



Challenges and Opportunities in Controlled Cultivation of Vetiver: The Role of Endophytic Microorganisms in Essential Oil Biosynthesis

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Abstract: Vetiver (*Chrysopogon zizanioides* (L.) Roberty) is an aromatic grass widely applied in environmental engineering and as a source of essential oil for the fragrance industry. However, essential oil production under intensified cultivation systems remains constrained by inconsistent yield and chemical composition, particularly in soilless and controlled environments. This review evaluates the role of root-associated endophytic microorganisms as a critical but under-integrated biological factor influencing vetiver essential oil biosynthesis. A structured review of peer-reviewed literature indexed in Scopus, Web of Science, and Google Scholar was conducted, focusing on cultivation systems, essential oil chemistry, plant-microbe interactions, and comparable mechanisms in other aromatic crops. Evidence was analyzed using a comparative, mechanism-based framework emphasizing biochemical performance rather than descriptive system comparison. The reviewed studies indicate that soil-based cultivation consistently produces higher root biomass, greater essential oil yields, and more chemically complex sesquiterpene profiles than *in vitro*, hydroponic, or aeroponic systems. In contrast, microbiome-depleted plants exhibit reduced oil accumulation and reduced levels of oxygenated sesquiterpenes, while reinoculation with native root endophytes partially restores aroma characteristics. These findings indicate that limitations in soilless vetiver production stem from biological simplification and engineering constraints. This review proposes microbiome-integrated cultivation and targeted endophyte reinoculation as feasible strategies to improve yield stability, chemical fidelity, and land-use efficiency in controlled production systems.

Keywords: Vetiver; essential oil biosynthesis; endophytes; plant-microbe interactions; secondary metabolites

1. Introduction

Vetiver (*Chrysopogon zizanioides* (L.) Roberty) is a multifunctional perennial grass situated at the intersection of the global fragrance industry, sustainable agriculture, and environmental engineering. Native to the Indian subcontinent and now widely cultivated throughout tropical Asia, Africa, and the Americas, vetiver is primarily valued for its essential oil, which serves as an irreplaceable natural fixative widely used in fine perfumery [1]. The global vetiver oil industry has demonstrated sustained growth, with recent estimates placing annual production at approximately 250 metric tons and total market

value approaching USD 800 million by the mid-2020s [2]. Vetiver oil production remains geographically concentrated, with major output originating from Haiti, Indonesia (Java), China, India, and Brazil [1, 2]. Within the ASEAN region, which accounts for approximately 40–45 % of global vetiver oil production, cultivation has historically emphasized ecological and engineering applications—particularly erosion control, watershed stabilization, and phytoremediation—rather than optimization for essential oil yield or aromatic quality [2–4]. This orientation is reflected in national development programs in countries such as Indonesia and Thailand, where vetiver has been widely deployed as a bioengineering solution for land rehabilitation and infrastructure protection [3, 4]. In contrast, efforts to commercialize vetiver for essential oil production in the Philippines and neighboring Southeast Asian countries remain fragmented and largely small-scale despite favorable agroclimatic conditions [5].

The industrial significance of vetiver oil lies in its chemical complexity and functional irreplaceability. It serves as a foundational base note in a substantial proportion of fine fragrances and men's perfumes, with no synthetic substitute capable of reproducing its odor longevity, molecular complexity, or fixative behavior [1]. Beyond perfumery, vetiver oil is used in cosmetics, aromatherapy, food flavoring, and traditional medicine, while the plant itself is widely applied for slope stabilization, heavy-metal phytoremediation, and wastewater treatment [6, 7]. Chemically, vetiver oil is among the most complex essential oils, dominated by sesquiterpenes and oxygenated sesquiterpenoids; its principal quality markers—khusimol, α -vetivone, and β -vetivone—account for a substantial proportion of the oil, while numerous minor constituents collectively define its sensory and biological properties [8, 9]. This compositional complexity is highly sensitive to genotype, environmental conditions, root maturity, and extraction protocols, complicating standardization in intensified production systems. In addition, a growing body of research has demonstrated antimicrobial, antioxidant, anti-inflammatory, anxiolytic, cytotoxic, antihyperglycemic, and enzyme-inhibitory activities, highlighting the broader bioactive potential of vetiver oil [9–12].

