Sustainable Agriculture Development: The Role of Biofertilizers in Soil Fertility and Crop Yield Improvement

Ayesha Areej[1], Muhammad Usama[1], Umer Zulfiqar[1], Fatima Sarwer[1], Maryam[1], Aneela Ashiq [1*]

Abstract

This review explores the role of biofertilizers, specifically focusing on phosphate-solubilizing microorganisms, nitrogen-fixing bacteria, algal biofertilizers, and fungal biofertilizers, in enhancing soil fertility and promoting sustainable agricultural practices. Biofertilizers offer a natural alternative to chemical fertilizers, improving nutrient availability and reducing environmental impacts associated with synthetic inputs. Phosphate-solubilizing microorganisms play a crucial role in mobilizing bound phosphates, making them accessible to plants, while nitrogen-fixing bacteria convert atmospheric nitrogen into forms usable by crops, significantly enhancing soil fertility. Algal biofertilizers provide essential nutrients and improve soil structure, promoting beneficial microbial activity and water retention. Furthermore, fungal biofertilizers establish symbiotic relationships with plant roots, enhancing nutrient uptake and overall plant health. Despite their benefits, challenges such as production costs, application efficiency, and the need for field-specific adaptations exist. Ongoing research is vital to optimize biofertilizer formulations and applications to address these challenges effectively. This review highlights the potential of biofertilizers to contribute to sustainable agriculture by improving crop yields, enhancing soil health, and reducing reliance on chemical fertilizers. By promoting the use of biofertilizers, farmers can adopt more environmentally friendly practices, ultimately leading to increased food security and more resilient agricultural systems. The integration of biofertilizers into existing farming practices is essential for creating sustainable and productive agricultural landscapes globally.

Keywords: Biofertilizers, Phosphate-solubilizing microorganisms, Nitrogen-fixing bacteria, Sustainable agriculture, Soil fertility

Significance | The study demonstrated sustainable agriculture by promoting biofertilizers, improving soil fertility, and reducing chemical fertilizer reliance for better crop yield.

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Introduction

Agriculture is the cornerstone of human civilization, serving as the primary source of food, fiber, and fuel. However, conventional agricultural practices, characterized by the heavy reliance on synthetic fertilizers and pesticides, have led to widespread environmental degradation, soil depletion, and adverse health effects. The excessive application of these chemical inputs has resulted in significant soil deterioration, water pollution, and a decline in biodiversity. Studies have shown that long-term dependence on chemical fertilizers not only compromises soil health causing nutrient depletion, soil acidification, and reduced fertility but also negatively impacts crop productivity, thereby threatening food security globally (Singh et al., 2016; Biomcare, n.d.).

In light of these challenges, there is an urgent need to transition

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towards more sustainable agricultural practices that prioritize environmental conservation and human health. One promising avenue is the adoption of biofertilizers and biopesticides, which are increasingly recognized for their role in promoting sustainable agriculture. These biological alternatives not only mitigate the negative effects of chemical inputs but also enhance soil health and fertility. Biofertilizers, in particular, consist of beneficial microorganisms that improve nutrient availability in the soil, facilitate nitrogen fixation, and promote plant growth through various mechanisms (Kour et al., 2020).

Biofertilizers can be categorized based on their specific functions and the types of microorganisms they contain, including nitrogen-fixing, phosphate-solubilizing, plant growth-promoting, and micronutrient biofertilizers. Among these, nitrogen-fixing biofertilizers, such as Rhizobium and Azospirillum, are among the most widely utilized. These microorganisms not only enhance the solubility of other nutrients, such as phosphates, but also contribute to the formation of humus, improving overall soil texture and fertility (Online Biology Notes, n.d.). The first commercial biofertilizer, Rhizobium inoculants, was developed in the 1930s to enhance legume growth, highlighting the long-standing tradition of using microbial solutions in agriculture. Research indicates that the application of nitrogen-fixing biofertilizers can significantly boost crop yields; for instance, one study reported a yield increase of 10-20% in rice production (Mahmud et al., 2021).

