

The green revolution 2.0: A critical review of probiotics in enhancing plant productivity and sustainability.

Chandrasekhar Bhoi^{1*}, Monalisha Sahoo²

¹Department of Botany, Maharaja Purna Chandra Autonomous College, Baripada, India

²Department of Biotechnology, Ramadevi University, Bhubaneswar, India

Abstract

The global demand for sustainable agricultural practices has led to the exploration of innovative approaches to enhance plant productivity while minimizing environmental impact. Probiotics, traditionally associated with beneficial microorganisms in human and animal health, are now gaining attention for their promising role in promoting plant growth, nutrient uptake, and stress tolerance. It delves into the current understanding of plant-microbe interactions, elucidating the intricate mechanisms by which probiotics influence plant physiology and development. Furthermore, the review critically assesses the existing body of research on various types of plant associated probiotics, including bacteria and fungi, their modes of action, and their effects on key agricultural parameters such as crop yield, soil fertility, and resistance to biotic and abiotic stresses. Additionally, it highlights the importance of considering ecological, ethical, and socio-economic factors in the adoption of probiotic technologies on a global scale. Ultimately, the green revolution 2.0, rooted in probiotic applications, emerges as a promising paradigm shift towards a more resilient and sustainable future for agriculture.

Keywords: Probiotics, Sustainable agriculture, Microbial symphony, Bio fertilizer, Green revolution 2.0.

Introduction

In the ever-evolving realm of agricultural sciences, the pursuit of sustainable and efficient methods to enhance crop productivity has become paramount. The green revolution, characterized by the adoption of high-yielding varieties and modern agricultural techniques, marked a pivotal moment in history, drastically increasing global food production. One emerging frontier in this agricultural revolution is the integration of probiotics into plant cultivation practices. Traditionally associated with human health, probiotics have now found their way into the soil, fostering a symbiotic relationship with plants and unlocking new possibilities for sustainable agriculture. Amidst concerns about climate change, soil degradation, and the environmental impact of conventional farming practices, the integration of probiotics into agricultural strategies emerges as a promising avenue. By exploring the symbiotic relationship between beneficial microorganisms and plants, this review seeks to contribute to the ongoing discourse on sustainable agriculture and pave the way for informed decision-making in the pursuit of a more resilient and ecologically friendly future for global food production [1]. This critical review not only scrutinizes the scientific underpinnings of probiotics in agriculture but also evaluates their practical

applicability across diverse crop systems and environmental conditions.

Literature Review

Microbial Symphony in the rhizosphere

Beneath the surface of agricultural landscapes, a hidden orchestra of microscopic life conducts a symphony in the rhizosphere, a dynamic and intricate realm surrounding plant roots. This microbial symphony plays a crucial role in shaping the health, productivity, and sustainability of plants, influencing nutrient cycling, disease resistance, and overall soil ecosystem dynamic [2]. The rhizosphere is a bustling microcosm where plants and a diverse community of microorganisms engage in a sophisticated dance of chemical signals, nutrient exchanges, and symbiotic relationships. At the heart of this symphony are the plant roots, exuding a myriad of compounds that serve as signals and sustenance for a plethora of microorganisms. Bacteria, fungi, archaea, and other microbes establish intricate relationships with plants, forming symbiotic alliances that contribute to enhanced nutrient uptake, improved stress tolerance, and protection against pathogens. As we unravel the secrets of the microbial symphony in the rhizosphere, the

*Correspondence to: Chandrasekhar Bhoi, Chandrasekhar Bhoi, Department of Botany, Maharaja Purna Chandra Autonomous College, Baripada, India; E-mail: cbhoi7918@gmail.com

Received: 30-Jan-2024, Manuscript No. AAASCB-24-126369; Editor assigned: 02-Feb-2024, AAASCB-24-126369 (PQ); Reviewed: 16-Feb-2024, QC No. AAASCB-24-126369; Revised: 11-Feb-2025, Manuscript No. AAASCB-24-126369 (R); Published: 18-Feb-2025, DOI: 10.35841/aaascb-9.1.279

implications for sustainable agriculture, soil management, and environmental conservation become apparent. Harnessing the potential of this intricate network offers opportunities to optimize plant-microbe interactions, enhance crop yields, and mitigate the environmental impacts of conventional farming practices [3].

