishment in non-sterile soil. The fourth is management compatibility, including fertiliser rate, pesticides, soil pH, irrigation and organic substrate. These factors determine whether a mechanistically active strain becomes a dependable input.

Quality control should include strain identity, viable cell count, contamination testing, carrier properties and expiry. Field protocols should compare inoculant plus reduced fertiliser against both full fertiliser and uninoculated reduced-fertiliser controls. This design distinguishes true nutrient substitution from a general growth response. Repeated sampling can determine persistence. Economic analysis should include product cost, application labour and yield-quality value, not only percentage changes in biomass.

Table 4 places microbial evidence in a hierarchy from mechanistic proof to field application. The literature supports a credible biological role for the rhizosphere in mint oil production, but the greatest uncertainty lies between controlled efficacy and reproducible farm performance.

Table 4. Microbial biofertiliser mechanisms, evidence and translational constraints in mint

Microbial intervention or mechanism	Evidence demonstrated	Likely agronomic relevance	Principal translational constraint	Supporting references
Rhizobacterial volatile organic compounds	Increased peppermint growth and oil biosynthesis under controlled exposure	Signals can alter aerial secondary metabolism without direct nutrient transfer	Volatile concentration and exposure geometry differ in field soil	Santoro et al. (2011, 2016)
Native *Pseudomonas* strains	In vitro plant-growth-promoting traits and peppermint responses	Locally adapted strains may improve root development or nutrient mobilisation	In vitro traits do not guarantee rhizosphere persistence	Santoro et al. (2015)
PGPR-induced hormonal and trichome responses	Higher jasmonate/salicylate levels, glandular-trichome density and oil production	Provides a mechanistic link between rhizosphere signalling and oil yield	Evidence is based mainly on selected strains and controlled conditions	Cappellari et al. (2017, 2019)
PGPR under salinity or water deficit	Improved physiological status, antioxidants or oil-related outcomes	May stabilise production where stress restricts nutrient uptake	Stress intensity, cultivar susceptibility and field heterogeneity affect response	Bharti et al. (2014); Cappellari et al. (2020); Ozhuner (2025)
AMF inoculation	Species-dependent mycorrhizal infection and changes in growth or oil traits	Potentially valuable in P-limited soils and for water acquisition	Indigenous fungi, soil P and host genotype influence colonisation and benefit	Heydarizadeh et al. (2013)
Biofertiliser integrated with FYM	Multi-year field improvement in Japanese mint yield, oil and selected soil indicators	Shows that microbial inputs can operate within an organic nutrient programme	Product identity, local validation and complete nutrient balances remain necessary	Kumar et al. (2025)

Note. AMF = arbuscular mycorrhizal fungi; PGPR = plant growth-promoting rhizobacteria.

7. Towards Integrated Nutrient Management

7.1 Integration is a design principle, not a fixed recipe

Integrated nutrient management is often described as combining mineral fertilisers, organic inputs and biofertilisers. This description is incomplete unless the components are assigned distinct functions. Soluble mineral fertilisers can meet rapid, predictable demand. Organic materials can supply part of the nutrient requirement while building carbon and buffering soil processes. Microbial inputs may improve nutrient mobilisation, root function or stress tolerance. Integration is effective when these functions complement one another; it can fail when inputs duplicate nutrients, release them at the wrong time or create antagonisms.

The historical mint–mustard work of Patra et al. (2000) and Chand et al. (2004) illustrates system-level integration: manure and distillation residues were evaluated alongside mineral NPK, and residual soil effects were considered. Verma et al. (2016) found that integrated nutrient management influenced peppermint biomass, oil yield, composition and residual fertility in a hilly soil. The latter context is valuable because sloping or structurally vulnerable soils may benefit disproportionately from organic matter. Yet neither study establishes a universal proportion of organic and mineral nutrients. The proportion should be calculated from soil supply, organic-input analysis, expected mineralisation and crop demand.

A useful starting point is a whole-season nutrient budget. Soil-test results define existing fertility; organic amendments contribute total and potentially mineralisable nutrients; irrigation water may contribute N or salts; the previous crop leaves residues; and the target yield determines likely removal. Mineral fertiliser should fill the predicted shortfall and be split to reduce temporal mismatch. After harvest, residual soil mineral N and crop uptake can refine the next season's plan. This adaptive loop is more sustainable than repeating a fixed recommended dose irrespective of site conditions.