Despite its economic value, current vetiver cultivation strategies remain insufficiently aligned with the biological complexity underlying essential oil biosynthesis [13]. The production of sesquiterpene-rich root oils is governed not only by plant genotype and developmental stage but also by environmental cues and biotic interactions within the root system [13, 14]. As a result, intensified production approaches such as *in vitro* propagation and soilless cultivation have been explored to increase output while reducing land use; however, these systems often impose axenic or near-axenic conditions that decouple vetiver roots from their native microbial communities, which are increasingly recognized as contributors to secondary metabolism [14, 15]. Experimental observations indicate that removal of root-associated microorganisms is associated with altered root development, reduced differentiation of essential-oil-accumulating structures, and changes in volatile profiles [14]. At the same time, endophytic bacteria inhabiting internal root tissues may interact with sesquiterpene metabolism, including the transformation of oil constituents and associations with changes in plant terpene synthase gene expression [14, 15]. Consequently, cultivation systems that limit these biological interactions can compromise both plant development and oil quality [14, 16]. This limitation is particularly evident in high-pressure aeroponic systems, where vetiver plants may exhibit reduced root biomass, atypical morphology, and altered volatile composition, including reduced levels of hydrocarbon and oxygenated sesquiterpenes relative to soil-grown plants [17]. Together, these findings suggest that both microbial interactions and cultivation context play important roles in determining essential oil yield and composition.

Accordingly, this review synthesizes current evidence to evaluate the role of root-associated endophytic microorganisms as an important yet under-integrated determinant of vetiver essential oil yield and chemical composition, particularly in controlled cultivation systems. By examining cultivation strategies ranging from tissue culture to hydroponic and aeroponic production, this work evaluates the extent to which production can be intensified without compromising phytochemical integrity. It further advances the hypothesis that targeted isolation, characterization, and reintegration of vetiver-associated endophytes may enable controlled systems to achieve improved yield stability and chemical fidelity, thereby supporting sustainable intensification of high-value aromatic crops in the ASEAN region.

2. Materials and Methods

2.1 Literature Search Strategy

A structured literature search was conducted across Scopus, Web of Science, and Google Scholar to identify peer-reviewed studies relevant to vetiver, essential oils, endophytic microorganisms, and cultivation systems. Searches employed combinations of keywords, including vetiver, essential oil, sesquiterpenes, endophytes, plant microbiome, hydroponics, aeroponics, and aromatic plants, connected using Boolean operators (AND, OR). Search strings were adjusted to comply with database-specific syntax. The search was conducted with coverage up to May 2026. Across the three databases combined, the initial query returned approximately 480 records; after removing duplicates and applying inclusion criteria, 42 primary sources (journal articles, book chapters, and technical reports) were included in the analysis. Although a formal PRISMA flow diagram was not prepared, the structured nature of the search strategy and the explicit inclusion/exclusion criteria applied satisfy the transparency requirements of a structured narrative review.

2.2 Inclusion and Exclusion Criteria

Included studies were peer-reviewed journal articles addressing vetiver biology, essential oil production, endophyte–plant interactions, or comparable mechanisms in aromatic or medicinal plants. Studies focusing exclusively on erosion control or civil engineering applications that were not relevant to essential oil biosynthesis were excluded, as were non-peer-reviewed sources, conference abstracts, patents, and non-English publications.

2.3 Analytical Framework

The selected literature was synthesized using a comparative, mechanism-based framework that emphasizes differences among soil-based, container-based, hydroponic, aeroponic, and in *vitro* cultivation systems. Analysis focused on biological and environmental mechanisms linking endophytic microorganisms to essential oil yield and composition, rather than on descriptive cataloging of studies. Given the limited availability of recent peer-reviewed, vetiver-specific studies—particularly those addressing cultivation systems and microbiome–metabolite interactions—selected grey literature (e.g., conference proceedings, technical reports, and development publications) was deliberately included to supplement empirical evidence, while being interpreted with appropriate caution regarding data rigor and reproducibility.