Bio-fertilizers of tomorrow

Introduction to biofertilizers: Biofertilizers are microorganisms that enhance nutrient availability and uptake by plants. They play a crucial role in sustainable agriculture by promoting natural processes and reducing reliance on synthetic fertilizers.

Microbial diversity: Tomorrow's biofertilizers will likely harness a diverse range of beneficial microorganisms, including nitrogen-fixing bacteria, phosphate solubilizers, and mycorrhizal fungi. The focus will be on selecting strains that adapt well to various soil conditions.

Nitrogen-fixing bacteria: The use of nitrogen-fixing bacteria like *Rhizobium* and *Azotobacter* is expected to increase. These bacteria form symbiotic relationships with plants, converting atmospheric nitrogen into a form usable by plants, reducing the need for nitrogen fertilizers.

Phosphate-solubilizing microorganisms: Biofertilizers will leverage phosphate-solubilizing bacteria and fungi, enhancing the availability of phosphorus to plants. This is crucial for root development, flowering, and overall plant growth.

Mycorrhizal fungi: Future biofertilizers will likely incorporate mycorrhizal fungi that form mutually beneficial relationships with plant roots. These fungi improve nutrient and water absorption, leading to better plant health and resilience.

Biological nitrogen fixation: Advancements in understanding the molecular mechanisms of biological nitrogen fixation will enable the development of more effective biofertilizers. This could lead to increased nitrogenfixing efficiency and reduced environmental impact.

Customized formulations: Biofertilizers will be formulated based on specific crop needs and soil conditions. Customized blends of microorganisms may be designed to address deficiencies and enhance nutrient cycling in diverse agricultural systems.

Microbial consortia: The use of microbial consortia, combinations of multiple beneficial microorganisms, is anticipated. These consortia can provide a synergistic effect, improving nutrient availability and plant resilience.

Adaptability and resilience: Biofertilizers of tomorrow will be developed to withstand various environmental stresses, ensuring their efficacy in diverse climates and soil types. This adaptability is crucial for widespread adoption in global agriculture.

Environmentally friendly and sustainable: The focus will be on developing biofertilizers that contribute to sustainable

agriculture, reducing the environmental impact associated with conventional fertilizers. This includes minimizing nutrient runoff and soil degradation.

Research and innovation: Ongoing research and technological innovations will drive the evolution of biofertilizers. The integration of biotechnology, genomics, and data analytics will enhance our understanding and ability to design more effective microbial solutions.

Farmers' adoption and education: Successful implementation of biofertilizers of tomorrow will require extensive education and outreach to farmers. Encouraging adoption through awareness programs and showcasing real-world benefits will be essential.

The continuous evolution of these microbial solutions will shape the future of farming practices worldwide.

Unlocking nutrient uptake

Unlocking nutrient uptake in plants through probiotics involves harnessing the potential of beneficial microorganisms to enhance nutrient availability, absorption, and overall plant health. While the field of plant-microbe interactions is complex and dynamic, here are some general strategies and concepts associated with using probiotics for nutrient uptake:

Phosphate solubilization: Certain bacteria, such as Phosphate-Solubilizing Bacteria (PSB), play a crucial role in converting insoluble forms of phosphorus in the soil into soluble forms that plants can absorb. This helps improve phosphorus availability for plants, promoting root development and overall growth.

Nitrogen fixation: Nitrogen-fixing bacteria, like those in the *Rhizobium* genus, have the ability to convert atmospheric nitrogen into ammonia, which is a form of nitrogen that plants can readily use. This process occurs in the root nodules of leguminous plants, enhancing nitrogen availability and promoting plant growth.

Production of plant growth-promoting substances: Probiotic microorganisms, particularly Plant Growth-Promoting Rhizobacteria (PGPR), may produce substances such as auxins, cytokinins, and gibberellins that stimulate plant growth and development. These substances can positively influence nutrient uptake by promoting root elongation and branching [4]. Biofertilizers: Probiotics used as (biofertilizers contain live) microorganisms that contribute to nutrient cycling in the soil. This includes the release of organic acids, enzymes, and other compounds that break down organic matter, releasing nutrients for plant uptake.

Enhanced nutrient absorption: Probiotics can improve nutrient absorption by influencing the root architecture of plants. They may stimulate the development of a well-branched and extensive root system, which enhances the plant's ability to explore the soil for nutrients.

