

Bio-fertilizers as sustainable nutrient sources for enhancing growth and biomass production in basil

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Abstract: The growing concern over soil degradation, declining nutrient-use efficiency, environmental pollution and excessive dependence on synthetic fertilizers has generated renewed interest in biologically based approaches to plant nutrition. Bio-fertilizers have emerged as an important component of sustainable nutrient management because they employ beneficial microorganisms to improve nutrient availability, stimulate root development and support soil biological activity. Basil (*Ocimum basilicum* L.), an economically important aromatic and medicinal plant belonging to the family Lamiaceae, requires balanced plant nutrition for satisfactory vegetative growth, biomass accumulation and production of valuable secondary metabolites. The present article examines the potential of bio-fertilizers as sustainable nutrient sources for enhancing the growth and biomass production of basil. Particular attention is given to nitrogen-fixing bacteria, phosphate-solubilizing microorganisms, plant-growth-promoting rhizobacteria and arbuscular mycorrhizal fungi and their interactions with the basil rhizosphere. The available literature indicates that microbial inoculation can influence plant height, branching, leaf development, root architecture, fresh and dry biomass and nutrient acquisition through mechanisms including biological nitrogen fixation, phosphorus solubilization, mineral mobilization, phytohormone production and improved root-soil interactions. Bio-fertilizers may additionally contribute to long-term soil fertility by strengthening microbial activity and reducing dependence on high levels of synthetic nutrient inputs. Nevertheless, their performance is not universally uniform and may be influenced by microbial strain, soil properties, climatic conditions, cultivar, application method and interactions with native soil microorganisms. From an international perspective, increasing interest in microbial inoculants reflects the broader transition towards resource-efficient, climate-resilient and environmentally responsible agricultural systems. The article concludes that bio-fertilizers should be viewed neither as a simplistic substitute for all conventional fertilizers nor merely as growth stimulants, but as biological components of integrated nutrient-management strategies. Future research should therefore concentrate on basil-specific microbial consortia, multi-location field validation, microbiome-based formulations, precision application techniques and integrated assessment of biomass, essential-oil quality, soil health and environmental performance.

Keywords: Bio-fertilizers; *Ocimum basilicum*; Basil; Sustainable Agriculture; Plant Growth-Promoting Rhizobacteria; Arbuscular Mycorrhizal Fungi; Biomass Production; Nutrient Management; Soil Health; Microbial Inoculants.

INTRODUCTION

Agricultural productivity has traditionally depended upon the capacity of soil to provide plants with adequate quantities of essential nutrients. With the intensification of agriculture,

however, natural nutrient cycles have increasingly been supplemented by manufactured fertilizers. Chemical fertilizers have made an undeniable contribution to agricultural productivity, yet their excessive or inefficient use can create economic and environmental concerns. Nutrient losses through leaching, volatilization and runoff may reduce fertilizer-use efficiency and contribute to water pollution, soil imbalance and greenhouse-gas emissions. Sustainable agriculture therefore requires approaches that maintain crop productivity while using external inputs more efficiently and protecting the biological foundations of soil fertility.

Bio-fertilizers have attracted particular attention within this transition. The term generally refers to formulations containing beneficial living microorganisms which, when introduced to seed, plant surfaces, roots or soil, improve plant nutrition by increasing the availability or acquisition of essential nutrients. Unlike conventional fertilizers that primarily supply nutrients directly, microbial bio-fertilizers influence biological processes occurring within the rhizosphere. Nitrogen-fixing organisms can transform atmospheric nitrogen into biologically usable forms, phosphate-solubilizing microorganisms can improve the accessibility of otherwise poorly available phosphorus, while arbuscular mycorrhizal fungi can effectively extend the nutrient-absorbing surface of plant roots. Plant-growth-promoting rhizobacteria may further stimulate plant development through phytohormone production, siderophore activity and improvement of rhizosphere functioning.

This biological understanding of plant nutrition is particularly relevant to medicinal and aromatic plants. In such crops, agricultural quality cannot always be assessed simply by total yield. Vegetative biomass, leaf production and the concentration and composition of secondary metabolites can all influence commercial and therapeutic value. Nutrient management consequently becomes a complex interaction between productivity, physiological performance, phytochemical quality and environmental sustainability.

