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EDITED AND REVIEWED BY
Davey Jones,
Bangor University, United Kingdom

*CORRESPONDENCE

Muhammad Shaaban
✉ shabanbzu@hotmail.com
Behnam Asgari Lajayer
✉ basgari@dal.ca

RECEIVED 23 October 2025

ACCEPTED 27 October 2025

PUBLISHED 06 November 2025

CITATION

Shaaban M, Asgari Lajayer B and Nazir G
(2025) Editorial: Promoting the use of bio-
fertilizers to improve soil health.
Front. Agron. 7:1730845.
doi: 10.3389/fagro.2025.1730845

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Editorial: Promoting the use of bio-fertilizers to improve soil health

Muhammad Shaaban^{1*}, Behnam Asgari Lajayer^{2*}
and Gazala Nazir³

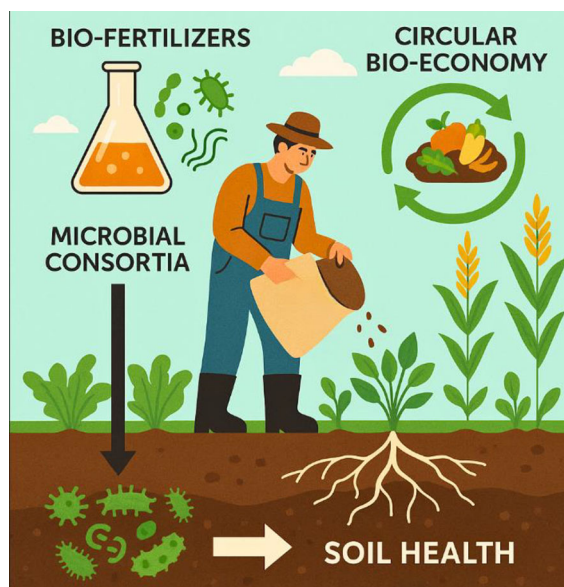
¹College of Agriculture, Henan University of Science and Technology, Luoyang, China, ²Department of Engineering, Faculty of Agriculture, Dalhousie University, Truro, NS, Canada, ³Krishi Vigyan Kendra (KVK) Ganderbal, Sher-e-Kashmir University of Agricultural Sciences and Technology, Ganderbal, India

KEYWORDS

bio-fertilizers, soil health, nutrient cycling, soil microbiome, sustainable agriculture, climate-smart farming

Editorial on the Research Topic

Promoting the use of bio-fertilizers to improve soil health



GRAPHICAL ABSTRACT

1 Introduction

Healthy soils are the cornerstone of sustainable agriculture, food security, and environmental stability. They provide not only the physical and chemical foundation for plant growth but also a complex biological network that regulates nutrient cycling, water retention, and resistance to pests and diseases (Lehmann et al., 2020). However, over the past several decades, the global expansion of intensive agriculture has led to widespread soil degradation, nutrient imbalance, and biodiversity loss (Lehmann et al., 2020; Zhang et al., 2024). Excessive reliance on chemical fertilizers and pesticides has altered soil microbial diversity and reduced long-term soil fertility, while simultaneously contributing to greenhouse gas emissions and water contamination (Pahalvi et al., 2021). In this context, restoring and maintaining soil health through biologically based solutions has emerged as a top priority in sustainable agricultural systems worldwide (Lehmann et al., 2020). In response to these needs, researchers are increasingly turning to biologically based interventions such as bio-fertilizers.