7.2 Soil and Plant Diagnostics

Soil testing before planting should include pH, electrical conductivity, organic carbon, available N, P and K, and locally relevant micronutrients. Soil texture and bulk density help interpret water and nutrient behaviour. Tissue analysis during vegetative growth can identify emerging deficiency or confirm whether high fertiliser rates are creating luxury uptake. Diagnostic interpretation requires locally calibrated sufficiency ranges; where these are unavailable, comparisons among well-managed fields and omission plots can provide provisional guidance.

Plant appearance alone is insufficient. Chlorosis, stunting and marginal necrosis can have overlapping causes, including waterlogging, salinity, root disease and nutrient imbalance. Foliar correction without diagnosis may mask symptoms temporarily while leaving the root-zone problem unresolved. Likewise, high tissue concentration can result from restricted growth rather than adequate supply. Diagnosis should combine plant symptoms, soil conditions, tissue concentration and management history.

Digital sensing offers potential for canopy-based N management, but mint-specific calibration is limited. Chlorophyll meters or spectral vegetation indices may detect N status, yet dense canopies, variable leaf orientation and differences among cultivars complicate interpretation. These tools should be validated against biomass, tissue N and oil outcomes rather than imported from cereals. Their greatest value may be in identifying spatial variability and guiding targeted sampling.

7.3 Coordinating Nutrients with Irrigation and Harvest

Nutrient availability and water supply are inseparable. Mineral N applied to dry soil may remain unavailable until irrigation, whereas heavy irrigation after application can move nitrate below the active root zone. Organic mineralisation also depends on moisture and temperature. Keshavarz-Mirzamohammadi et al. (2021) showed relationships among irrigation regime, fertilisation, soil properties and peppermint oil profile. Integrated management should therefore schedule N around irrigation events and avoid high soluble-N applications immediately before intense rainfall.

Water quality deserves attention in irrigated mint regions. Saline or sodic water can impair root function and alter nutrient availability. Organic matter and PGPR may improve tolerance, but they do not eliminate salt loading. Bharti et al. (2014) and Cappellari et al. (2020) provide mechanistic evidence for microbial mitigation of salinity effects, not a substitute for drainage and salinity management. Monitoring soil electrical conductivity and sodium status remains necessary.

Harvest should be treated as part of the nutrient plan. Cutting removes nutrients and changes subsequent demand. A post-cut N application may support regrowth, but the rate should consider residual leaf area, expected second-harvest duration and weather. Oil analysis from each harvest is needed because composition can differ across cuts. Ostadi et al. (2020) and Zheljazkov et al. (2010) show that fertilisation and harvest timing interact; management should therefore target a combined yield–quality optimum.

7.4 Essential-oil Quality as a Routine Agronomic Endpoint

Many nutrient experiments treat oil composition as an optional laboratory measurement. For commercial mint, it is a primary outcome. GC–MS or validated gas-chromatographic profiling should quantify major constituents and undesirable compounds relevant to the species and market. Oil samples should be obtained through a standardised distillation protocol, with harvest moisture, distillation duration and storage reported. Without such controls, treatment effects can be confounded by recovery and oxidation.

The target profile must be declared before interpretation. A rise in menthone may indicate incomplete conversion to menthol in menthol mint, whereas a particular menthol–menthone balance may be acceptable in peppermint depending on specification. Zhao et al. (2022) summarised peppermint phytochemistry and applications, illustrating the breadth of compounds that determine biological and commercial characteristics. Agronomic studies should avoid labelling any increase in a single constituent as "improved quality" without reference to a defined standard.

Quality monitoring also protects against over-fertilisation. If a higher N rate raises biomass but shifts composition outside specification, the marginal yield has little value. Conversely, a treatment that modestly reduces biomass may be profitable if oil recovery and price improve. Economic analysis should use saleable oil yield and quality premiums or penalties rather than fresh-herb yield alone.