Basil (*Ocimum basilicum* L.) is among the best-known aromatic members of the Lamiaceae family. Its leaves and essential oils are used in culinary preparations, traditional practices, cosmetics, fragrances and other value-added products. The economic value of basil is substantially associated with vegetative development because leaves and above-ground biomass constitute important harvestable components. Plant height, number of branches, leaf area, fresh weight, dry matter accumulation and root development are therefore significant agronomic characteristics.

The growth of basil depends on genetic characteristics as well as environmental conditions, including temperature, light, moisture, soil properties and nutrient availability. Nitrogen is particularly important for vegetative development, chlorophyll formation and protein synthesis, whereas phosphorus is essential for energy transfer, root development and metabolic processes. Potassium contributes to water regulation, enzyme activity and stress responses. Micronutrients are also necessary for normal physiological functioning. A nutrient-management system that improves access to these nutrients without unnecessarily increasing synthetic fertilizer use can consequently have considerable value in basil cultivation.

Bio-fertilizers offer such a possibility because their functions extend beyond the simple addition of nutrients. The root zone represents a biologically active environment in which plant roots, microorganisms, organic compounds and mineral nutrients continuously interact. Roots release compounds that influence microbial communities, while microorganisms alter nutrient transformations and can affect root architecture and plant metabolism. Consequently, successful microbial inoculation may create conditions in which nutrients already present in soil become more biologically accessible to plants.

The concept also corresponds with the broader understanding of sustainable agriculture. Sustainability does not mean eliminating all external agricultural inputs regardless of agronomic circumstances. Rather, it requires improving resource-use efficiency, preserving productive capacity and reducing avoidable ecological costs. Bio-fertilizers can contribute to this objective when used as part of integrated nutrient management, combining biological processes with organic matter management and carefully calibrated mineral nutrition where required.

Research involving basil provides encouraging evidence. Studies involving arbuscular mycorrhizal fungi and rhizobacteria have reported improvements in growth, plant nutritional status, biomass and essential-oil-related characteristics. Such findings are significant because they suggest that microbial nutrient management may simultaneously affect agronomic productivity and the quality attributes that make aromatic crops commercially valuable.

At the same time, the benefits of bio-fertilizers should not be overstated. A microorganism that performs effectively under controlled conditions may respond differently in field soil. Temperature, pH, moisture, organic matter, native microbial competition, inoculum quality and crop genotype can influence establishment and biological activity. Sustainable application

therefore requires an evidence-based understanding of both the potential and limitations of microbial products.

The present article examines bio-fertilizers as sustainable nutrient sources for enhancing growth and biomass production in basil plants. It discusses the historical evolution of biological fertilization, principal categories and mechanisms of bio-fertilizers, their relevance to basil physiology and biomass development, sustainability implications, international perspectives, current limitations and future research priorities. The central proposition is that biologically assisted nutrient management can provide a scientifically meaningful pathway towards productive and environmentally responsible basil cultivation when microbial technologies are selected and managed according to crop and agro-ecological conditions.

HISTORICAL BACKGROUND

The scientific foundations of bio-fertilization developed gradually from discoveries concerning microorganisms, nutrient cycling and plant–microbe relationships. Traditional agriculture had long depended upon biological processes without describing them in microbiological terms. Farmers maintained fertility through crop residues, animal manure, rotations and leguminous crops, thereby indirectly encouraging microbial decomposition and biological nutrient cycling. The emergence of soil microbiology during the nineteenth and early twentieth centuries subsequently provided scientific explanations for many of these observations.

Recognition of biological nitrogen fixation represented a particularly important development. Research into legume–Rhizobium associations demonstrated that microorganisms could make atmospheric nitrogen available within agricultural systems. This discovery transformed the understanding of soil fertility by establishing that nutrient availability was not governed exclusively by the mineral composition of soil. Microbial activity could actively modify the nutritional environment experienced by plants.

The identification and study of free-living and associative nitrogen-fixing microorganisms, including *Azotobacter* and *Azospirillum*, widened the potential application of biological nutrient management beyond classical legume symbioses. Researchers subsequently explored organisms capable of solubilizing phosphorus and other mineral nutrients. These

investigations established the foundation for microbial inoculants intended to increase the availability of nutrients already present in soil but inaccessible to plant roots.

Mycorrhizal associations constitute an even older biological relationship in evolutionary terms. Scientific understanding of their agricultural significance expanded as researchers demonstrated that fungal hyphae associated with roots could substantially increase the effective absorptive area available for acquisition of phosphorus and other nutrients. Arbuscular mycorrhizal fungi consequently became an important subject of research in horticultural, medicinal and low-input agricultural systems.

