

Influence of bio-fertilizer application on growth, physiological performance and sustainable cultivation of basil

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Abstract: The increasing ecological consequences associated with intensive use of synthetic fertilizers have encouraged the search for biologically based nutrient-management strategies capable of maintaining crop productivity while preserving soil health. Bio-fertilizers, consisting primarily of beneficial microorganisms that improve nutrient availability and plant-soil interactions, have emerged as promising inputs for sustainable agriculture. Basil (*Ocimum basilicum* L.), an important aromatic, culinary and medicinal plant, responds considerably to nutrient availability and environmental conditions, making biological nutrient management particularly relevant to its cultivation. The present article critically examines the influence of bio-fertilizer application on the growth, physiological performance and sustainable cultivation of basil. Particular emphasis is placed on plant growth-promoting rhizobacteria, nitrogen-fixing microorganisms, phosphate-solubilizing bacteria and arbuscular mycorrhizal fungi. These microorganisms may enhance nutrient acquisition through biological nitrogen fixation, phosphorus solubilization, mineral mobilization and improved root exploration, while also influencing phytohormonal activity, photosynthetic performance, water relations and plant responses to environmental stress. Available research on basil indicates that appropriate microbial inoculation can improve plant height, root development, branching, fresh and dry biomass, nutrient accumulation and essential-oil characteristics. Nevertheless, bio-fertilizer performance varies according to microbial strain, basil genotype, soil properties, environmental conditions, formulation and management practices. From a sustainability perspective, bio-fertilizers can contribute to reduced dependence on excessive synthetic fertilizer inputs, improved nutrient-use efficiency, preservation of soil biological activity and development of more resilient cultivation systems. International developments in microbial biotechnology, microbiome research and precision agriculture further expand their future potential. The article concludes that bio-fertilizers should be incorporated into integrated nutrient-management systems rather than regarded as universal substitutes for conventional fertilizers. Future research should prioritize basil-specific microbial consortia, physiological and molecular investigations, multi-location field trials, essential-oil quality, climate-stress resilience and digitally assisted precision bio-fertilization.

Keywords: Bio-fertilizers; *Ocimum basilicum*; Basil; Plant Growth-Promoting Rhizobacteria; Arbuscular Mycorrhizal Fungi; Physiological Performance; Sustainable Cultivation; Nutrient-Use Efficiency; Soil Health; Essential Oils.

INTRODUCTION

The challenge of modern agriculture is no longer confined to increasing crop production. Contemporary agricultural systems are expected to produce sufficient quantities of high-quality crops while simultaneously conserving soil resources, reducing environmental

pollution, using water and nutrients efficiently and remaining resilient under increasingly variable climatic conditions. This shift in agricultural priorities has generated considerable interest in biological approaches to plant nutrition. Among these approaches, bio-fertilizers have acquired particular significance because they seek to improve crop performance by strengthening natural biological processes within the soil–plant system rather than depending exclusively upon direct application of soluble mineral nutrients.

Bio-fertilizers are generally understood as microbial preparations containing beneficial organisms capable of improving nutrient availability, nutrient acquisition or plant performance after application to seeds, roots, plants or soil. Their action differs fundamentally from that of conventional chemical fertilizers. A mineral fertilizer supplies nutrients in defined chemical forms, whereas a microbial bio-fertilizer primarily influences biological processes responsible for nutrient transformation, mobilization and acquisition. Nitrogen-fixing bacteria, phosphate-solubilizing microorganisms, potassium-mobilizing organisms, plant growth-promoting rhizobacteria (PGPR) and arbuscular mycorrhizal fungi (AMF) are among the most extensively studied groups.

The importance of these organisms has increased as the limitations of excessive or poorly managed chemical fertilization have become more apparent. Mineral fertilizers have played an indispensable role in improving agricultural productivity, but inefficient application can lead to nutrient losses, contamination of water bodies, soil nutrient imbalance and disruption of beneficial biological processes. Sustainable agriculture therefore requires a more balanced approach in which productivity is maintained through efficient use of both biological and conventional resources.

Basil (*Ocimum basilicum* L.) provides a particularly appropriate crop for examining this transition. Belonging to the family Lamiaceae, basil is widely cultivated as a culinary herb and as a medicinal and aromatic plant. Its economic value is associated with fresh leaves, dried plant material and essential oils. Basil is also valued because of the diverse phytochemical constituents associated with its aroma and biological properties.