7.5 Environmental Safeguards and Circularity

Integrated nutrient management should reduce losses, not merely reduce purchased fertiliser. A manure-based treatment can still lose N if applied far in advance of crop demand, left on the surface or used at excessive rates. Compost can accumulate P. Biofertilisers can fail, leading to nutrient deficiency and reduced land-use efficiency. Environmental evaluation therefore requires nutrient balances, residual mineral N, leaching indicators and, where feasible, nitrous oxide and ammonia measurements.

Mint distillation residue is a priority circular resource because it is generated within the value chain. Its return can reduce waste and add carbon, but the most sustainable pathway depends on moisture, transport distance and processing. Direct incorporation may be suitable for well-characterised material and adequate decomposition time. Composting or vermicomposting may improve stability but adds processing requirements. Balkrishna et al. (2024) supports the potential of vermicomposting medicinal and aromatic plant wastes, while the mint-specific field evidence shows biological benefits from residue return (Chand et al., 2004). Decision-making should compare nutrient value, avoided disposal, transport energy and soil effects.

7.6 An Evidence-informed Decision Framework

Table 5 translates the synthesis into a decision framework. The framework deliberately avoids universal rates. It prioritises diagnosis, functional assignment of inputs, synchronisation and verification. Confidence is highest for correcting diagnosed macronutrient limitations and for using organic materials to support soil carbon where quality and nutrient content are known. Confidence is moderate for integrated organic–mineral strategies because field responses are positive but site specific. Confidence is lower for broad substitution claims involving microbial or novel micronutrient products without local validation.

Table 5. Evidence-informed decision framework for sustainable nutrient management in cultivated mint

Decision point	Preferred management action	Monitoring requirement	Confidence in current evidence	Supporting references
Baseline fertility	Test soil pH, salinity, organic carbon and available macro- and micronutrients before setting rates	Soil test plus field history and previous organic inputs	High for the diagnostic principle; local calibrations vary	Bünemann et al. (2018); Misra and Sharma (1991)
Rapid crop demand	Use mineral N strategically to fill the predicted shortfall, preferably in synchronised splits	Tissue N, canopy growth, irrigation/rainfall and residual mineral N	Moderate to high for response; limited for universal rates	Seif Sahandi et al. (2019); Zheljazkov et al. (2010)

Decision point	Preferred management action	Monitoring requirement	Confidence in current evidence	Supporting references
Soil-carbon maintenance	Apply analysed, mature FYM or compost at agronomically justified rates	Organic-input nutrient analysis, soil carbon, bulk density and available P/K	Moderate; benefits are consistent but develop at different rates	Mäder et al. (2002); Patra et al. (2000); Rostaei et al. (2024)
Distillation-residue recycling	Compost, co-compost or incorporate quality-controlled residue according to decomposition and nutrient content	Moisture, C:N ratio, salinity, maturity and residual soil nutrients	Moderate for soil biological benefit; lower for universal handling protocols	Balkrishna et al. (2024); Chand et al. (2004)
Biofertiliser use	Select identified strains with local field evidence and integrate them with an adequate nutrient base	Viability, application method, colonisation or persistence and yield-quality response	Moderate for mechanisms; low to moderate for broad field generalisation	Cappellari et al. (2019); Kumar et al. (2025); Santoro et al. (2016)
Irrigation interaction	Coordinate soluble nutrients with irrigation and avoid application before likely leaching events	Soil moisture, irrigation water quality and electrical conductivity	Moderate; direct mint factorial evidence remains limited	Keshavarz-Mirzamohammadi et al. (2021); Ozhuner (2025)
Oil-quality control	Evaluate oil concentration, total oil yield and complete market-relevant composition at each harvest	Standardised distillation and GC–MS or validated chromatography	High for the need to measure quality; response targets are species specific	Ostadi et al. (2020); Rohloff (1999); Zhao et al. (2022)
Annual refinement	Update the nutrient budget using crop removal, residual fertility, yield, quality and economic return	Field records and post-harvest soil testing	Conceptually strong; limited long-term mint datasets	Patra et al. (2000); Verma et al. (2016)

8. Methodological Weaknesses and Sources of Inconsistency

8.1 Inadequate Treatment Comparability

A central weakness is comparison of nutrient sources without equivalent available nutrient supply. An organic treatment may receive the same nominal N as a mineral treatment, but only a fraction mineralises during the crop season. Alternatively, organic inputs may provide substantial P and K that are not counted when the comparison is framed as N replacement. Without analysis of the amendment and estimates of mineralisation, a yield difference cannot be attributed cleanly to source. Studies should report dry-matter content, total nutrients, mineral N, carbon-to-nitrogen ratio and application timing for every organic material.