3. Results and Discussion

3.1 Comparative Performance of Vetiver Cultivation Systems

Across the reviewed literature, vetiver cultivation systems exhibit clear, system-dependent differences in plant growth, root development, and essential oil yield and composition (Table 1). Soil-based field cultivation consistently serves as the primary benchmark against which alternative systems are evaluated. Field studies, including extensive multi-location trials conducted in major production regions such as India, commonly report root yields of approximately 2.3 t ha⁻¹ (dry weight). In contrast, essential oil recoveries typically range from ~0.3 to 2.0%, depending on genotype, plant age, environmental conditions, and post-harvest handling practices [1, 13, 18]. Oils obtained under these conditions display chemically complex sesquiterpene profiles dominated by compounds such as khusimol and α - and β -vetivone, which are widely recognized as key determinants of commercial oil quality [1, 8, 9]. Controlled soil-based systems, including greenhouse and experimental plot studies, generally produce moderate to high root biomass with more uniform growth due to reduced environmental variability. However, these systems do not consistently outperform field conditions in terms of essential oil yield. Reported yields are generally within the field range (~0.3–2.0%), reflecting the maintenance of core physiological processes required for sesquiterpene biosynthesis, as well as the influence of factors such as reduced rooting depth, shorter cultivation cycles, and controlled environmental regimes [13, 19]. The qualitative composition of the oil remains comparable to that of field-grown plants, indicating that soil-based conditions, regardless of scale, preserve the fundamental biochemical pathways associated with essential oil production. Container- and pot-based systems represent an intermediate condition in which physical root confinement begins to influence plant performance. Limited rooting volume restricts root expansion and can reduce biomass accumulation, thereby contributing to lower or more variable essential oil yields relative to field systems [13]. In addition, oil composition in these systems

may vary due to differences in substrate composition, nutrient availability, and plant maturity. However, establishing consistent compositional patterns is difficult, as existing data are limited and derived from heterogeneous experimental conditions.

In semi-hydroponic systems, where plants are grown in substrates supplemented with nutrient solutions, further modifications in growth performance are observed. Available evidence suggests that root biomass is generally reduced compared to soil-grown plants, and essential oil yields may also be lower, although the magnitude of these effects varies among studies and remains insufficiently quantified [13, 19]. While the overall sesquiterpene profile may be broadly retained, available data are limited, and reported variations in the relative abundance of key constituents suggest that simplified or partially artificial growth environments may influence metabolic efficiency and expression. Fully soilless systems, including hydroponic and high-pressure aeroponic approaches, show more pronounced departures from soil-based performance. Vetiver plants grown under these systems can form roots; however, they frequently exhibit altered morphology, such as a finer structure or reduced density, and more variable biomass accumulation [17]. Essential oil production is not eliminated, but yields tend to be lower or more inconsistent than in soil-based systems. Volatile compounds continue to be synthesized under these conditions, although reported differences in overall composition and relative sesquiterpene abundance suggest shifts in metabolic regulation rather than complete inhibition of biosynthetic pathways [17].

At the end of this gradient, *in vitro* and axenic systems produce very low biomass and poorly differentiated root structures. Although these systems can synthesize certain terpenoid compounds, overall essential oil accumulation is extremely limited, and the resulting volatile profile is often incomplete [14, 15, 17]. In contrast, roots grown under natural soil conditions harbor diverse endophytic and rhizosphere microbial communities, which are increasingly implicated in regulating plant secondary metabolism [14, 15]. The absence of these biological interactions in sterile or simplified systems is therefore considered an important contributing factor to reduced metabolite development, although the extent and specificity of microbial influence remain subjects of ongoing investigation. Taken together, these observations indicate that differences among cultivation systems extend beyond nutrient availability and water delivery. Instead, they reflect the integrated effects of root structural development, cultivation duration, and plant–microbe interactions, all of which contribute to regulating secondary metabolism. The general pattern of reduced oil yield and modified compositional profiles observed in simplified or soilless systems should therefore be interpreted as a shift in metabolic performance arising from altered biological and environmental conditions, rather than a complete loss of biosynthetic capacity.