Unlike crops in which commercial performance is assessed predominantly by grain or fruit yield, basil cultivation involves a complex relationship between vegetative growth and biochemical quality. Plant height, branching, number and area of leaves, fresh biomass and dry matter accumulation influence productivity. At the same time, essential-oil concentration

and chemical composition can determine the quality and economic utility of the harvested material. Nutritional management must consequently support vigorous plant growth without compromising the biochemical attributes for which the crop is valued.

Nitrogen has an important role in chlorophyll synthesis, amino-acid formation, proteins and vegetative growth. Phosphorus participates in energy transfer, nucleic-acid metabolism and root development, whereas potassium is involved in enzyme activation, osmotic regulation and stomatal function. Micronutrients are similarly indispensable for enzyme systems, photosynthesis and metabolic regulation. In conventional cultivation, these requirements are commonly met through fertilizer application. Bio-fertilization offers an alternative or complementary pathway by making existing soil nutrients more accessible and improving the capacity of plants to acquire them.

The rhizosphere provides the biological setting within which these processes operate. It is not merely the soil surrounding a root but a highly dynamic ecological interface influenced by root exudates, microbial populations, nutrient transformations and biochemical signalling. Beneficial microorganisms colonizing this environment can alter the conditions under which plants obtain nutrients and respond to environmental stress.

PGPR may stimulate plants through direct and indirect mechanisms. Some fix atmospheric nitrogen, while others solubilize phosphorus or mobilize additional nutrients. Certain bacteria produce or influence plant-growth regulators such as indole-3-acetic acid and cytokinins. Others produce siderophores that affect iron acquisition or enzymes such as ACC deaminase that may influence plant responses to stress. These functions demonstrate why the term “bio-fertilizer” increasingly overlaps with the broader concept of microbial biostimulation.

Arbuscular mycorrhizal fungi establish a different but complementary relationship with plant roots. Their hyphal networks extend beyond the nutrient-depletion zone immediately surrounding roots and can improve access to relatively immobile nutrients, particularly phosphorus. Mycorrhizal symbiosis may also affect root architecture, water acquisition and physiological responses to drought or salinity.

The influence of bio-fertilizers on basil should therefore be evaluated at more than one level. The first is morphological growth, including plant height, branching, leaf production and biomass. The second is physiological performance, including nutrient status, photosynthetic functioning, chlorophyll, water relations and stress responses. The third concerns quality,

particularly essential oils and secondary metabolites. Finally, the sustainability dimension considers soil fertility, nutrient-use efficiency, input reduction and environmental effects.

This article examines these interconnected dimensions and evaluates the potential of bio-fertilizers to contribute to scientifically sound and environmentally responsible basil production.

HISTORICAL BACKGROUND

The conceptual roots of bio-fertilization extend far beyond the modern terminology used to describe microbial agricultural inputs. Traditional farming systems relied extensively on biological processes through crop rotation, animal manure, compost, green manuring and leguminous crops. Although early farmers could observe improvements in soil fertility following these practices, the microbial mechanisms responsible for many such benefits were not understood until the emergence of microbiology during the nineteenth century.

Scientific recognition of biological nitrogen fixation represented a decisive development. Research on microorganisms associated with leguminous plants demonstrated that atmospheric nitrogen could be converted into forms contributing to plant nutrition. The identification of symbiotic nitrogen-fixing bacteria subsequently provided the scientific basis for microbial inoculation as an agricultural technique.

Commercial microbial inoculation developed progressively thereafter. Early *Rhizobium* preparations demonstrated that deliberately introducing selected beneficial microorganisms could improve biological nutrient acquisition. Research later expanded towards free-living and associative organisms such as *Azotobacter* and *Azospirillum*, thereby extending microbial nutrient management beyond legumes.

Another important development was the recognition that the quantity of a nutrient present in soil and its availability to plants are not identical. Considerable phosphorus may be present in insoluble or chemically fixed forms. The discovery of microorganisms capable of solubilizing phosphate demonstrated that microbial metabolism could alter nutrient availability without necessarily adding large quantities of new phosphorus to the soil.

Scientific understanding of mycorrhizal associations developed alongside these advances. Mycorrhizal fungi had long existed as natural partners of terrestrial plants, but research gradually established their importance for phosphorus acquisition, water relations and plant

adaptation to environmental constraints. Arbuscular mycorrhizal fungi consequently became important components of biological approaches to soil fertility.