Complex treatment packages create a related problem. Organic manure plus inoculant may be compared with mineral fertiliser alone. A positive response demonstrates package efficacy but not the contribution of each component. Factorial designs or additive controls are needed to separate manure, microbial and interaction effects. Al-Amri (2021) and Kumar et al. (2025) provide valuable integrated comparisons, but mechanistic attribution remains limited where several inputs change together.

8.2 Short Duration and Weak Soil-Health Inference

Many studies last one season or use pots. Such designs can reveal immediate crop responses but are poorly suited to claims about soil health. Soil organic carbon and structure change slowly, and repeated amendment can produce cumulative effects. A short-term increase in available nutrients or microbial respiration is not equivalent to improved long-term function. Multi-year sequence studies such as Patra et al. (2000), Chand et al. (2004) and Kumar et al. (2025) are therefore especially valuable, but the evidence remains geographically concentrated.

Pot experiments can exaggerate amendment contact with roots, restrict rooting volume and alter water dynamics. Microbial inoculants often perform better in sterilised or simplified substrates than in field soil. Controlled studies should be described as mechanistic evidence and followed by field validation rather than presented as direct agronomic recommendations. The same distinction applies to hydroponic micronutrient thresholds.

8.3 Incomplete Reporting of Soil, Water and Weather

Baseline soil fertility determines response, yet some studies omit organic carbon, available nutrients, pH or texture. Without these variables, a non-response may indicate adequate baseline supply rather than an ineffective treatment. Irrigation amount and water quality are also frequently under-reported. This is particularly problematic for N and salinity research because water controls nutrient movement and root function.

Weather and phenology need equivalent attention. Essential-oil composition is sensitive to temperature, radiation and developmental stage. Studies should report major weather variables and harvest stage, not just the calendar date. Seasonal evidence from Souza et al. (2024) and harvest-interaction studies from Ostadi et al. (2020) and Zheljazkov et al. (2010) show that environmental and temporal variation can be as important as fertiliser source.

8.4 Inconsistent Oil Measurement

Oil concentration is variously reported on fresh-weight or dry-weight bases, and distillation duration differs. Some studies pool replicate samples before GC–MS, reducing the statistical unit for composition. Others report only selected compounds or identify peaks without quantification standards. Such differences limit cross-study comparison. Minimum reporting should include sample moisture, plant part, harvest stage, distillation method and duration, oil yield calculation, analytical platform, compound-identification criteria and replicate structure.
The designation “quality” should be tied to species-specific commercial or pharmacopoeial criteria. A rise in total terpenes is not necessarily favourable if undesirable constituents also increase. Complete profiles are preferable to selective reporting. Rohloff (1999) demonstrates how leaf position alone changes peppermint composition, reinforcing the need for standardised sampling.

8.5 Statistical and Design Limitations

Small experiments with many correlated outcomes are vulnerable to false-positive interpretation. Plant height, fresh mass, dry mass, oil percentage and multiple compounds may all be tested separately without adjustment or a pre-specified primary endpoint. Repeated harvests are sometimes analysed as independent observations despite temporal correlation. Spatial field variation may be inadequately blocked. These limitations do not invalidate the literature, but they reduce confidence in marginal effects.

Dose–response designs are preferable to comparisons of one treatment against one control. They can identify the plateau or threshold beyond which additional nutrient provides little benefit. Factorial designs are needed for nutrient × irrigation, fertiliser × inoculant and source × harvest interactions, but they require adequate replication. Multi-location trials should treat site as an environment rather than pooling indiscriminately. Reporting effect sizes and confidence intervals would improve interpretation beyond significance testing.

8.6 Geographical Concentration and External Validity

A substantial proportion of field evidence comes from South Asia, particularly India, or from individual experimental stations in Iran and other regions. These locations are highly relevant to commercial mint production but do not represent all soils and climates. The performance of FYM, distillation residues and inoculants depends on local material quality and infrastructure. Recommendations for temperate peppermint systems or other species require validation.