3.2 Role of Endophytic Microorganisms in Essential Oil Biosynthesis

A recurring observation across field-based and experimental studies is the consistent colonization of vetiver roots by diverse endophytic microbial communities inhabiting internal root tissues, including cortical regions associated with essential oil accumulation [14, 15, 20]. In this context, endophytes refer specifically to microorganisms residing within plant tissues rather than on root surfaces, as demonstrated in microscopic localization studies [14, 15]. These internal microbial communities are associated with enhanced plant growth, improved stress tolerance, and increased accumulation of secondary metabolites, suggesting functional roles that extend beyond nutrient acquisition alone [15, 16]. More recent microbiome analyses have provided improved taxonomic resolution, identifying a range of bacterial groups—including members of *Bacillus*, *Pseudomonas*, and other proteobacteria—associated with vetiver roots under different environmental conditions [16]. In contrast, microbiome-depleted or axenic vetiver systems—commonly generated through *in vitro* propagation or maintained under sterile conditions—consistently exhibit reduced essential oil accumulation and simplified volatile profiles relative to soil-grown plants [14, 17]. These observations suggest that endophytic microorganisms contribute to the normal development of oil-producing tissues and their associated metabolic pathways. Experimental studies indicate that endophytes are involved in sesquiterpene metabolism and may influence biosynthetic processes, including reported associations with changes in terpene synthase gene expression and volatile emission patterns [14, 15]. In addition, certain endophytic bacteria have been shown to metabolize terpenoid compounds or their precursors, suggesting the possibility of bidirectional metabolic interactions between host plant and associated microorganisms [14, 15].

Table 1. Comparison of vetiver cultivation systems and production outcomes.

Cultivation system	Root yield/ growth performance	Essential oil yield (%)	Oil chemistry characteristics	Key references
Field-grown (Soil, open field)	High root biomass; well-developed, deep root system, 2.3 t ha ⁻¹ dry weight depending on conditions	~0.3–2.0% (varies with genotype, age, environment)	Complex sesquiterpene-rich profile; major constituents include khusimol, α - and β -vetivone; composition varies with environment and processing	1, 8, 9, 13, 18
Controlled soil systems (greenhouse/ experimental plots)	Moderate to high biomass; more uniform growth compared to the field; environmental variability reduced	Generally, within the reported field range (~0.3–2.0%), but dependent on cultivation conditions	Similar qualitative sesquiterpene profile as field plants; relative proportions influenced by controlled conditions (e.g., soil, climate, genotype)	13, 19
Container-based soil/ substrate systems (pots, nursery)	Moderate biomass; constrained root development due to limited volume	Limited quantitative data; potential reductions due to root confinement	Oil composition influenced by substrate composition, plant age, and growth conditions; variability reported	13
Semi-hydroponic system (substrate + nutrient solution)	Reduced root biomass and density compared to soil-grown plants	Reported as lower or variable; quantitative data remain limited	Potential shifts; insufficient evidence	13, 19, 36
Hydroponic/ high-pressure aeroponic	Strongly reduced root biomass; roots often thin, underdeveloped, and morphologically altered	Lower or variable	Altered composition with reduced chemical complexity and reduced levels of hydrocarbon and oxygenated sesquiterpenes relative to soil-grown plants	17
<i>In vitro</i> (tissue culture system)	Very low biomass, highly abnormal roots	Extremely low oil	Poor or incomplete volatile profile; underdeveloped oil-producing structures similar to aeroponic trend	14, 15, 17

Consistent with this interpretation, cultivation systems that reduce or exclude microbial colonization—such as high-pressure aeroponic or sterile culture systems—are associated with altered root development, reduced differentiation of oil-associated structures, and lower levels of hydrocarbon and oxygenated sesquiterpenes relative to soil-based systems [17]. While these effects cannot be attributed solely to the absence of microbes, they support the broader hypothesis that plant–microbe interactions regulate secondary metabolism in vetiver roots. Taken together, the available evidence indicates that endophytic microorganisms likely function as active contributors to metabolic regulation rather than passive inhabitants of plant tissues, potentially influencing terpene biosynthesis through signaling interactions, modulation of precursor availability, and involvement in stress-responsive pathways [14–16]. Similar roles have been documented in other aromatic and medicinal plant systems, although such comparative evidence supports but does not replace direct mechanistic validation in vetiver [21–25].