During the latter half of the twentieth century, rising agricultural intensification and the expansion of manufactured fertilizer use changed the context in which bio-fertilizers were considered. Synthetic fertilizers supported major increases in crop production, but concerns about input costs, nutrient losses, environmental pollution and long-term soil health encouraged renewed attention to biological alternatives. Bio-fertilizers increasingly came to be understood not simply as replacements for fertilizers but as tools for improving nutrient-use efficiency and restoring biological functions within managed soils.

The development of plant-growth-promoting rhizobacteria further broadened the field. Research demonstrated that beneficial bacteria could influence plant performance through mechanisms extending beyond nutrient supply. Certain organisms produce compounds related to plant hormonal regulation, mobilize minerals, produce siderophores, interact with pathogens and modify root architecture. This changed the conceptual understanding of microbial inoculation from a narrow fertilizer function towards management of the plant–soil–microbe system.

Interest in bio-fertilizers has increased further during the twenty-first century as sustainability, climate resilience and soil health have become central agricultural priorities. Modern research increasingly investigates microbial consortia rather than isolated strains, recognizing that natural rhizospheres function as communities. Advances in molecular biology, genomics and microbiome research have also made it possible to study interactions that could not be adequately characterized through conventional culture-based techniques.

For medicinal and aromatic plants such as basil, the historical development of bio-fertilizer research has particular significance. Earlier agronomic studies were primarily concerned with

yield, whereas contemporary research increasingly examines how microbial nutrition influences biomass together with essential oils, antioxidant properties, mineral composition and secondary metabolism. Thus, the history of bio-fertilization reflects a transition from the simple concept of microbial nutrient supply towards an integrated understanding of biological soil fertility and plant functional performance.

BIO-FERTILIZERS AND THEIR FUNCTIONAL SIGNIFICANCE

Bio-fertilizers comprise diverse groups of beneficial microorganisms rather than a single uniform class of agricultural inputs. Their usefulness depends upon the biological functions performed by particular organisms and the extent to which those functions complement crop nutritional requirements.

Nitrogen-fixing microorganisms are among the most established categories. Nitrogen is essential for amino acids, nucleic acids, proteins and chlorophyll, and vigorous basil foliage consequently depends heavily upon adequate nitrogen nutrition. Associative or free-living nitrogen-fixing bacteria may contribute biologically fixed nitrogen while simultaneously influencing rhizosphere processes. Their contribution is especially relevant when the objective is to reduce, rather than necessarily eliminate, dependence on synthetic nitrogen sources.

Phosphate-solubilizing microorganisms represent another important category. Although many soils contain considerable quantities of total phosphorus, much of it may occur in forms unavailable for immediate plant uptake. Certain bacteria and fungi release organic acids or otherwise modify the rhizosphere in ways that improve phosphorus solubility. Because phosphorus is closely associated with energy metabolism, root establishment and cellular processes, enhanced availability may indirectly support stronger vegetative development and biomass formation.

Arbuscular mycorrhizal fungi form intimate associations with plant roots. Their hyphal networks explore soil beyond the immediate root surface and can enhance acquisition of relatively immobile nutrients, particularly phosphorus. Mycorrhizal associations can additionally influence water relations and plant responses to environmental stresses. In basil, such effects are relevant because both vegetative biomass and aromatic quality can be sensitive to nutrient and moisture conditions.

Plant-growth-promoting rhizobacteria represent a functionally diverse group. Their benefits may arise through nutrient mobilization, biological nitrogen fixation, phytohormone-related effects, siderophore production and indirect suppression of harmful microorganisms. Root architecture can be particularly important: a plant with a larger or more highly branched root system has a greater capacity to explore soil resources, potentially translating microbial stimulation below ground into improved shoot development above ground.

Microbial consortia have emerged as another promising approach. Instead of relying on one organism to perform multiple functions, consortia combine organisms with complementary characteristics. A formulation may, for example, include nitrogen-fixing and phosphate-solubilizing organisms together with fungi that enhance nutrient exploration. Theoretically, such functional complementarity may provide a more balanced biological contribution to plant nutrition, although compatibility among strains and survival under field conditions require careful evaluation.

INFLUENCE ON GROWTH PARAMETERS OF BASIL

The agronomic effects of bio-fertilizers can be assessed through measurable characteristics such as plant height, branch number, leaf number, leaf area, root length, fresh weight and dry weight. These variables are interconnected expressions of physiological performance rather than isolated traits.