During the twentieth century, industrially produced nitrogen, phosphorus and potassium fertilizers became central to intensive agricultural production. Their contribution to increasing crop yields was substantial. At the same time, decades of high-input agriculture revealed that nutrient management could not be evaluated exclusively in terms of immediate yield. Nutrient-use efficiency, soil degradation, water contamination, energy consumption and loss of biological diversity became increasingly important concerns.

The concept of PGPR expanded the field further during the later twentieth century. Beneficial rhizobacteria were found to affect plants not only through nutrient supply but also through phytohormonal regulation, root development, siderophore production and interactions with pathogens and environmental stress. The distinction between “fertilizer” and “biostimulant” therefore became increasingly complex.

The twenty-first century has witnessed a further transition from single-organism inoculants towards microbial consortia and microbiome-based approaches. Molecular tools now permit researchers to examine plant-associated microbial communities in considerably greater detail. The contemporary concept of bio-fertilization therefore represents the culmination of more than a century of research into biological nitrogen fixation, mineral solubilization, mycorrhizal symbiosis and rhizosphere ecology.

For medicinal and aromatic plants such as basil, this historical progression has been particularly important. Research is no longer limited to whether microbial inoculation increases plant size. Current studies investigate nutrient status, photosynthetic performance, antioxidant responses, essential-oil concentration and composition, stress resilience and soil biological health. Thus, bio-fertilization has evolved from a relatively narrow nutrient-supplementation technique into an important component of sustainable plant-production science.

MAJOR BIO-FERTILIZERS RELEVANT TO BASIL CULTIVATION

Several categories of microbial bio-fertilizers have potential relevance to basil. Their effectiveness depends upon the organisms involved and the biological functions they perform.

Nitrogen-fixing bacteria contribute to plant nutrition by converting atmospheric nitrogen into biologically usable forms. Free-living or associative organisms such as *Azotobacter* and *Azospirillum* have been investigated in numerous crops. Because basil is harvested primarily for vegetative tissues, adequate nitrogen availability is particularly important for vigorous foliage development.

Phosphate-solubilizing bacteria constitute another important group. Phosphorus availability can be limited even in soils containing substantial total phosphorus because the nutrient can become chemically fixed. Certain microorganisms produce organic acids, enzymes and other metabolites that convert unavailable phosphorus into more accessible forms. Improved phosphorus nutrition can support root growth, energy metabolism and vegetative development.

PGPR constitute a broader functional category. In addition to nutrient mobilization, these organisms can influence root architecture and plant physiology. A better-developed root system provides a greater absorptive surface for water and minerals, establishing a biological connection between microbial colonization below ground and vegetative development above ground.

AMF establish symbiotic relationships in which the plant provides carbon compounds to the fungus while fungal hyphae increase the effective soil volume available for nutrient and water acquisition. The relationship is especially significant for phosphorus but may influence several mineral nutrients and physiological processes.

Combined inoculation or microbial consortia may offer additional advantages. A nitrogen-fixing bacterium, a phosphate-solubilizing organism and a mycorrhizal fungus perform different functions. Their compatible use may theoretically produce complementary effects, although biological compatibility must be established experimentally rather than assumed.

INFLUENCE ON VEGETATIVE GROWTH OF BASIL

Vegetative development is fundamental to basil productivity because the leaves and shoots constitute major harvested portions. Plant height, branching, leaf number, leaf area, shoot weight and root development provide useful indicators of treatment effects.

Bio-fertilizer application can influence plant height through improved nutrition and hormonal interactions. Nitrogen supports protein synthesis and leaf formation, whereas phosphorus

supports cellular energy metabolism. PGPR capable of producing plant-growth-related substances may further affect cell division and elongation.

Branching is particularly important because each additional productive branch may contribute new leaves and potentially increase total photosynthetic surface. Improved nutrient availability can support branching provided that environmental resources such as light and water remain adequate.

Leaf development represents another critical response. Increased leaf number or area can enhance interception of photosynthetically active radiation. When supported by adequate water and nutrient supply, a larger photosynthetic canopy can contribute to greater carbohydrate formation and biomass accumulation.

Root development deserves equal attention. Microbial effects on root length, root branching and root-hair development can increase soil exploration. This creates a reinforcing relationship: microorganisms promote root development, expanded roots support greater nutrient acquisition, and improved nutrition supports additional shoot growth.