External validity is also constrained by cultivar reporting. Some papers identify species but not cultivar, despite large genetic differences in oil profile. Authentication is particularly important for hybrids and vegetatively propagated material. Future studies should deposit or clearly document plant material and use consistent taxonomic nomenclature.

8.7 Limited Environmental and Economic Assessment

Most experiments measure yield and selected soil variables but not nutrient losses, greenhouse gases, energy use or life-cycle impacts. Reduced mineral fertiliser is sometimes treated as an environmental benefit without testing whether manure application increases ammonia or nitrous oxide losses. Similarly, biofertiliser efficacy is reported without accounting for product cost and failure risk. A sustainable recommendation requires evidence that benefits persist when environmental and economic outcomes are considered together.

Economic analysis should value oil composition and saleable oil, not fresh biomass. Costs should include manure transport, composting, inoculant storage, application labour, soil and oil testing and any additional irrigation. Distillation-residue recycling may be economically favourable near processing units but impractical over long distances. These context-dependent costs are essential for adoption.

9. Future Directions

The immediate research priority is a coordinated set of multi-location, multi-year field experiments that compare mineral, organic and microbial nutrient strategies on an equivalent nutrient basis. Treatments should include a soil-test-based mineral reference, graded mineral N, analysed organic inputs, integrated organic–mineral combinations and inoculant treatments with appropriate uninoculated controls. Sites should span contrasting soil textures, baseline organic carbon, climates and irrigation systems. Repeated harvests and a following crop should be included so that residual fertility and system productivity can be assessed. Such designs would resolve whether the favourable integrated responses reported by Patra et al. (2000), Verma et al. (2016) and Kumar et al. (2025) are robust across environments.

A second priority is nutrient synchrony and efficiency. Studies should measure soil mineral N through the season, crop nutrient uptake, apparent recovery, partial factor productivity and post-harvest residual nutrients. Split N, fertigation, controlled-release formulations and decision support based on canopy or tissue status should be compared at equal seasonal rates. Irrigation amount and nitrate movement should be monitored jointly. The objective is not merely to identify the highest-yielding rate but to define the lowest loss-adjusted rate that achieves a marketable oil yield and composition.

Oil quality requires standardisation. A core outcome set should include fresh and dry herbage, oil concentration on a defined basis, oil yield per hectare, complete GC–MS composition and pre-defined market-relevant quality indicators. Plant part, leaf position, phenological stage, distillation conditions and storage should be harmonised. Repeated compositional sampling across development would help distinguish direct nutrient effects from altered maturity. Genotype × nutrient × harvest experiments are especially needed because pathway regulation differs among species and cultivars (Akhtar et al., 2017; Rohloff, 1999; Zheljazkov et al., 2010).

Long-term soil-health studies should move beyond isolated indicators. At minimum, they should track soil organic carbon, aggregation, bulk density, infiltration, available nutrients, pH, salinity, microbial biomass and selected functional assays. Sampling must occur at consistent times relative to amendment and harvest. Where organic inputs are used, amendment chemistry and mineralisation should be quantified. Distillation residues deserve dedicated trials comparing direct incorporation, composting and vermicomposting, with attention to maturity, residual volatile compounds, nutrient retention, transport and disease risk (Balkrishna et al., 2024; Chand et al., 2004).

Microbial research should progress from strain discovery to ecological validation. Candidate PGPR and AMF should be genomically or taxonomically characterised, formulated under realistic storage conditions and tested in non-sterile soils. Field studies should verify survival or colonisation and determine whether responses persist across harvests. Mechanistic endpoints such as phytohormones, root architecture, nutrient acquisition and glandular-trichome density should be linked to field-scale oil yield. The mechanistic chain identified by Cappellari et al. (2019) is a strong starting point, but generalisation requires independent strains, cultivars and environments.

Environmental assessment should include nitrate leaching, ammonia volatilisation and nitrous oxide where feasible, together with whole-farm nutrient balances. Organic substitution should be evaluated for P accumulation and emissions, not only reduced mineral-N purchase. Life-cycle assessment could compare mineral fertiliser, transported manure, locally recycled distillation waste and inoculant-assisted systems. Such work would reveal whether apparent field-level sustainability persists when upstream processing and transport are included.