Plant height can respond to improved nutrient acquisition and microbial stimulation. Nitrogen supports vegetative tissue formation, while phosphorus contributes to metabolic energy and root development. Microbial production or modulation of plant-growth-related compounds may additionally influence cell division and elongation. Consequently, plants with a more favourable rhizosphere environment may exhibit stronger vertical growth.

Branching is particularly relevant in basil because greater branching can increase the number of leaf-bearing sites and potentially increase harvestable biomass. A nutrient-management strategy that encourages balanced vegetative growth rather than excessive weak elongation can therefore improve both plant structure and productive potential.

Leaf development is central to basil production. Leaves constitute major photosynthetic organs as well as an important commercial component of the crop. Enhanced nutrient availability can support chlorophyll formation, photosynthetic capacity and leaf expansion. Greater leaf area

can increase light interception and carbon assimilation, creating a positive relationship between nutrient status and biomass accumulation when water and other environmental conditions are not limiting.

Root development is equally important even though it is less visible. Root length, lateral branching and root biomass determine the volume of soil explored by the plant. Certain rhizobacteria can influence root architecture, while mycorrhizal fungal hyphae effectively extend the nutrient-absorbing network beyond root surfaces. Improved below-ground development can consequently support more stable above-ground growth.

ENHANCEMENT OF FRESH AND DRY BIOMASS

Biomass production represents the cumulative result of photosynthesis, nutrient acquisition, water relations and assimilate allocation over time. Fresh biomass includes a substantial water component, whereas dry biomass provides a clearer indication of accumulated structural and metabolic material. Both measures are valuable in basil because fresh foliage may be marketed directly, while dry material has importance for processing and medicinal or aromatic uses.

Research on *Ocimum basilicum* involving arbuscular mycorrhizal fungi and plant-growth-promoting rhizobacteria has demonstrated that biological fertilization can increase fresh and dry weights of shoots and roots along with other growth characteristics. Such responses are biologically plausible because improved nutrient availability supports leaf expansion and photosynthesis, while stronger roots enhance continued resource acquisition.

The relationship is nevertheless unlikely to be linear under all conditions. Once nutritional requirements are adequately satisfied, additional microbial activity may not generate proportionate biomass increases. Likewise, severe nutrient deficiency, unfavourable soil pH or inadequate water may restrict microbial establishment. This reinforces the need to evaluate bio-fertilizers as part of an integrated production system rather than as independent growth-enhancing products.

BIO-FERTILIZERS, SOIL HEALTH AND SUSTAINABLE NUTRIENT MANAGEMENT

The sustainability value of bio-fertilizers extends beyond immediate crop growth. Soil is a living ecological system whose productive capacity depends upon physical structure, chemical

characteristics and biological activity. Agricultural management that continually treats soil only as an inert medium for delivering soluble nutrients overlooks the microbial processes essential to nutrient cycling.

Bio-fertilizers can strengthen these processes by increasing populations or activities of beneficial microorganisms. Nitrogen fixation introduces biologically usable nitrogen into nutrient cycles. Phosphate solubilization improves the utilization of existing soil phosphorus. Mycorrhizal networks facilitate plant access to nutrients and may contribute indirectly to soil aggregation. Collectively, these processes can increase the biological efficiency with which soil resources are used.

Reduced dependence on excessive synthetic fertilization may also decrease the risk of nutrient losses. This does not imply that every mineral fertilizer application is environmentally damaging or that bio-fertilizers can replace mineral nutrients under every production condition. Rather, sustainable nutrient management aims to supply the right nutrients in appropriate quantities and forms while maximizing plant uptake and minimizing losses.

Bio-fertilizers are particularly suitable for integrated nutrient management because they can complement organic amendments and reduced mineral fertilizer doses. Organic materials can provide carbon and nutrients that support microbial processes, whereas carefully managed mineral fertilizers can address immediate nutrient deficiencies. Such combinations may be more realistic for commercial basil cultivation than an absolute distinction between “biological” and “chemical” systems.

RELATIONSHIP WITH ESSENTIAL-OIL-PRODUCING CROPS

Basil differs from many staple crops because commercial quality can depend on secondary metabolites as well as biomass. Essential oils contain complex mixtures of volatile compounds whose concentration and composition may be influenced by genotype, developmental stage, environment and nutrition.