Studies involving basil have reported that AMF and PGPR treatments can significantly enhance plant height, root length, shoot branching and fresh and dry weights. Such evidence supports the biological plausibility of using microbial inoculants to improve vegetative productivity.

EFFECTS ON PHYSIOLOGICAL PERFORMANCE

The physiological consequences of bio-fertilization are more informative than morphological measurements alone because they provide insight into how improved growth occurs.

Photosynthesis is central to biomass formation. Chlorophyll contains nitrogen, while several mineral nutrients participate directly or indirectly in photosynthetic reactions. Improved nutrient acquisition can therefore support chlorophyll formation and photosynthetic capacity. Microbial treatments that maintain leaf nutrient status may indirectly sustain carbon assimilation and growth.

Water relations represent another important physiological dimension. Plants continuously balance water uptake by roots with water loss through transpiration. Improved root architecture and mycorrhizal hyphal networks can increase access to soil water. Under water-

limited conditions, this may help plants maintain tissue hydration and physiological activity for longer periods.

Bio-fertilizers may also influence stomatal behaviour. Stomata regulate the exchange of carbon dioxide and water vapour between leaves and the atmosphere. Their behaviour affects photosynthesis and water-use efficiency. Microbial effects on root signalling, nutrient status and plant hormones can indirectly modify these processes.

Nutrient-use efficiency is particularly important in sustainable cultivation. Increased nutrient concentration alone is not necessarily desirable if it requires excessive external fertilizer application. A more sustainable objective is to produce greater useful biomass per unit of nutrient input. Bio-fertilizers may contribute by increasing the proportion of soil nutrients that become biologically accessible.

Plant antioxidant systems represent another area of interest. Environmental stresses frequently increase reactive oxygen species within plant cells. Enzymatic and non-enzymatic antioxidant systems help protect membranes, proteins and photosynthetic structures from oxidative damage. Research on microbial bio stimulants increasingly suggests that beneficial microorganisms can influence antioxidant responses and stress-related signalling.

BIO-FERTILIZERS AND BASIL BIOMASS PRODUCTION

Fresh and dry biomass are major indicators of basil productivity. Fresh weight reflects structural growth together with tissue water content, whereas dry weight represents accumulated organic matter after water removal.

Improved nitrogen acquisition supports leaf protein and chlorophyll synthesis. Better phosphorus availability contributes to ATP-dependent metabolic processes and root development. Enhanced potassium nutrition supports water regulation and enzyme activation. Consequently, microbial enhancement of several nutrients may produce a cumulative effect on biomass.

Experimental research involving basil and beneficial microorganisms has documented improvements in shoot and root fresh and dry weights. Particularly noteworthy is evidence that combinations of mycorrhizal fungi and rhizobacteria can improve mineral nutrition together with biomass.

However, greater biomass should not automatically be interpreted as superior overall performance in medicinal and aromatic crops. The biochemical quality of the plant material must also be considered. A sustainable nutrient programme should ideally increase usable biomass while maintaining or improving essential-oil quality.

ESSENTIAL OILS AND SECONDARY METABOLISM

Basil's economic and medicinal significance is closely connected with its essential oils. Their composition varies according to genotype, environment, developmental stage and cultivation practices.

Plant secondary metabolism is responsive to nutrient status. Changes in nitrogen or phosphorus availability can alter the allocation of carbon and metabolic precursors between primary growth and secondary-compound production. Bio-fertilizers may therefore influence essential-oil yield indirectly through increased biomass and directly through physiological or metabolic changes.

Basil research has reported changes in essential-oil content and constituents following AMF and PGPR application. This suggests that microbial nutrient management has potential not only for quantitative production but also for crop quality.

Nevertheless, the relationship requires careful interpretation. An increase in essential-oil percentage is different from an increase in total oil yield. Total essential-oil production depends upon both oil concentration and plant biomass. Future experiments should therefore report both parameters.

ROLE IN ABIOTIC STRESS MANAGEMENT

Climate variability makes plant resilience increasingly important. Basil cultivation can be affected by drought, salinity, high temperature and nutrient stress. These factors interfere with photosynthesis, nutrient uptake, membrane stability and plant-water relations.

PGPR can potentially improve stress responses through several mechanisms. Some organisms influence phytohormones or produce ACC deaminase, which can modify stress-related ethylene responses. Others improve root architecture, nutrient acquisition or osmotic adjustment.

Mycorrhizal fungi may contribute to drought tolerance by extending soil exploration through hyphal networks. Better phosphorus nutrition can also support metabolic processes required for stress adaptation.