In addition to enhancing nutrient availability, biofertilizers can bolster plant vigor, thereby increasing resistance to pests and diseases. The integration of biofertilizers with biopesticides—a practice common in integrated pest management (IPM)—has been shown to enhance crop resilience further. Biopesticides, derived from natural materials such as plants, bacteria, fungi, or insects, offer a sustainable alternative to chemical pesticides, helping to manage crop pests and diseases through biological means. For example, biopesticides based on Trichoderma have effectively controlled certain fungal diseases in crops, while Bacillus thuringiensis has proven successful against insect pests (Saritha & Prasad Tollamadugu, 2019).

Despite the clear benefits of biofertilizers and biopesticides, their effectiveness depends on several key factors, including the selection of suitable strains, optimal soil conditions, timing and method of application, storage conditions, and compatibility with other agricultural inputs. Understanding these variables is critical to maximizing the potential of these biological products. As awareness of the environmental and health implications of conventional agriculture grows, the future of biofertilizers and biopesticides appears promising. Continued research and development in this field will likely lead to the formulation of more efficient products that enhance crop yields while safeguarding ecosystems and human health (Bio-Fit, n.d.).

This review article aims to explore the diverse types of biofertilizers and biopesticides, elucidate their modes of action, and evaluate their potential benefits and limitations. Furthermore, it will discuss how these biological solutions can be effectively integrated into sustainable agricultural practices to promote the overall health of agroecosystems. The synergistic effects of combining biofertilizers and biopesticides will also be highlighted, illustrating their interrelated roles in advancing agricultural sustainability. Through this exploration, we aim to underscore the significance of adopting biological alternatives in fostering resilient and productive agricultural systems, crucial for achieving global food security in the face of environmental challenges (Daniel et al., 2022; Bhardwaj et al., 2014; Nelson, 2004; Aasfar et al., 2021; Stacey, 2006).

Biofertilizers

Biofertilizers are vital for sustainable agriculture because they enhance nutrient availability and stimulate plant growth through complex microbial interactions in the rhizosphere—the soil zone surrounding plant roots. This zone hosts a variety of beneficial microorganisms that work in tandem with plants to optimize nutrient uptake, reduce dependence on chemical fertilizers, and support soil health over time (Singh, Singh, & Prabha, 2016). Biofertilizers include different types of microorganisms, such as nitrogen-fixing bacteria (e.g., Rhizobium and Azotobacter), phosphorus-solubilizing bacteria (Bacillus and Pseudomonas), mycorrhizal fungi, and algae, each playing a role in nutrient cycling, plant growth promotion, and soil fertility enhancement (Kour et al., 2020; Kumar, Diksha, Sindhu, & Kumar, 2022).

The main mechanisms of biofertilizers revolve around nitrogen fixation and phosphorus solubilization. Nitrogen-fixing biofertilizers convert atmospheric nitrogen into ammonia, which plants can assimilate. For instance, Rhizobium species form symbiotic associations with legumes, creating specialized root structures (nodules) where they fix atmospheric nitrogen into bioavailable forms (Mahmud, Upadhyay, Srivastava, & Bhojiya, 2021). In contrast, free-living bacteria like Azotobacter enhance nitrogen content in non-leguminous plants, promoting general plant health and resilience against environmental stresses. Phosphate-solubilizing microorganisms, such as Bacillus and Pseudomonas, produce organic acids that lower soil pH, converting insoluble phosphorus compounds into soluble forms available for root absorption. This enzymatic breakdown, driven by phosphatase production, directly improves phosphorus availability, which is critical for plant metabolism, energy transfer, and root development (Saritha & Prasad Tollamadugu, 2019; Bio-Fit, n.d.).

Additionally, biofertilizers contribute to soil organic matter transformation, which boosts soil structure and microbial activity. These transformations increase soil carbon content, enhance water retention, and improve overall soil fertility, leading to sustained crop productivity. For example, phosphate biofertilizers encourage root growth, indirectly increasing plants' ability to absorb water and nutrients from a larger soil volume. This process not only enhances plant biomass but also reduces reliance on synthetic fertilizers, making it a cornerstone for sustainable agricultural practices (Biomcare, n.d.; Online Biology Notes, n.d.).