Nutrient management can therefore generate both quantitative and qualitative effects. A treatment that produces more vegetative biomass may increase total essential-oil yield even where oil concentration changes little. Conversely, microbial interactions may influence secondary metabolism and thereby alter oil composition.

Published basil research involving mycorrhizal fungi and rhizobacteria has reported not only improvements in plant biomass and nutrient status but also changes in essential-oil production and components. Such observations expand the significance of bio-fertilization from simple yield enhancement to quality-oriented cultivation. Nevertheless, responses can vary among cultivars and environments, and therefore biochemical outcomes should be measured directly rather than inferred solely from increased plant growth.

ENVIRONMENTAL AND ECONOMIC SIGNIFICANCE

The environmental relevance of bio-fertilizers arises largely from their potential to improve nutrient-use efficiency and reduce avoidable reliance on resource-intensive synthetic inputs. Nitrogen fertilizer manufacturing requires considerable energy, while poorly synchronized fertilizer application can contribute to reactive nitrogen losses. Phosphorus fertilizers depend upon finite geological resources and can accumulate in forms unavailable to crops. Biological approaches that improve the utilization of nitrogen and phosphorus can therefore contribute to resource conservation.

Microbial nutrient management may also have implications for soil carbon. Improved root growth can increase below-ground carbon inputs, while microbial activity affects organic-matter dynamics. Recent meta-analytic evidence has indicated that microbial bio-fertilization can contribute positively to soil organic carbon under certain conditions, although outcomes differ among bio-fertilizer groups and production environments.

From an economic perspective, the benefits depend upon the relationship between inoculant cost, crop response, fertilizer savings, product quality and consistency of performance. Basil is a comparatively high-value crop in many markets, meaning that improvements in biomass or essential-oil quality may justify investment in biological inputs more readily than in some low-value commodities. However, farmers require dependable products with adequate shelf life, viable microbial populations and clear application recommendations.

INTERNATIONAL PERSPECTIVES

Bio-fertilizers have become part of a wider international movement towards sustainable intensification and biologically informed agriculture. The Food and Agriculture Organization of the United Nations recognizes bio-fertilizers as bio-inputs that employ beneficial microorganisms to improve nutrient availability and uptake, enhance soil health and reduce

dependence on synthetic fertilizers. This international orientation is significant because it positions microbial inoculants within broader strategies for resilient and sustainable agri-food systems.

In Asia, where smallholder agriculture coexists with highly intensive production systems, bio-fertilizers have considerable potential for improving nutrient-use efficiency. India has a long history of research and commercial development involving *Rhizobium*, *Azotobacter*, *Azospirillum*, phosphate-solubilizing bacteria and mycorrhizal fungi. The increasing cultivation of medicinal and aromatic plants provides additional opportunities for crop-specific microbial formulations.

European agricultural research has increasingly emphasized soil biodiversity, reduced external inputs and microbiome-informed crop management. Scientific attention has moved towards understanding the ecological compatibility of introduced microorganisms with native soil communities. This is important because successful inoculation depends not simply upon laboratory performance but upon ecological establishment in the rhizosphere.

Research in Mediterranean and Middle Eastern production environments is particularly relevant to basil and other aromatic plants because these regions have substantial traditions of medicinal and herb cultivation. Studies have examined microbial inoculation under water limitation, salinity and nutrient constraints, thereby linking bio-fertilization with climate adaptation.

North American research has similarly expanded into plant microbiomes, biological products and precision nutrient management. Advances in sequencing technologies are enabling researchers to characterize microbial communities associated with productive plants and identify organisms or combinations that may improve nutrient acquisition.

Across these regions, a common scientific challenge remains: microbial products that show promising results in controlled experiments must demonstrate consistent performance under diverse field conditions. International progress therefore depends upon standardized quality control, appropriate regulation, transparent product labelling, field validation and farmer-oriented application protocols.

CONSTRAINTS AND CHALLENGES

Despite considerable potential, bio-fertilizers face several practical limitations. Microbial viability is fundamental. Products containing inadequate populations of viable organisms are unlikely to provide expected agronomic benefits. Storage temperature, carrier material, shelf life and handling can all influence product quality.

Field variability presents another challenge. Soil pH, temperature, moisture, salinity and organic matter affect microbial survival. Native microorganisms may compete with introduced strains, while certain agricultural chemicals can interfere with microbial establishment. Crop genotype may also determine whether a particular plant–microbe association is beneficial.