3.3 Interpreting the Constraints of Soilless Cultivation Systems

Two complementary and non-exclusive hypotheses have been advanced to explain the recurring limitations of soilless cultivation systems in reproducing the yield and chemical complexity of soil-grown vetiver essential oil. The first hypothesis attributes these limitations to the disruption of soil-mediated biotic interactions, particularly those involving endophytic and rhizosphere microorganisms that contribute directly and indirectly to sesquiterpene biosynthesis. This interpretation is supported by experimental observations showing that axenic vetiver plants produce very low amounts of essential oil with altered chemical profiles. In contrast, reintroduction of native endophytes has been associated with restored sesquiterpene accumulation, changes in plant sesquiterpene synthase gene expression, and the release of characteristic vetiver volatiles [14, 15]. The second hypothesis proposes that current hydroponic and aeroponic systems do not fully provide the environmental and developmental conditions required for complete metabolic expression, even when mineral nutrition is optimized. Evidence supporting this view includes delayed or incomplete accumulation of sesquiterpenes in shortened cultivation cycles, reduced differentiation of essential oil-storing tissues, and persistent oil deficiencies under controlled soilless conditions [17]. High-pressure aeroponic cultivation, in particular, has been associated with atypical root morphology, immature tissue development, and a marked reduction in hydrocarbon and oxygenated sesquiterpenes, suggesting that key structural, temporal, or biological cues normally present in soil environments are absent [17].

Available evidence indicates that these mechanisms act synergistically rather than independently. Microbial deprivation and environmental simplification collectively influence root development, metabolic regulation, and signaling processes that underpin secondary metabolism. Loss of microbial partners may reduce biosynthetic activation and metabolite transformation capacity, while shortened developmental trajectories and simplified growth environments further constrain precursor availability and oil-cell maturation [14, 15, 17]. This integrated constraint model provides a coherent explanation for the underperformance of soilless vetiver systems and underscores the need to consider cultivation systems as biologically integrated environments rather than purely physicochemical growth platforms.

3.4 Implications for Intensified Vetiver Production

The available evidence highlights a key limitation of current vetiver intensification strategies: reductions in essential oil yield and compositional complexity observed in hydroponic and aeroponic systems may reflect not only technical constraints but also the absence of biological interactions inherent to soil-based cultivation. In vetiver-specific studies, controlled systems have been associated with reduced accumulation and altered composition of hydrocarbon and oxygenated sesquiterpenes that define industrial-grade vetiver oil [14, 17]. This trade-off is particularly relevant for crops such as vetiver, where oil quality rather than biomass alone determines economic value [1]. However, much of the evidence supporting these observations is derived from studies conducted outside Southeast Asia or under controlled experimental conditions, and recent peer-reviewed datasets specific to ASEAN commercial production systems remain limited in the available literature. Available regional information is largely drawn from conference reports, development

programs, or case studies with limited quantitative detail [26, 27]. As such, extrapolating current findings to ASEAN production contexts should be interpreted cautiously. Although vetiver cultivation in the region has been widely associated with environmental applications such as erosion control, slope stabilization, and phytoremediation, the extent to which production systems are transitioning toward high-value essential oil markets is not well documented in recent empirical studies.

Rather than advocating the exclusion of controlled or soilless systems, the existing evidence indicates a need to refine intensification strategies to better account for biological factors that influence secondary metabolism. Studies in vetiver systems [14, 15, 17] and, by analogy, in well-studied agronomic and horticultural crops (e.g., wheat, maize, tomato) and selected aromatic species (e.g., *Mentha* and *Ocimum*) suggest that microbial associations, developmental maturity, and environmental signaling play important roles in regulating metabolite production [24, 28–33]. While these mechanisms are directly supported in vetiver at the experimental level, their broader application to intensification strategies remains partly inferred from non-vetiver systems. Approaches integrating these factors—such as microbiome management, extended cultivation cycles, or hybrid soil–soilless systems—therefore represent plausible pathways for improving both yield and oil quality, although their feasibility at a commercial scale remains insufficiently assessed. Future intensification efforts should consider not only operational efficiency but also the maintenance of biological processes associated with essential oil biosynthesis, while recognizing that region-specific evidence supporting such approaches is still emerging [14, 34].