Bio-fertilizers, microbial inoculants that include nitrogen fixers, phosphorus solubilizers, potassium mobilizers, and plant growth-promoting rhizobacteria (PGPR), are gaining recognition as effective tool to restore soil health (Gul et al., 2023). By colonizing plant rhizospheres and forming mutualistic associations, bio-fertilizers can increase nutrient use efficiency, promote root growth, improve soil structure, and stimulate the activity of beneficial enzymes and microbial populations (Chaudhary et al., 2022). Importantly, bio-fertilizers can also play a vital role in mitigating the environmental footprint of agriculture by reducing dependency on synthetic fertilizers and enhancing nutrient recycling within agroecosystems (Gul et al., 2023). Recent advances in molecular biology, soil microbiome research, and formulation technology have greatly expanded our understanding of how bio-fertilizers function at the microbial, biochemical, and ecosystem levels (Zhao et al., 2024). Beyond traditional inoculants such as *Rhizobium*, *Azospirillum*, or *Azotobacter*, modern bio-fertilizers now include diverse microbial consortia and multifunctional strains capable of simultaneously promoting plant growth, controlling pathogens, and improving abiotic stress tolerance (Zhao et al., 2024). Moreover, there is increasing interest in integrating bio-fertilizers with organic amendments (e.g., compost, biochar, and crop residues) to create synergistic effects that improve soil structure and nutrient dynamics (Rao et al., 2025). Despite these advances, the large-scale adoption of bio-fertilizers remains limited due to multiple scientific, technical, and socio-economic constraints. The variability of field performance, influenced by soil type, climate, and management practices, continues to be a major bottleneck. Many commercial bio-fertilizers fail to demonstrate consistent benefits outside controlled environments, often due to the loss of microbial viability during storage or application, or poor compatibility with native soil communities. In addition, farmers in many developing

regions lack access to high-quality products, training, and incentives to adopt these technologies (Sun and Shahrajabian, 2025). Therefore, the optimization and broader deployment of bio-fertilizers require multidisciplinary efforts that integrate soil ecology, agronomy, microbiology, biotechnology, and socio-economic research. A deeper understanding of how microbial inoculants interact with indigenous soil biota, plant genotypes, and management practices is essential to ensure predictable outcomes. Furthermore, policy frameworks that encourage bio-based input, together with awareness campaigns and farmer engagement, are key to transforming bio-fertilizers from experimental tools into mainstream agricultural technologies.

To further advance the progress in this field, the *Frontiers in Agronomy* Research Topic titled “Promoting the Use of Bio-fertilizers to Improve Soil Health” was launched under the *Plant-Soil Interactions* section. The special topic aimed to compile recent progress in bio-fertilizer research and to stimulate discussion on their role in sustainable soil fertility management. Manuscripts were invited that explored the influence of bio-fertilizers on soil quality, crop productivity, and stress tolerance, as well as those employing molecular and metagenomic approaches to unravel microbe-soil-plant interactions. The response to this call was encouraging, reflecting the global momentum in this field.

2 Highlights of the contributions

In their review article, Rani et al. provided a comprehensive synthesis on the synergistic use of hyperaccumulator plants and zinc-tolerant rhizobacteria for the remediation of Zn-contaminated soils. They highlighted the physiological and molecular mechanisms through which hyperaccumulator plants tolerate and sequester heavy metals, as well as the beneficial role of rhizobacteria in enhancing these processes. Such plant-microbe interactions can simultaneously detoxify soils, improve nutrient cycling, and restore soil fertility through mechanisms such as phytostabilization, phytoextraction, and phytomining. The review also identified promising bacterial genera, such as *Pseudomonas*, *Bacillus*, and *Rhizobium*, with strong Zn tolerance and plant growth-promoting potential. The authors concluded that integrating rhizobacteria with hyperaccumulator plants offers a sustainable, low-cost strategy for rehabilitating metal-contaminated soils and enhancing their long-term productivity. Yu et al. explored the novel concept of human urine (HU) as a nutrient-rich bio-based fertilizer in controlled pot experiments. Their findings demonstrated that HU application significantly enriched soil nutrient content and enhanced enzyme activities such as invertase, urease, and catalase, key indicators of soil metabolic potential. However, they also noted a decline in microbial diversity and a compositional shift toward certain bacterial taxa at higher HU rates, emphasizing the need for balanced applications. This work bridges the gap between sanitation and sustainable agriculture by demonstrating that