Inducing systemic resistance: Some beneficial microorganisms can induce systemic resistance in plants, making them more resilient to diseases and environmental

Citation: Bhoi C, Sahoo M. The green revolution 2.0: A critical review of probiotics in enhancing plant productivity and sustainability. *J Agric Sci Bot.* 2025;9(1):279

stress. When plants are under less stress, they are more efficient in nutrient uptake and utilization.

Competition with pathogens: Probiotics can compete with harmful pathogens for nutrients and space around the plant roots. By suppressing the growth of pathogens, they create a healthier rhizosphere environment, allowing plants to focus on nutrient absorption rather than defense mechanisms.

Improved soil structure: Certain probiotics contribute to the formation of stable soil aggregates, improving soil structure. This enhances water infiltration, root penetration, and nutrient movement in the soil, benefiting overall nutrient availability to plants.

It's important to note that the effectiveness of probiotics in nutrient uptake can vary depending on factors such as soil type, plant species, and specific microbial strains. Research and field trials are ongoing to better understand and optimize the use of probiotics in agriculture for sustainable nutrient management

Bolstering plant resilience

Probiotics can indeed play a role in bolstering plant resilience by enhancing the overall health and robustness of plants. The term "probiotics" in the context of plant health typically refers to beneficial microorganisms, such as certain bacteria and fungi, that can positively interact with plants. Here are ways in which probiotics contribute to plant resilience:

Disease suppression: Certain probiotic microorganisms act as biocontrol agents by inhibiting the growth of harmful pathogens. By colonizing the rhizosphere (the soil region influenced by plant roots), these beneficial microbes create a competitive environment that limits the proliferation of plant pathogens. This helps in preventing or mitigating diseases, thereby enhancing plant resilience.

Induction of systemic resistance: Probiotics can stimulate a plant's immune response, leading to the induction of systemic resistance. This means that even parts of the plant not directly in contact with the microorganisms can become more resistant to diseases. This systemic defense mechanism contributes to the overall resilience of the plant.

Stress tolerance: Some probiotics enhance a plant's ability to tolerate various environmental stresses, such as drought, salinity, and extreme temperatures. This is often achieved through the production of stress-responsive proteins or by modulating the plant's physiological responses to stressors [5].

Nutrient uptake efficiency: As mentioned earlier, probiotics can improve nutrient availability and absorption by solubilizing nutrients in the soil and promoting root development. This improved nutrient status contributes to the overall vigor and resilience of plants, making them better equipped to withstand environmental challenges.

Promotion of growth-promoting substances: Probiotics may produce plant growth-promoting substances, such as auxins and cytokinins, that stimulate growth and development. This not only supports the overall health of the plant but also aids in the recovery from stress or damage.

Enhanced root development: The presence of beneficial microorganisms can stimulate the development of a robust and extensive root system. This increased root mass helps plants access water and nutrients more efficiently, providing a foundation for resilience against environmental fluctuations.

Improved soil structure: Some probiotics contribute to soil aggregation, improving soil structure. Better soil structure enhances water retention, aeration, and nutrient availability, all of which contribute to the resilience of plants growing in these conditions.

Reduced dependence on chemical inputs: By promoting natural mechanisms of disease resistance and nutrient uptake, probiotics can potentially reduce the need for chemical fertilizers and pesticides. This can lead to more sustainable agricultural practices and healthier, resilient plants.

Integrating probiotics into agricultural practices holds promise for promoting plant resilience in a sustainable and environmentally friendly manner.

Biocontrol agents: A probiotic biocontrol agent is a beneficial microorganism that is used to control the growth and activities of harmful pathogens, pests, or diseases in agriculture. These microorganisms act as biocontrol agents by establishing a competitive advantage in the plant's environment and suppressing the proliferation of pathogenic organisms [6]. The goal is to enhance plant health, reduce reliance on chemical pesticides, and promote sustainable agricultural practices. Here are some key aspects of probiotic biocontrol agents:

Beneficial microorganisms: Probiotic biocontrol agents often include bacteria, fungi, or other microorganisms that exhibit antagonistic properties against plant pathogens. Examples include certain strains of bacteria (e.g., *Bacillus* spp.), fungi (e.g., *Trichoderma* spp.), and yeast.

Competitive exclusion: Probiotic biocontrol agents work through a mechanism known as competitive exclusion. They outcompete harmful pathogens for resources, such as nutrients and space in the rhizosphere (the soil region influenced by plant roots), preventing the establishment and growth of pathogenic organisms.