Historically, the significance of biofertilizers became clear during the late 19th and early 20th centuries, when scientists like Winogradsky and Beijerinck discovered nitrogen-fixing microorganisms, marking a turning point in understanding soil nutrient dynamics. By the 20th century, further research established biofertilizers, especially rhizobia, as essential for leguminous crop productivity (Daniel et al., 2022; Bhardwaj, Ansari, Sahoo, & Tuteja, 2014). Today, the role of plant growth-promoting rhizobacteria (PGPR) like Rhizobium, Azospirillum, and Azotobacter is well-recognized for their benefits in nutrient cycling, soil health, and resilience to biotic and abiotic stresses (Nelson, 2004).

Phosphate biofertilizers, in particular, are essential for promoting sustainable agriculture by making phosphorus available through solubilization and mineralization. They also promote root elongation and branching, improving the efficiency of nutrient and water uptake. In combination with nitrogen-fixing biofertilizers, these organisms create a more resilient agricultural system, reducing environmental impacts, conserving resources, and supporting the long-term productivity of arable land (Singh et al., 2016; Kour et al., 2020). In summary, biofertilizers are indispensable for environmentally friendly farming practices, reducing reliance on chemical inputs while enhancing soil health and fostering sustainable, resilient crop systems.

Nitrogen-Fixing Biofertilizers and Their Role in Sustainable Agriculture

Nitrogen-fixing biofertilizers are pivotal in modern agriculture, transforming atmospheric nitrogen into forms that plants can readily absorb and utilize. Key microorganisms involved in this process include Rhizobium, Azotobacter, and cyanobacteria. These organisms enhance soil fertility by facilitating the conversion of atmospheric nitrogen into ammonia and nitrates, essential nutrients for plant growth (Nelson, 2004; Aasfar et al., 2021; Stacey, 2006). The symbiotic relationships that Rhizobium forms with leguminous plants exemplify the beneficial interactions that promote nitrogen fixation, ultimately leading to increased agricultural productivity while simultaneously reducing the environmental impacts typically associated with synthetic fertilizers (Pedraza et al., 2020; Dwivedi, 2020; Byjus, n.d.).

Algal Biofertilizers: Enhancing Soil Fertility

In addition to nitrogen-fixing bacteria, algal biofertilizers, particularly those derived from species such as Scenedesmus, have shown considerable potential in improving soil fertility. These algae produce biologically active compounds that significantly enhance crop yields (Bhardwaj et al., 2014; Daniel et al., 2022). For instance, research has demonstrated that Scenedesmus spp. can stimulate plant growth, leading to increased biomass in ornamental crops such as petunias (Biomcare, n.d.; Kour et al., 2020; Singh et al., 2016). Moreover, Aulosira fertilissima has been recognized for its beneficial effects on rice seedlings, primarily due to its ability to produce growth-stimulating cytokinins (Biomcare, n.d.; Kour et al., 2020).

Algal biofertilizers also exhibit remarkable capabilities in mitigating salt stress during seed germination, an increasingly critical factor in crop establishment under saline conditions. Species like Dunaliella spp. and Phaeodactylum spp. help enhance seedling resilience, thus improving overall crop establishment and yield potential (Biomcare, n.d.; Kour et al., 2020).

Integrating Biofertilizers into Sustainable Practices

The incorporation of nitrogen-fixing bacteria and algal biofertilizers into agricultural systems aligns well with sustainable practices by enhancing nutrient availability, improving crop yields, and decreasing reliance on synthetic fertilizers (Mahmud et al., 2021; Bio-Fit, n.d.). The nutrient-rich nature of algal biofertilizers enhances soil structure, contributing to erosion prevention and fostering healthier ecosystems (Mahmud et al., 2021; Online Biology Notes, n.d.). Additionally, these biofertilizers can accelerate the decomposition of organic matter, thereby enriching soil nutrient profiles (Mahmud et al., 2021; Online Biology Notes, n.d.). Despite these advantages, challenges remain in the widespread adoption of biofertilizers. Economic and operational constraints, such as high production and processing costs, pose significant barriers to their broader use in agriculture (Daniel et al., 2022; Mahmud et al., 2021).

Fungal Biofertilizers and Their Contributions

Fungal biofertilizers further contribute to sustainable agriculture by establishing symbiotic relationships with plant roots. This association enhances nutrient exchange and increases plant resilience to various environmental stresses (Singh et al., 2016; Kour et al., 2020). Fungi such as mycorrhizae play crucial roles in facilitating the uptake of nutrients, especially phosphorus, thereby promoting plant health and productivity.