nutrient recovery from human waste can contribute to circular economy models, though it requires careful monitoring to ensure environmental safety. The study underscores the potential for integrating waste recycling into agricultural systems, aligning with global efforts to close nutrient loops. Miller et al. conducted a nine-year field experiment in a semi-arid region of northern Utah, USA, to evaluate the effects of contrasting nitrogen sources, synthetic ammonium sulfate versus steer manure compost, on silage corn productivity and soil nitrogen dynamics. Compost application increased soil total nitrogen (STN) by 23% relative to synthetic fertilizer but resulted in lower yields and nitrogen use efficiency (NUE). Interestingly, a moderate rate of ammonium sulfate (AS100) achieved comparable yields to the higher rate (AS200) but with superior NUE, suggesting that fertilizer inputs could be reduced without yield penalties. The authors advocated integrating compost with reduced synthetic N rates to enhance soil organic matter accumulation and long-term fertility, highlighting the value of balanced nutrient management strategies that sustain both productivity and soil health. Cheng et al. examined the synergistic effects of straw and biochar co-application in red soils of southern China under continuous pepper cultivation. The combination treatment (biochar + straw, BS) produced notable improvements in pepper yield (+144%) and soil biological properties. The BS treatment enhanced microbial biomass (bacteria +425%, fungi +947%, actinomycetes +233%) and enriched beneficial microbial groups such as *Bacteroidota* and *Verrucomicrobiota* while suppressing pathogens like *Ascomycota*. Enhanced microbial diversity and enzyme activities (e.g., dehydrogenase, phosphatase) were closely linked with improved soil nutrient availability and structure. This study provides convincing experimental evidence that integrating biochar with crop residues can rehabilitate degraded soils, increase microbial resilience, and restore productivity in intensive horticultural systems.

3 Emerging insights and research directions

The studies in this Research Topic highlight that bio-fertilizers, especially when combined with organic inputs such as compost, straw, or biochar, play a vital role in improving soil health, nutrient cycling, and microbial balance. Microbial consortia enhance soil enzyme activities and nutrient availability, demonstrating strong synergistic effects when integrated with organic amendments, as shown in the straw-biochar study by (Cheng et al.). Bio-fertilizers also contribute to a circular bio-economy by transforming biological and agricultural wastes into valuable fertilizers, though safety and quality standards remain essential for large-scale adoption. Long-term field studies, like that of Miller et al.

highlight the importance of sustained monitoring to capture the cumulative benefits on soil fertility and microbial structure. Advances in metagenomics and related omics tools enabling deeper understanding of plant-microbe-soil interactions, guiding the development of next-generation, crop-specific bio-fertilizers. However, broader adoption is still limited by inconsistent product performance, lack of awareness, and inadequate policy support. Bridging scientific innovation with farmer engagement and regulatory frameworks is therefore critical. Overall, bio-fertilizers offer a promising path toward climate-smart, sustainable agriculture by improving nutrient efficiency, enhancing soil biodiversity, and supporting global efforts to restore and maintain soil health.

4 Conclusion

The studies compiled in this *Frontiers in Agronomy Research* Topic collectively reaffirm that bio-fertilizers and biologically derived amendments are indispensable tools for building resilient and sustainable agroecosystems. They provide holistic means to restore degraded soils, recycle nutrients, and harmonize productivity with ecological integrity. The integration of bio-fertilizers into conventional and organic farming systems requires continuous innovation, both in the laboratory and in the field. Ultimately, achieving global food security while preserving soil resources will depend on how effectively science, industry, and policy collaborate to mainstream biofertilizer use. The contributions in this Research Topic highlight both the significant potential and the critical challenges that lie ahead on this path.

Author contributions

MS: Investigation, Resources, Validation, Visualization, Conceptualization, Supervision, Writing – original draft, Writing – review & editing, Methodology, Software. BA: Visualization, Methodology, Conceptualization, Validation, Supervision, Writing – review & editing. GN: Writing – review & editing, Visualization, Supervision, Conceptualization, Validation.

Acknowledgments

The Guest Editors express their sincere gratitude to all authors, reviewers, and the Frontiers editorial staff for their valuable contributions and cooperation. Their collective efforts have enriched our understanding of the soil-microbe-plant nexus and set the stage for the next generation of microbial technologies for sustainable agriculture.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The author(s) declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

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