Antibiosis: Some probiotic microorganisms produce antimicrobial compounds, such as antibiotics, which inhibit the growth of pathogenic microbes. This antibiosis mechanism contributes to disease suppression by directly targeting and killing harmful organisms.

Induced Systemic Resistance (ISR): Probiotic biocontrol agents can stimulate the plant's own defense mechanisms. This process, known as Induced Systemic Resistance (ISR), primes the plant's immune system to better respond to potential threats, enhancing its resilience against diseases.

Plant growth-promoting properties: Beyond biocontrol, many probiotics also possess plant growth-promoting properties. They may produce hormones, fix nitrogen, or solubilize nutrients, contributing to improved plant health, vigor, and overall resilience.

Sustainable agriculture: The use of probiotic biocontrol agents aligns with principles of sustainable agriculture by reducing the reliance on synthetic chemicals. This approach aims to maintain or increase crop yields while minimizing the environmental impact associated with traditional pest and disease management practices [7].

Compatibility with Integrated Pest Management (IPM): Probiotic biocontrol agents are often integrated into broader pest management strategies, such as Integrated Pest Management (IPM). IPM emphasizes a holistic and environmentally friendly approach to pest and disease control, combining biological, cultural, and chemical control methods.

Commercial products: Probiotic biocontrol agents are available in various commercial formulations, such as bio-pesticides or bio-fungicides. These products are designed for application in agriculture to support plant health and mitigate the impact of pathogens.

It's important to note that the effectiveness of probiotic biocontrol agents can vary depending on factors like the specific microorganism used, the target pathogen, environmental conditions, and crop type. Ongoing research aims to identify and optimize the use of these beneficial microorganisms for sustainable and effective pest and disease management in agriculture.

Discussion

Harmony in diversity

Probiotics play a crucial role in maintaining and enhancing plant diversity, ecosystem health, and overall ecological balance. By forming symbiotic relationships with plant roots, probiotics enhance nutrient uptake for the plants and provide a favorable environment for the microorganisms to thrive. This specificity promotes a diverse range of microbial communities in the rhizosphere, supporting a variety of plant species within an ecosystem. Furthermore, probiotics contribute to the breakdown of organic matter, releasing essential nutrients in a form that plants can absorb, thus supporting the diverse nutritional needs of various plant species and fostering a harmonious coexistence.

Moreover, by influencing biotic interactions among plants and promoting sustainable agricultural practices, probiotics contribute to the resilience of the entire ecosystem. Understanding and promoting probiotics harmony in plant diversity is essential for maintaining the health and resilience of ecosystems, whether in natural settings or agricultural landscapes.

From lab to land: The successful transition of probiotics from the laboratory to the field, often referred to as "lab to land," involves several key considerations to ensure that the benefits observed in controlled laboratory conditions can be effectively applied in real-world agricultural settings [8].

Here are some factors influencing the success of this transition:

Strain selection: Lab research: In the laboratory, researchers often identify specific strains of beneficial microorganisms (probiotics) that demonstrate positive effects on plant growth, disease suppression, or nutrient uptake. Field application: The selected strains must be well-suited to the field environment, considering factors such as soil type, climate, and the specific crops grown. Strains should be resilient and able to thrive under field conditions.

Field trials and adaptability: Lab research: Initial positive results in the lab need to be validated through field trials. It's essential to assess the adaptability and performance of probiotics in diverse field conditions. Field application: Field trials help determine the efficacy of probiotics under real-world conditions, providing insights into their interactions with the soil, plants, and other environmental factors.

Formulation and application methods: Lab research: Researchers often work on developing effective formulations for probiotics, considering factors such as stability, viability, and compatibility. Field application: Formulations must be practical and suitable for large-scale application. Considerations include ease of application, compatibility with existing agricultural practices, and cost-effectiveness.

Integration with agricultural practices: Lab research: Laboratory studies focus on the isolated effects of probiotics, but successful field application requires integration with existing agricultural practices. Field application: Farmers need to understand and adopt application methods that fit into their existing routines. This integration is critical for the widespread adoption of probiotic technologies.

Scale-up considerations: Lab research: Initial studies are often conducted on a small scale, providing insights into the potential benefits of probiotics. Field application: Successful scaling up involves addressing logistical challenges, ensuring sufficient coverage, and optimizing application rates for larger agricultural areas.