The integration of diverse microbial inoculants, including nitrogen-fixing bacteria, algal biofertilizers, and fungi, underscores their critical roles in enhancing soil fertility and achieving sustainable agricultural productivity (Kumar et al., 2022; Singh et al., 2016). By leveraging these natural solutions, farmers can cultivate healthier crops while minimizing the environmental footprint of agricultural practices.

Conclusion

The utilization of biofertilizers, including phosphate-solubilizing microorganisms, nitrogen-fixing bacteria, algal biofertilizers, and fungal biofertilizers, represents a sustainable approach to enhancing soil fertility and crop productivity. These biological agents improve nutrient availability, promote healthy plant growth, and reduce reliance on chemical fertilizers, thereby minimizing environmental impacts. Phosphate-solubilizing microorganisms release bound phosphates, while nitrogen-fixing bacteria convert atmospheric nitrogen into usable forms, significantly benefiting various crops. Algal biofertilizers contribute essential nutrients and enhance soil structure, while fungi form symbiotic relationships with plant roots to facilitate nutrient exchange. Despite challenges such as production costs and efficiency, ongoing research and development efforts are essential to optimize biofertilizer application and promote sustainable agricultural practices. Ultimately, embracing biofertilizers can lead to more resilient ecosystems and improved food security globally.

Author contributions

A.A. conceptualized the project and developed the methodology. M.U. conducted a formal analysis and drafted
the original writing. U.Z. contributed to the methodology. F.S. conducted investigations, provided resources, and
visualized the data. M. contributed to the reviewing and editing of the writing.

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Competing financial interests

The authors have no conflict of interest.

References

Aasfar, A., Bargaz, A., Yaakoubi, K., Hilali, A., Bennis, I., Zeroual, Y., & Meftah Kadmiri, I. (2021). Nitrogen fixing Azotobacter species as potential soil biological enhancers for crop nutrition and yield stability. Frontiers in Microbiology, 12, Article 628379. https://doi.org/10.3389/FMICB.2021.628379

Ali, M. A., Merzah, N. R., & Jubair, A. F. (2021). Isolation and diagnosis of pathogenic fungi associated with zucchini Cucurbita pepo roots and their bio-control. IOP Conference Series: Earth and Environmental Science, 923. doi:10.1088/1755-1315/923/1/012014

Alobwede, E. (2023, May 29). The advantages of algae as biofertilisers in agriculture. In Grantham Centre for Sustainable Futures. https://grantham.sheffield.ac.uk/journal-club-with-emanga-alobwede/

Ammar, E. E., Aioub, A. A. A., Elesawy, A. E., Karkour, A. M., Mouhamed, M. S., Amer, A. A., & EL-Shershaby, N. A. (2022). Algae as bio-fertilizers: Between current situation and future prospective. Saudi Journal of Biological Sciences, 29, 3083. doi:10.1016/j.sjbs.2022.03.020

Begum, N., Qin, C., Ahanger, M. A., Raza, S., Khan, M. I., Ashraf, M., Ahmed, N., & Zhang, L. (2019). Role of arbuscular mycorrhizal fungi in plant growth regulation: Implications in abiotic stress tolerance. Frontiers in Plant Science, 10, Article 1068. https://doi.org/10.3389/FPLS.2019.01068

Benjamin, R. K., Blackwell, M., Chapela, I. H., Humber, R. A., Jones, K. G., Klepzig, K. D., Lichtwardt, R. W., Malloch, D., Noda, H., Roeper, R. A., & et al. (2004). Insect- and other arthropod-associated fungi. In Biodiversity of fungi: Inventory and monitoring methods (pp. 395–433). doi:10.1016/B978-012509551-8/50021-0

Bharathi, S., & Radhakrishnan, M. (2023). Symbiotic microbes from corals. In Microbial symbionts (pp. 441–456). doi:10.1016/B978-0-323-99334-0.00004-9

Bhardwaj, D., Ansari, M. W., Sahoo, R. K., & Tuteja, N. (2014). Biofertilizers function as key players in sustainable agriculture by improving soil fertility, plant tolerance, and crop productivity. Microbial Cell Factories, 13, Article 66. https://doi.org/10.1186/1475-2859-13-66