3.5 Endophyte Reinoculation as an Optimization Strategy

Across plant systems, targeted inoculation of beneficial endophytic microorganisms has been associated with enhanced plant growth, improved stress tolerance, and increased accumulation of secondary metabolites, including terpenoids, alkaloids, and phenolic compounds [16, 29]. These relationships are well established in agronomic and model crops (e.g., wheat, maize, and tomato) and, to a more limited extent, in selected aromatic species such as mint and basil, and are here extended to vetiver by analogy, where direct evidence remains limited. The underlying mechanisms—including phytohormone modulation, improved nutrient acquisition, and activation of stress-responsive metabolic pathways—are therefore generally supported, although their expression may vary across plant systems [29–33]. In the case of vetiver specifically, microbiome studies have identified a range of potentially functionally relevant taxa—including *Bacillus*, *Pseudomonas*, *Serratia*, *Kosakonia*, *Microbacterium*, and *Janthinobacterium*—associated with plant growth-promoting and biocontrol activities across diverse environments [16]. Experimental evidence further suggests that endophytes are associated with sesquiterpene biosynthesis and aroma development, as axenic (*in vitro*-derived) plants exhibit markedly reduced essential oil yields and simplified chemical profiles. In contrast, reinoculation with native endophytes is associated with partial restoration of sesquiterpene accumulation, changes in terpene synthase gene expression, and recovery of characteristic volatile emissions [14, 15]. These findings provide preliminary mechanistic insight into vetiver but remain limited in scope compared with the evidence available in other crop systems.

From an application perspective, microbial inoculation strategies—such as liquid formulations (e.g., fertigation or root dipping) and solid carrier-based systems (e.g., peat or compost matrices)—are primarily documented in non-vetiver crop systems, including cereals and horticultural crops [30, 31], and are conceptually transferable to vetiver production. However, introducing cultured endophytes into simplified or soilless systems requires careful consideration, as the absence of complex native microbial communities may influence competitive dynamics and colonization stability. Such effects are well documented in general plant–microbiome research but remain only partially validated in vetiver-specific systems [16, 31]. To ensure efficacy and reproducibility, advanced metabolomic tools such as UHPLC-QTOF-IMS and GC-MS profiling enable high-resolution characterization of plant secondary metabolites and volatile compounds [23]. These approaches have been more extensively applied in experimental studies of medicinal and aromatic crops, where they are used to characterize and compare metabolite profiles under different biological and environmental conditions, but remain comparatively underutilized in vetiver research. Additionally, large-scale deployment of microbial inoculants must comply with national biosafety and plant health regulations, which vary across regions and are typically defined within broader agricultural frameworks

rather than crop-specific guidelines for vetiver. Overall, endophyte reinoculation is a promising strategy for improving vetiver essential oil yield and quality under controlled cultivation. While its mechanistic basis is partially supported by experimental evidence in vetiver, its practical implementation and scalability remain partly informed by analogy with other crop systems and require further validation under region-specific production conditions.

3.6 Broader Relevance to ASEAN and Aromatic Crop Systems

The implications of the present findings extend beyond vetiver to a broader class of high-value aromatic and medicinal crops whose economic traits depend on developmentally regulated secondary metabolites, including terpenoids and related compounds [35,36]. Across these systems, secondary metabolism is influenced by plant-microbe interactions and environmental context, a relationship that is well established in agronomic and model crops (e.g., wheat, maize, tomato) and supported by emerging evidence in aromatic species such as mint and basil, and is here applied to vetiver systems by analogy, where direct comparative data remain limited [16, 29–33]. This consideration is particularly relevant for ASEAN countries, where agricultural systems face multiple pressures, including land scarcity, environmental degradation, and the need to diversify toward higher-value crops while maintaining ecosystem services [37, 38]. Within this regional context, vetiver has historically been promoted primarily as an environmental crop for erosion control, slope stabilization, water management, and land rehabilitation [26, 27, 39]. While available reports and development programs support this characterization, there is limited recent empirical evidence quantifying the extent of aromatic-grade vetiver production or its integration into formal value chains across the region. Consequently, the classification of vetiver as an underutilized aromatic crop should be interpreted as a plausible but incompletely documented trend. Strategies that integrate microbiome-informed crop management may offer a pathway to enhance secondary metabolite production while maintaining environmental functions; however, such approaches have been demonstrated primarily in non-vetiver crop systems and have not yet been systematically validated under ASEAN field conditions for vetiver [16, 24]. From a policy perspective, these strategies should therefore be considered evidence-informed but not yet empirically validated solutions, whose feasibility will depend on region-specific agroecological, economic, and institutional factors. More broadly, biologically informed intensification strategies align conceptually with emerging models of sustainable agriculture that emphasize system redesign over input intensification [34]; however, evidence demonstrating their scalability, economic viability, and long-term impact in ASEAN vetiver systems remains limited. Accordingly, while integrating microbial and ecological processes into vetiver cultivation represents a promising direction, further regionally grounded research is required to substantiate its applicability and inform policy and investment decisions.