Long-term effects and sustainability: Lab research: Short-term studies in the lab may demonstrate immediate benefits, but it's essential to assess the long-term effects of probiotics on soil health, plant productivity, and overall sustainability. Field application: Continuous monitoring and research in the field help determine the sustained impact of probiotics on crop yields, disease resistance, and soil fertility over multiple seasons [9].

Education and outreach: Lab research: Researchers focus on understanding the mechanisms and benefits of probiotics. Field application: Farmers need education and outreach programs to understand the benefits of probiotics and how to integrate them into their farming practices. Extension services, workshops, and training sessions are essential for successful adoption.

Regulatory compliance: Lab research: Researchers may not always consider regulatory aspects, but transitioning to the field requires compliance with local regulations and standards. Field application: Probiotic products may need approval from relevant regulatory authorities. Meeting these requirements ensures that farmers can use probiotics legally and safely.

Citation: Bhoi C, Sahoo M. The green revolution 2.0: A critical review of probiotics in enhancing plant productivity and sustainability. *J Agric Sci Bot.* 2025;9(1):279

The successful translation of probiotics from lab to land requires a collaborative effort involving researchers, farmers, extension services, and regulatory bodies. Continuous feedback, adaptation, and research are necessary to refine probiotic applications for real-world agricultural challenges.

Balancing act

Probiotics play a crucial role in maintaining the health and resilience of ecosystems. By forming symbiotic relationships with plant roots, probiotics enhance nutrient uptake for the plants and provide a favorable environment for the microorganisms to thrive. This specificity promotes a diverse range of microbial communities in the rhizosphere, supporting a variety of plant species within an ecosystem [10].

Moreover, probiotics act as a balancing force between environmental conservation and sustainability in agricultural practices. Their ability to reduce the need for chemical inputs promotes sustainable agriculture, resulting in the cultivation of a more diverse range of crops and agroecosystems [11]. This, in turn, contributes to long-term agricultural sustainability and ecological balance.

Economics of the future

Probiotics can offer several economic benefits to farmers when integrated into agricultural practices. These benefits arise from the positive effects of probiotics on soil health, plant growth, and overall crop productivity. Here are ways in which probiotics can contribute to economic advantages for farmers:

Reduced dependency on chemical inputs: Probiotics can enhance nutrient availability in the soil, reducing the need for chemical fertilizers. Farmers can save costs associated with the purchase and application of synthetic fertilizers, contributing to overall input cost reduction.

Disease suppression and pest control: Probiotics may have biocontrol properties that help suppress soil-borne pathogens and pests. This can lead to a decrease in the need for chemical pesticides, resulting in cost savings for farmers and reducing the environmental impact of pest control practices.

Increased crop yields: Improved nutrient uptake and disease resistance facilitated by probiotics can lead to increased crop yields. Higher yields mean more produce to sell, contributing to increased revenue and improved economic outcomes for farmers [12].

Enhanced soil health: Probiotics contribute to the overall health of the soil by promoting beneficial microbial activity and improving soil structure. Healthy soils are more resilient, reducing the need for expensive soil amendments and fostering sustainable agricultural practices.

Water use efficiency: Probiotics can enhance water use efficiency by improving the ability of plants to absorb and utilize water. In regions facing water scarcity, this improvement can lead to more efficient water management and potential cost savings for farmers.

Premium prices for sustainable products: Crops grown using probiotics may be perceived as more environmentally friendly and sustainable [13]. Farmers adopting probiotics may have the opportunity to market their produce as premium, attracting consumers willing to pay higher prices for sustainably grown products.

Reduction in crop losses: Probiotics can contribute to a reduction in crop losses due to diseases and pests. This reduction directly translates to economic benefits for farmers by preserving the value of their harvests and minimizing financial losses [14].

Access to niche markets: Growing crops with probiotics may open doors to niche markets that prioritize environmentally friendly and sustainable agriculture. Farmers can explore these markets, potentially accessing consumers willing to pay a premium for products grown using probiotic technologies.

Long-term sustainability: The use of probiotics supports sustainable farming practices, contributing to the long-term viability of agricultural systems. Sustainable practices are often more economically resilient and adaptable to changing environmental conditions.