Bio-Fit. (n.d.). What are biofertilizers? Retrieved May 29, 2023, from https://bio-fit.eu/q8/lo1-why-biofertilizers?start=1

Biological Products Industry Alliance. (2023, May 29). History of biopesticides. https://www.bpia.org/history-of-biopesticides/

Biomcare. (n.d.). Microbiome analysis service | Research & pro services | Get quote. Retrieved May 28, 2023, from https://biomcare.com/

Britannica. (2023, May 29). Nitrogen-fixing bacteria | Definition & types. In Encyclopedia Britannica. https://www.britannica.com/science/nitrogen-fixing-bacteria

Byjus. (n.d.). Rhizobium - Role of Rhizobium bacteria in nitrogen fixation. Retrieved May 29, 2023, from https://byjus.com/biology/rhizobium/

Daniel, A. I., Fadaka, A. O., Gokul, A., Bakare, O. O., Aina, O., Fisher, S., Burt, A. F., Mavumengwana, V., Keyster, M., & Klein, A. (2022). Biofertilizer: The future of food security and food safety. Microorganisms, 10, Article 1220. https://doi.org/10.3390/MICROORGANISMS10061220

Daniel, A. I., Fadaka, A. O., Gokul, A., Bakare, O. O., Aina, O., Fisher, S., Burt, A. F., Mavumengwana, V., Keyster, M., & Klein, A. (2022). Biofertilizer: The future of food security and food safety. Microorganisms, 10. doi:103390/microorganisms10061220

Dwivedi, M. (2020). Gluconobacter. In Beneficial microbes in agro-ecology: Bacteria and fungi (pp. 521–544). https://doi.org/10.1016/B978-0-12-823414-3.00025-3

Gonçalves, A. L. (2021). The use of microalgae and cyanobacteria in the improvement of agricultural practices: A review on their biofertilising, biostimulating and biopesticide roles. Applied Sciences, 11(2), 1–21. doi:10.3390/app11020871

Hermosa, R., Rubio, M. B., Cardoza, R. E., Nicolás, C., Monte, E., & Gutiérrez, S. (2013). The contribution of Trichoderma to balancing the costs of plant growth and defense. International Microbiology, 16, 69–80. doi:10.2436/20.1501.01.181

Hocking, M. B. (2005). Ammonia, nitric acid and their derivatives. In Handbook of Chemical Technology and Pollution Control (pp. 321–364). https://doi.org/10.1016/B978-012088796-5/50014-4

Kalayu, G. (2019). Phosphate solubilizing microorganisms: Promising approach as biofertilizers. International Journal of Agronomy, 2019, Article 4917256. https://doi.org/10.1155/2019/4917256

Kour, D., Rana, K. L., Yadav, A. N., Yadav, N., Kumar, M., Kumar, V., Vyas, P., Dhaliwal, H. S., & Saxena, A. K. (2020). Microbial biofertilizers: Bioresources and eco-friendly technologies for agricultural and environmental sustainability. Biocatalysis and

Agricultural Biotechnology, 23, 101487. https://doi.org/10.1016/J.BCAB.2019.101487

Kumar, J., Ramlal, A., Mallick, D., & Mishra, V. (2021). An overview of some biopesticides and their importance in plant protection for commercial acceptance. Plants, 10. doi:10.3390/plants10061185

Kumar, S., & Singh, A. (2015). Biopesticides: Present status and the future prospects. Journal of Biofertilizers & Biopesticides, 6. doi:10.4172/jbfbp.1000e129

Kumar, S., Diksha, Sindhu, S. S., & Kumar, R. (2022). Biofertilizers: An ecofriendly technology for nutrient recycling and environmental sustainability. Current Research in Microbial Sciences, 3, 100094. https://doi.org/10.1016/J.CRMICR.2021.100094

Lindström, K., & Mousavi, S. A. (2020). Effectiveness of nitrogen fixation in rhizobia. Microbial Biotechnology, 13, 1314. doi:10.1111/1751-7915.13517