Economic and implementation research is equally necessary. Trials should calculate net return from saleable oil, incorporating composition-based premiums or penalties. They should measure labour, testing, transport, composting and inoculant costs and identify the farm scales at which residue recycling becomes viable. Participatory on-farm experiments could test simplified diagnostic and record-keeping tools. The most useful decision support will probably be modular: a core soil-test and nutrient-budget protocol, supplemented by region-specific response functions and locally validated organic resources or inoculants.

In the longer term, omics and sensor technologies may help connect soil processes with oil biosynthesis. Rhizosphere metagenomics, root exudate profiling and transcriptomics could identify microbial functions associated with nutrient acquisition and trichome regulation. Canopy spectroscopy and proximal soil sensors could support spatially variable nutrient management, but their algorithms must be calibrated against tissue nutrients, oil yield and composition in mint. Technology should be evaluated for decision value and affordability, not novelty alone.

10. Conclusions

Sustainable nutrient management in cultivated mint is best understood as optimisation of a coupled soil–plant–oil system. The most secure evidence concerns the central role of adequate nitrogen in canopy development and total oil production. Its effect on oil concentration and monoterpene composition is less predictable because genotype, water supply, leaf development and harvest stage modify the response. Phosphorus, potassium and micronutrients can constrain production, but the evidence does not support routine escalation without diagnosis. Soil and tissue testing, nutrient budgeting and synchronised application are therefore more defensible than universal rates.

Organic manures, composts and mint distillation residues can contribute nutrients while supporting soil carbon, microbial biomass and physical buffering. Their value depends on chemical characterisation, maturity, application timing and realistic estimates of plant-available nutrients. Complete substitution of mineral fertiliser is neither inherently sustainable nor universally effective. Integrated systems are most convincing when mineral inputs meet rapid demand, organic resources maintain soil function and microbial products are used only where their identity and local efficacy are established.

Rhizosphere research provides credible mechanisms linking beneficial microorganisms with nutrient acquisition, stress tolerance, hormonal signalling, glandular-trichome development and essential-oil biosynthesis. The mechanistic evidence is stronger than the evidence for consistent commercial performance. Field validation, formulation quality and ecological persistence remain decisive constraints.

A practical strategy should begin with baseline soil and water assessment, set explicit herbage and oil-quality targets, allocate each nutrient source a defined function, coordinate application with irrigation and harvest, and use chromatographic oil profiling as a routine agronomic endpoint. Annual refinement should incorporate crop uptake, residual fertility, soil change, saleable oil and economic return. Such adaptive integration offers a more credible route to productivity and soil stewardship than either high-input mineral fertilisation or uncritical replacement with organic and microbial products.

11. Limitations

As a critical narrative review, this synthesis is intrinsically vulnerable to selection and interpretive bias despite the use of transparent search concepts, explicit eligibility criteria and reference verification. Complete subscription-database exports were not available, so the search relied on accessible scholarly indexes, official article records, repositories and citation searching. English-language restriction may have excluded relevant regional studies. The evidence base is heterogeneous in species, cultivar, climate, soil, nutrient formulation, irrigation, harvest timing and oil-analysis method, which prevented quantitative synthesis and limits direct comparison of rates or effect sizes.

The field literature is geographically uneven and includes relatively few long-term, multi-location experiments. Several mechanistic conclusions rely on greenhouse, pot, hydroponic or in vitro studies that cannot be assumed to predict farm performance. Soil-health claims are constrained by short study duration and inconsistent indicator sets, while environmental outcomes such as nutrient loss and greenhouse-gas emissions are rarely measured. Economic evidence is also sparse and often fails to value oil composition. These limitations mean that the decision framework should guide local testing and adaptive management rather than be read as a universal fertiliser prescription.

Declaration of AI Use

This manuscript was prepared through the combined contributions of all author(s), including contributions to the study design, data, content development, results, interpretation, and related scholarly work. The author(s) acknowledge the use of Grammarly and ChatGPT to assist with grammar checking, language refinement, reference formatting. These AI-assisted tools were not used as authors and did not replace the intellectual contributions or scholarly judgment of the author(s). All AI-assisted outputs, including content, references, and interpretations, were carefully reviewed, revised, verified, and approved by the author(s). The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

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Peer-review history:
The peer review history for this paper can be accessed here:
https://pr.sdiarticle5.com/review-history/162849