Research and innovation opportunities: The adoption of probiotics may stimulate research and innovation in agricultural practices, creating opportunities for farmers to benefit from new technologies, products, and practices that can further enhance economic outcome.

Navigating regulations and future prospects

Navigating regulations and understanding the future prospects of probiotics in agriculture is crucial for farmers, researchers, and businesses involved in the development and application of probiotic technologies. Here are key considerations regarding regulations and future trends:

Regulations: Regulatory authorities: Different countries have different regulatory agencies overseeing agricultural products. In the United States, for example, the Environmental Protection Agency (EPA) regulates biopesticides, while the U.S. Department of Agriculture (USDA) may be involved in the regulation of Genetically Modified Organisms (GMOs) or organic farming practices [15].

Product classification: Probiotics used in agriculture may fall under various classifications, such as biopesticides, biofertilizers, or soil amendments. Understanding the regulatory category of a probiotic product is essential for compliance [16].

Registration and approval: Many countries require registration or approval for agricultural products, including probiotics. This process often involves demonstrating product safety, efficacy, and adherence to regulatory standards.

Labeling requirements: Clear and accurate labeling is crucial for regulatory compliance. Probiotic products must provide information on usage instructions, active ingredients, safety precautions, and other relevant details.

Environmental impact assessments: Some probiotics, especially those with biocontrol properties, may require environmental impact assessments to evaluate potential effects on non-target organisms and ecosystems [17].

Global harmonization: Efforts are underway to harmonize regulations globally, promoting consistency and facilitating international trade. Organizations like the Organization for Economic Co-operation and Development (OECD) work towards harmonizing guidelines for the risk assessment of microbial pesticides.

Future prospects

Increased adoption: As awareness of the benefits of probiotics in agriculture grows, there is potential for increased adoption. Farmers may increasingly integrate probiotics into their practices for sustainable and environmentally friendly crop management [18].

Advanced formulations: Ongoing research is likely to lead to the development of more advanced and stable probiotic formulations. Improved formulations can enhance shelf life, viability, and ease of application.

Strain development: Continued research in microbial strain development may yield probiotics with enhanced capabilities, such as increased nutrient solubilization, disease resistance, or stress tolerance.

Precision agriculture: Advances in precision agriculture may lead to more targeted and efficient application of probiotics. This can optimize resource use, reduce waste, and enhance overall effectiveness.

Integration with other technologies: Probiotics may be integrated with other agricultural technologies, such as precision farming, remote sensing, and data analytics. This integration could result in more data-driven and efficient farming practices [19].

Focus on sustainability: The global push for sustainable agriculture may further drive the adoption of probiotics. The ability of probiotics to support sustainable practices aligns with increasing consumer and regulatory demands for environmentally friendly farming.

Research in microbiome science: Advances in microbiome science may lead to a deeper understanding of the interactions between microorganisms and plants. This knowledge can inform the development of more effective probiotics tailored to specific crops and environments.

Market growth: The market for microbial products, including probiotics, is expected to grow. Companies investing in research and development, as well as those addressing regulatory challenges, are likely to play a significant role in shaping the future of the probiotics market in agriculture.

Navigating the regulatory landscape and staying informed about future trends is essential for stakeholders involved in the development and use of probiotics in agriculture [20]. Collaboration between researchers, regulatory bodies, and

industry players can contribute to the responsible and successful integration of probiotics into sustainable agricultural practices [21].

Conclusion

The critical analysis presented in the review emphasizes the need for a nuanced understanding of probiotic applications, considering factors such as strain specificity, environmental conditions, and regulatory frameworks. By harnessing the power of beneficial microorganisms, the agricultural sector has the opportunity to usher in a new era of sustainable and eco-friendly practices, mitigating the environmental impact associated with conventional farming method. Looking ahead, the Green Revolution 2.0, propelled by the application of probiotics, holds promise for promoting ecological balance, reducing the environmental footprint of agriculture, and enhancing the overall well-being of both crops and ecosystems. The review serves as a foundational resource, guiding researchers, farmers, and policymakers in realizing the full potential of probiotics in shaping a sustainable and productive future for global agriculture. As ongoing research continues to unlock the intricacies of plant-microbe interactions, the insights gleaned from this critical review provide a roadmap for harnessing the transformative power of probiotics in the agricultural landscapes of tomorrow.