Mahmud, A. A., Upadhyay, S. K., Srivastava, A. K., & Bhojiya, A. A. (2021). Biofertilizers: A nexus between soil fertility and crop productivity under abiotic stress. Current Research in Environmental Sustainability, 3, 100063. https://doi.org/10.1016/J.CRSUST.2021.100063

Nelson, L. M. (2004). Plant growth promoting rhizobacteria (PGPR): Prospects for new inoculants. Crop Management, 3, 1–7. https://doi.org/10.1094/CM-2004-0301-05-RV

Online Biology Notes. (n.d.). Biofertilizer- Advantages, types, methods of application and disadvantages. Retrieved May 29, 2023, from https://www.onlinebiologynotes.com/biofertilizer-advantages-types-methods-of-application-and-disadvantages/

Pedraza, R. O., Filippone, M. P., Fontana, C., Salazar, S. M., Ramírez-Mata, A., Sierra-Cacho, D., & Baca, B. E. (2020). Azospirillum. In Beneficial microbes in agro-ecology: Bacteria and fungi (pp. 73–105). https://doi.org/10.1016/B978-0-12-823414-3.00006-X

Reddy, P. M., James, E. K., & Ladha, J. K. (2002). Nitrogen fixation in rice. In Nitrogen fixation at the millennium (pp. 421–445). doi:10.1016/B978-044450965-9/50015-X

ResearchGate. (2023, May 29). Mycorrhiza-mediated phosphorus use efficiency in plants. https://www.researchgate.net/publication/362253016_Mycorrhiza-mediated_phosphorus_use_efficiency_in_plants

Saritha, M., & Prasad Tollamadugu, N. V. K. V. (2019). The status of research and application of biofertilizers and biopesticides: Global scenario. In Recent developments in applied microbiology and biochemistry (pp. 195–207). https://doi.org/10.1016/B978-0-12-816328-3.00015-5

Sharma, S. B., Sayyed, R. Z., Trivedi, M. H., & Gobi, T. A. (2013). Phosphate solubilizing microbes: Sustainable approach for managing phosphorus deficiency in agricultural soils. SpringerPlus, 2, Article 587. https://doi.org/10.1186/2193-1801-2-587

Sheteiwy, M. S., Ali, D. F. I., Xiong, Y. C., Brestic, M., Skalicky, M., Hamoud, Y. A., Ulhassan, Z., Shaghaleh, H., AbdElgawad, H., & Farooq, M. (2021). Physiological and biochemical responses of soybean plants inoculated with arbuscular mycorrhizal fungi and Bradyrhizobium under drought stress. BMC Plant Biology, 21. doi:10.1186/s12870-021-02949-z

Singh, D. P., Singh, H. B., & Prabha, R. (2016). Microbial inoculants in sustainable agricultural productivity: Vol. 1: Research perspectives (pp. 1–343). https://doi.org/10.1007/978-81-322-2647-5/COVER

Stacey, G. (2006). The Rhizobium-legume nitrogen-fixing symbiosis. In Biology of the Nitrogen Cycle (pp. 147–163). https://doi.org/10.1016/B978-044452857-5.50011-4

Sumbul, A., Ansari, R. A., Rizvi, R., & Mahmood, I. (2020). Azotobacter: A potential bio-fertilizer for soil and plant health management. Saudi Journal of Biological Sciences, 27, 3634–3641. https://doi.org/10.1016/J.SJBS.2020.08.004

U.S. Environmental Protection Agency. (2023, May 29). What are biopesticides? https://www.epa.gov/ingredients-used-pesticide-products/what-are-biopesticides

Wang, Q., Liu, J., & Zhu, H. (2018). Genetic and molecular mechanisms underlying symbiotic specificity in legume-rhizobium interactions. Frontiers in Plant Science, 9, 313. doi:10.3389/fpls.2018.00313

Zahran, H. H. (1999). Rhizobium-legume symbiosis and nitrogen fixation under severe conditions and in an arid climate. Microbiology and Molecular Biology Reviews, 63(4), 968–989. https://doi.org/10.1128/MMBR.63.4.968-989.1999

Zambrano-Mendoza, J. L., Sangoquiza-Caiza, C. A., Campaña-Cruz, D. F., & Yánez-Guzmán, C. F. (2021). Use of biofertilizers in agricultural production. Technology in Agriculture. https://doi.org/10.5772/INTECHOPEN.98264