Under salinity, microbial treatments may assist plants in maintaining nutrient balance and physiological functioning. However, microbial strains differ considerably in stress tolerance, meaning that organisms intended for saline or drought-prone environments should be specifically selected for those conditions.

SOIL HEALTH AND RHIZOSPHERE FUNCTIONING

Sustainable basil cultivation cannot be evaluated solely through the condition of the plant. The long-term quality of the soil is equally important.

Repeated high-input cultivation can alter nutrient balance and microbial communities. Bio-fertilizers seek to restore biological processes to a more central position in nutrient management. Beneficial organisms participate in nutrient transformations and interact with plant roots and organic matter.

Microbial activity contributes to nutrient cycling, while mycorrhizal associations can influence soil aggregation. Improved root development also increases the quantity of root-derived carbon entering the rhizosphere.

Bio-fertilization should therefore be understood as rhizosphere management. The goal is not merely to add microorganisms but to create conditions in which beneficial plant–microbe relationships can become functionally significant.

SUSTAINABLE CULTIVATION OF BASIL

Sustainability involves environmental, economic and agronomic dimensions. A cultivation practice that protects the environment but consistently fails to produce an economically viable crop cannot easily be adopted at commercial scale. Similarly, a high-yield system that progressively damages soil resources cannot be regarded as sustainable over the long term.

Bio-fertilizers can contribute to environmental sustainability by improving nutrient-use efficiency and potentially reducing excessive mineral fertilizer requirements. Reduced nutrient losses can lower the risk of water pollution, while improved soil biological activity can support long-term fertility.

Agronomic sustainability requires consistent plant performance. This is one of the principal challenges facing microbial inoculants. Performance observed under controlled conditions may not always be reproduced under field conditions because soil, climate and native microbial communities vary considerably.

Economic sustainability requires reliable benefit relative to product and application costs. Bio-fertilizer formulations must therefore have adequate shelf life, microbial viability and straightforward application procedures.

The most practical approach is consequently integrated nutrient management. Bio-fertilizers can be combined with compost, organic amendments and carefully determined quantities of mineral nutrients. Such integration avoids the scientifically questionable assumption that biological inputs must always completely replace conventional fertilizers.

INTERNATIONAL PERSPECTIVES

International interest in bio-fertilizers reflects a broader transformation towards resource-efficient agricultural systems. Bio-fertilizers are increasingly considered within discussions of soil health, sustainable intensification, climate resilience and reduction of unnecessary synthetic inputs.

In India and other parts of Asia, microbial fertilizers have been investigated extensively because of the need to sustain production under diverse agro-climatic conditions while managing input costs and soil fertility. Nitrogen fixers, phosphate-solubilizing microorganisms, PGPR and mycorrhizal fungi have all received considerable research attention.

European research increasingly places microbial products within a wider framework of soil biodiversity, sustainable nutrient management and biological alternatives to high-input cultivation. Attention is also being directed towards product regulation and scientific demonstration of efficacy.

Mediterranean and West Asian research has particular relevance to aromatic crops because water limitation, salinity and climatic stress frequently influence herb production. The capacity of selected microorganisms to simultaneously support nutrient acquisition and stress resilience makes bio-fertilization particularly attractive in these environments.

North American and other technologically advanced agricultural research systems are increasingly integrating microbial ecology with genomics, metabolomics and precision agriculture. Instead of asking only whether a microorganism improves crop growth, researchers are investigating why it works, how it interacts with native microbiomes and whether field conditions can be predicted to favour successful colonization.

The international trajectory therefore appears to be moving from generalized microbial products towards crop-specific, environment-specific and functionally characterized formulations.

LIMITATIONS AND PRACTICAL CHALLENGES

Despite encouraging results, several limitations must be recognized. Bio-fertilizers contain living organisms, and their effectiveness consequently depends upon viability. Improper storage, high temperatures, unsuitable carrier materials or extended shelf periods may reduce viable populations.

Rhizosphere colonization presents another difficulty. An introduced strain must compete or cooperate with microorganisms already present in the soil. Strong performance in laboratory culture does not guarantee ecological success in agricultural soil.

Environmental conditions can substantially affect outcomes. Soil pH, temperature, moisture, organic matter, nutrient status and salinity influence microbial survival and function. The same formulation may therefore produce different responses across locations.

Microbial specificity is another concern. Different basil cultivars may release different root exudates and establish different microbial associations. A strain highly effective with one genotype may not necessarily produce identical effects in another.