References

1. Doll JE, Ulbrich TC, Reimer AP. Biologicals: The new Green Revolution or snake oil for ag? Reflections from agricultural stakeholders. *Agric Res Technol*. 2020;25(1).
2. Arora NK, Fatima T, Mishra I, et al. Microbe-based inoculants: role in next green revolution. *Environ Concern Sustain Develop*. 2020;191-246.
3. Delitte M, Caulier S, Bragard C, et al. Plant microbiota beyond farming practices: a review. *Front Sustain Food Syst*. 2021;5:624203.
4. Basu A, Prasad P, Das SN, et al. Plant growth promoting rhizobacteria (PGPR) as green bioinoculants: recent developments, constraints, and prospects. *Sustainability*. 2021;13(3):1140.
5. Pandey SS, Jain R, Bhardwaj P, et al. Plant probiotics–endophytes pivotal to plant health. *Microbiol Res*. 2022;263:127148.
6. Finkel OM, Castrillo G, Paredes SH, et al. Understanding and exploiting plant beneficial microbes. *Curr Opin Plant Biol*. 2017;38:155-63.
7. Dubey A, Malla MA, Kumar A, et al. Plants endophytes: unveiling hidden agenda for bioprospecting toward sustainable agriculture. *Crit Rev Biotechnol*. 2020;40(8): 1210-31.
8. Verma P, Yadav AN, Khannam KS, et al. Potassium-solubilizing microbes: diversity, distribution, and role in plant growth promotion. *Microorganisms for green revolution: Volume 1: Microb Sustain Crop Prod*. 2017:125-49.

Citation: Bhoi C, Sahoo M. The green revolution 2.0: A critical review of probiotics in enhancing plant productivity and sustainability. *J Agric Sci Bot*. 2025;9(1):279

9. Vyas RV, Panpatte DG, Jhala YK, et al. Wonders of microbes in agriculture for productivity and sustainability. *Microorganisms for Green Revolution: Volume 1: Microb Sustain Crop Prod.* 2017;1-23.
10. Sudheer S, Bai RG, Usmani Z, et al. Insights on engineered microbes in sustainable agriculture: biotechnological developments and future prospects. *Curr Genomics.* 2020;21(5):321-33.
11. Upadhayay VK, Chitara MK, Mishra D, et al. Synergistic impact of nanomaterials and plant probiotics in agriculture: A tale of two-way strategy for long-term sustainability. *Front Microbiol.* 2023;14:1133968.
12. Kim YC, Anderson AJ. Rhizosphere pseudomonads as probiotics improving plant health. *Mol Plant Pathol.* 2018;19(10):2349-59.
13. Mishra J, Singh R, Arora NK. Plant growth-promoting microbes: diverse roles in agriculture and environmental sustainability. *Prob Plant Health.* 2017;71-111.
14. John C J, Kumar S, Ge M. Probiotic prospects of PGPR for green and sustainable agriculture. *Arch Phytopathol Plant Protect.* 2020;53(19-20):899-914.
15. Naik K, Mishra S, Srichandan H, et al. Plant growth promoting microbes: Potential link to sustainable agriculture and environment. *Biocata Agric Biotechnol.* 2019;21:101326.
16. Mohanty S, Swain CK. Role of microbes in climate smart agriculture. *Microorganisms for Green Revolution: Volume 2: Microb Sustain Agro-Ecosyst.* 2018:129-40.
17. Trivedi P, Mattupalli C, Eversole K, et al. Enabling sustainable agriculture through understanding and enhancement of microbiomes. *New Phytol.* 2021;230(6): 2129-47.
18. Suman J, Rakshit A, Ogireddy SD, et al. Microbiome as a key player in sustainable agriculture and human health. *Front Soil Sci.* 2022;2:821589.
19. Garcia-Fraile P, Menendez E, Celador-Lera L, et al. Bacterial probiotics: A truly green revolution. *Prob Plant Health.* 2017:131-62.
20. Mohanty S, Pati S, Samal S, Samantaray DP. Probiotics for Sustainable Agriculture Prospects and Challenges. *Agr Mech Asia.* 2022;53(6):8561-73.
21. Singh BK, Trivedi P. Microbiome and the future for food and nutrient security. *Microb Biotechnol.* 2017;10(1):50.

Citation: Bhoi C, Sahoo M. The green revolution 2.0: A critical review of probiotics in enhancing plant productivity and sustainability. *J Agric Sci Bot.* 2025;9(1):279