The expectation that bio-fertilizers will automatically replace all mineral fertilizers is another conceptual problem. Biological processes cannot create phosphorus, potassium or micronutrients where the total nutrient resource is critically deficient. They primarily improve fixation, mobilization, transformation or acquisition. Integrated nutrient management is therefore generally more scientifically defensible than indiscriminate substitution.

Regulation and quality assurance remain uneven internationally. A product labelled as a bio-fertilizer should contain accurately identified organisms at effective viable concentrations and should be free from harmful contamination. Standardization of efficacy testing and quality criteria is essential to protect farmers and maintain confidence in biological technologies.

CONCLUSION

Bio-fertilizers provide an important biological pathway for improving nutrient availability, plant development and soil functioning in sustainable basil cultivation. Their relevance to *Ocimum basilicum* arises from the crop's requirement for balanced nutrition and its economic dependence upon vigorous vegetative growth, leaf production, biomass and valuable secondary metabolites.

Nitrogen-fixing bacteria, phosphate-solubilizing microorganisms, plant-growth-promoting rhizobacteria and arbuscular mycorrhizal fungi influence plant nutrition through distinct but complementary mechanisms. These include biological nitrogen fixation, nutrient solubilization and mobilization, improved root exploration, phytohormone-related stimulation and modification of rhizosphere interactions. Through these mechanisms, microbial

inoculation can potentially improve plant height, branching, leaf development, root growth and fresh and dry biomass.

The sustainability value of bio-fertilizers is equally significant. By improving biological nutrient cycling and nutrient-use efficiency, they can contribute to reduced dependence on excessive synthetic fertilizer inputs and support the maintenance of soil biological health. In aromatic plants, their possible influence on essential-oil production further strengthens their agronomic significance.

Nevertheless, bio-fertilizers are not universally predictable inputs. Their success depends upon microbial strain quality, crop genotype, soil conditions, climate, formulation, storage and application practices. Their most appropriate role is therefore within integrated nutrient-management systems that combine biological processes with sound soil management and evidence-based nutrient supplementation.

For basil production, the transition towards biologically informed fertilization offers an opportunity to reconcile productivity with environmental responsibility. The objective should not merely be to produce greater biomass, but to develop cultivation systems capable of maintaining soil fertility, improving resource-use efficiency and producing high-quality aromatic biomass over the long term.

FUTURE SCOPE

Future research on bio-fertilizers and basil should progress beyond simple comparisons between inoculated and uninoculated plants. Greater emphasis is required on understanding which microorganisms work, under what environmental conditions, through which mechanisms and with which basil genotypes. Multi-location and multi-season field experiments are particularly important because greenhouse responses do not necessarily represent commercial field performance.

The development of basil-specific microbial consortia represents a promising research frontier. Rather than selecting microorganisms exclusively on the basis of general plant-growth-promoting characteristics, future studies could identify microorganisms naturally associated with vigorous basil plants and evaluate their functional compatibility. Metagenomics and microbiome profiling can assist in understanding how inoculation restructures rhizosphere communities.

Research should also examine interactions between bio-fertilizers and different levels of mineral and organic nutrition. Determining the minimum effective mineral fertilizer dose in the presence of efficient microbial inoculation could provide practical strategies for reducing chemical input without compromising yield.

Climate-related research is another priority. Basil production can experience drought, heat and salinity stress, and microorganisms capable of simultaneously improving nutrient acquisition and stress tolerance may become increasingly valuable. Studies should therefore integrate growth parameters with physiological indicators such as chlorophyll status, photosynthetic efficiency, antioxidant activity and water-use efficiency.

Greater attention should be devoted to essential-oil quality. Future experiments should simultaneously measure biomass, oil concentration, total oil yield and chemical composition so that agronomic gains can be evaluated against commercial quality. This is particularly important because a treatment that maximizes biomass may not necessarily optimize the desired phytochemical profile.

Precision agriculture could further transform bio-fertilizer management. Soil sensors, remote sensing, imaging technologies and data-driven crop monitoring may help determine when environmental conditions are most favourable for microbial inoculation and where nutrient limitations are most responsive to biological intervention.

Finally, life-cycle and economic assessments are needed. The sustainability of a technology cannot be determined solely from plant height or biomass. Future studies should quantify fertilizer savings, energy requirements, greenhouse-gas implications, soil carbon effects, production costs, benefit–cost ratios and long-term changes in soil fertility. Such multidimensional research would provide a stronger scientific foundation for positioning bio-fertilizers as practical components of sustainable basil production.

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