Quality control is essential. Commercial products require accurate microbial identification, adequate viable counts and freedom from contamination. Farmers also require reliable instructions concerning application rate, timing, storage and compatibility with fertilizers or crop-protection products.

Finally, unrealistic claims can undermine the credibility of bio-fertilizer technology. These products should not be portrayed as universal replacements for all fertilizers under all

conditions. Their greatest scientific value lies in strengthening biological nutrient acquisition and allowing more efficient, integrated management of external inputs.

CONCLUSION

Bio-fertilizers represent a biologically informed approach to nutrient management with considerable potential for sustainable basil cultivation. Their importance extends beyond simple nutrient supplementation because beneficial microorganisms interact with roots, soil nutrients and physiological processes that collectively determine plant performance.

Available research indicates that PGPR, phosphate-solubilizing microorganisms, nitrogen-fixing bacteria and AMF can positively influence important growth parameters of *Ocimum basilicum*, including plant height, root development, branching and fresh and dry biomass. Improved nutrient acquisition provides an important explanation for these effects, but microbial influences on root architecture, phytohormonal regulation and plant stress responses are also significant.

The physiological dimension strengthens the case for bio-fertilization. Improved nutrient status may support chlorophyll formation and photosynthetic functioning, while enhanced root systems and mycorrhizal associations may improve water acquisition. Microbial inoculation may additionally contribute to antioxidant defence and tolerance of environmental stress.

For basil, essential-oil production adds another layer of importance. A sustainable nutrient-management system should seek not merely greater vegetative biomass but an appropriate balance between biomass production and biochemical quality.

From an environmental perspective, bio-fertilizers offer opportunities to improve nutrient-use efficiency, maintain soil biological functions and reduce unnecessary dependence on synthetic fertilizers. However, biological products are not automatically effective in every soil or climatic condition.

The most scientifically defensible approach is therefore to integrate bio-fertilizers within broader nutrient-management programmes. The future of sustainable basil cultivation is likely to depend on combining microbiological knowledge, plant physiology, soil science and precision agricultural technologies to develop cultivation systems that are productive, resilient and environmentally responsible.

FUTURE SCOPE

Future research should place greater emphasis on identifying microorganisms specifically adapted to the basil rhizosphere. Isolation of native beneficial microorganisms from high-performing basil plants may provide strains with better ecological compatibility than broadly marketed inoculants.

Microbial consortia constitute an important research frontier. Combining nitrogen-fixing, phosphate-solubilizing and plant-growth-promoting microorganisms with compatible AMF could potentially provide complementary functions. However, strain compatibility must be experimentally established.

Multi-location and multi-season experiments are essential. Much of the promise associated with microbial inoculants originates from controlled studies. Long-term field validation across contrasting soils and climatic environments is necessary before reliable agronomic recommendations can be developed.

Physiological research should expand beyond basic growth measurements. Chlorophyll fluorescence, gas exchange, stomatal conductance, relative water content, nutrient-use efficiency, antioxidant enzymes, osmolytes and membrane stability can provide deeper insight into how bio-fertilizers influence basil physiology.

Molecular research represents another important frontier. Transcriptomics, metabolomics, proteomics and microbiome sequencing can help identify plant pathways modified by beneficial microorganisms and explain differences among responsive and non-responsive cultivars.

The relationship between bio-fertilization and essential-oil biosynthesis deserves particular attention. Future studies should simultaneously evaluate plant biomass, oil concentration, total oil yield and individual volatile compounds.

Climate-resilience experiments should investigate microbial treatments under controlled drought, salinity and heat stress. Identification of microorganisms capable of supporting both nutrient acquisition and stress tolerance could be especially valuable for future cultivation environments.

Precision bio-fertilization offers another promising direction. Soil sensors, plant imaging, remote sensing and artificial intelligence could eventually assist in identifying field zones or developmental stages in which microbial treatments are most likely to be effective.

Future studies should also compare bio-fertilizer systems through environmental and economic indicators, including nutrient savings, energy consumption, carbon footprint, production cost and benefit–cost ratio. Sustainability cannot be established solely by demonstrating increased plant height or biomass.

Ultimately, future research should move from the question of whether bio-fertilizers can stimulate basil towards the more sophisticated question of how particular microbial communities can be integrated into location-specific cultivation systems to produce high-quality basil with fewer external inputs and greater resilience.

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