3.7 Limitations of the Current Evidence Base

Despite growing evidence that plant-microbe interactions are implicated in vetiver essential oil biosynthesis, the current evidence base remains constrained by several key limitations. First, long-term comparative studies evaluating reinoculated versus non-reinoculated vetiver plants under controlled cultivation systems are scarce. Existing demonstrations of microbial involvement in sesquiterpene biosynthesis are largely derived from short-term or laboratory-scale experiments, leaving uncertainty regarding the durability, stability, and agronomic relevance of reinoculation effects across full production cycles [14, 15]. Second, mechanistic insight is limited by the underrepresentation of integrated multi-omics approaches. Although individual studies have examined volatile profiles, root anatomy, and microbial communities, few have combined metabolomics, transcriptomics, and microbiome sequencing within a unified experimental design. Such integration has proven essential in other aromatic and medicinal crops for resolving host-microbe metabolic coupling, highlighting a methodological gap in vetiver research [23, 24]. Finally, much of the available evidence is system-specific. Findings derived from high-pressure aeroponic cultivation, in particular, cannot be readily generalized across hydroponic or substrate-based systems, complicating cross-study synthesis and limiting translation into broadly applicable cultivation strategies [17]. Collectively, these limitations underscore the need for longer-term, multi-platform, and mechanistically integrated investigations to support microbiome-informed vetiver production [14, 34].

3.8 Future Research Directions

Addressing the limitations identified above will require a shift toward longer-term, systems-level experimental designs that reflect commercially relevant cultivation contexts. Priority should be given to multi-cycle comparisons of reinoculated and non-reinoculated vetiver plants under hydroponic, aeroponic, and hybrid systems to assess microbial persistence, functional stability, and cumulative effects on root development and essential oil yield across harvests [14, 15]. Concurrently, progress in mechanistic understanding will depend on integrating metabolomics, transcriptomics, and microbiome sequencing within unified experimental frameworks, enabling direct linkage of microbial community dynamics with host sesquiterpene biosynthesis and chemical output [23, 24]. Application of these approaches across both soil-based and soilless systems would help distinguish platform-specific constraints from universal biological requirements for essential oil biosynthesis [17]. Finally, translation to scalable practice will require interdisciplinary collaboration among microbiologists, plant physiologists, and controlled-environment engineers to embed microbiome compatibility into cultivation design. Such integration may facilitate the transition from proof-of-concept microbiome interventions to robust, commercially viable vetiver production systems [23, 40].

4. Conclusions

This review evaluated the hypothesis that root-associated endophytic microorganisms represent important but under-integrated determinants of vetiver essential oil yield and chemical composition, particularly in controlled, intensified cultivation systems, and the convergent evidence synthesized herein provides considerable support for this hypothesis. Across studies, soil-grown vetiver generally outperforms hydroponic, aeroponic, and *in vitro* systems in both oil yield and the production of more chemically complex sesquiterpene profiles, while microbiome-depleted plants exhibit substantially reduced and altered essential oil accumulation, and reintroduction of native root endophytes is associated with partial restoration of sesquiterpene accumulation and characteristic aroma traits. Together, these observations indicate that microbial interactions likely play important roles in regulating secondary metabolism rather than acting solely as ancillary contributors to vegetative growth. The principal contribution of this review lies in reframing vetiver production through a unified, mechanism-based framework that links plant development, microbial function, and cultivation system design, thereby moving beyond descriptive comparisons to highlight biological disconnection as a potential central constraint of soilless intensification strategies. Current limitations—including the scarcity of long-term reinoculation trials, limited system-level mechanistic validation, and platform-specific evidence—underscore the need for more comprehensive and integrated research efforts, while future progress in vetiver intensification will depend on systematic functional characterization of core endophytic communities and rigorous evaluation of microbial reintegration strategies within hydroponic and aeroponic systems. Such approaches offer a viable pathway to reconcile land-use efficiency with metabolic performance, particularly in ASEAN contexts where vetiver is widely deployed for environmental services but remains underutilized as a high-value aromatic crop, and more broadly, the insights derived from vetiver provide a conceptual template for microbiome-informed optimization of other aromatic and medicinal crops, highlighting the importance of treating biological integration as a foundational design criterion in future controlled-environment agriculture.

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