MICRO ENVIRONER
https://doi.org/10.54458/mev.v5i02.05

Micro Environer
ISSN No - 2783-3526

REVIEW ARTICLE

Harnessing microbial fertilizers for sustainable ginger cultivation

Shoxnoza Zakirova, Nigora Kurbanova, Durdigul Botirova, Dilfuza Egamberdieva

Institute of Fundamental and Applied Research, National Research University TIIAME, Tashkent, Uzbekistan

Received: 05th November, 2025; Revised: 20th November, 2025; Accepted: 10th December, 2025; Available Online: 25th December, 2025

ABSTRACT

Ginger (*Zingiber officinale*), a medicinal and economic crop, holds immense significance due to its bioactive compounds and culinary applications. Sustainable cultivation practices are critical for addressing challenges such as soil degradation, nutrient depletion, and the adverse effects of chemical inputs. This review explores the role of microbial fertilizers in promoting ginger cultivation, emphasizing their contribution to soil fertility, microbial diversity, and plant resilience against diseases. Beneficial microorganisms enhance nutrient availability, produce phytohormones, and exhibit biocontrol properties, reducing dependency on chemical fertilizers. Microbial inoculants enhance plant growth through direct mechanisms such as producing phytohormones, fixing atmospheric nitrogen, solubilizing essential nutrients like phosphorus and potassium, and secreting siderophores that chelate iron, making it more available to plants. Indirectly, microbes suppress plant pathogens by producing antibiotics, competing for nutrients and niches, inducing systemic resistance in plants, and generating hydrolytic enzymes that degrade pathogen cell walls. Modern practices, such as hydroponics, which are integrated with microbial agents, further optimize ginger production by minimizing environmental risks and improving yield quality. The findings underscore the potential of microbial fertilizers as eco-friendly alternatives to conventional agrochemicals, paving the way for sustainable ginger farming and long-term agricultural viability.

Keywords: *Zingiber officinale*, Hydroponic, Rhizomes, Microbial fertilizers, Nutrition.

Micro Environer (2025); DOI: https://doi.org/10.54458/mev.v5i02.05

How to cite this article: Zakirova S, Kurbanova N, Botirova D, Egamberdieva D. Harnessing microbial fertilizers for sustainable ginger cultivation. Micro Environer. 2025;5(2):23-29.

Source of support: Nil.

Conflict of interest: None

INTRODUCTION

Ginger (*Zingiber officinale*) is a flowering plant that is part of the Zingiberaceae family. Its rhizome, often called ginger root, is extensively used as a spice and for its medicinal benefits. Native to Southeast Asia, ginger has been cultivated for thousands of years and is now grown in tropical and subtropical areas around the globe. Ginger is thought to have originated in the Indo-Malaya region of Southeast Asia and India before being introduced and cultivated in other tropical countries (Kizhakkayil and Sasikumar 2011). For example, India, Nigeria, Australia, China, and Jamaica are among the main ginger-exporting countries (Kubra 2012).

Plants from the Zingiberaceae family are found extensively across tropical and subtropical regions around the world. This family includes approximately 1,300 species across 50 genera (Kubra 2012). According to Syafitri et al. (2018), ginger can be classified into three main varieties: giant or white ginger (*Zingiber officinale* var. *Roscoe*), small white ginger or ginger emprit (*Zingiber officinale* var. *Amarum*), and red ginger (*Zingiber officinale* var. *Rubrum*). The plant can reach a height of about one meter and has a woody stem covered by a leaf sheath. Its rhizome is yellowish in color and has branches beneath the soil surface (Mansfield et al. 2012).

Ginger's medicinal properties are derived from its volatile and non-volatile compounds, with oleoresins constituting a significant part of the non-volatile fraction (Anasori 2008; Mia et al. 2015). This plant is rich in bioactive compounds, including phenolics, terpenes, and flavonoids, with [6]-gingerol and [6]-shogaol being the primary components responsible for its distinctive spicy flavor and notable physiological properties (Wohlmuth et al. 2005). These bioactive compounds, particularly polyphenols, contribute to ginger's widespread use as a natural remedy for various conditions, including diabetes, cancer, and inflammation (Li et al. 2012; Anh et al. 2020). By neutralizing free radicals generated by hyperglycemia, these antioxidants not only mitigate oxidative stress but also exhibit additional biological effects, such as reducing inflammation, modulating enzyme activity, and regulating gene expression (McKay et al. 2015). Gingerols, which are responsible for its spiciness, are heat-sensitive and convert to shogaols at high

**Author for Correspondence: email*

temperatures. Shogaol, the primary compound in dried ginger, is spicier and more potent than gingerol (Andriyani et al. 2015).

Various methods are used to successfully cultivate ginger, and they are continually refined based on scientific principles. The choice of method depends on soil quality, climatic conditions, and resource availability. In the traditional method, ginger is cultivated in tropical and subtropical climates with soil that is rich in organic matter. Research highlights that high-quality rhizomes require soil with good moisture retention and drainage properties (Smith 2020). The optimal temperature for ginger growth in greenhouses ranges between 22°C and 28°C (Jones et al. 2018). Hydroponics is a modern and efficient method in which ginger is grown without soil, using a nutrient solution. This technology accelerates plant growth and enables the efficient use of resources. Studies show that using microbial fertilizers in hydroponic systems enhances the chemical composition and biological activity of ginger rhizomes (Kumar et al. 2022).

Ginger cultivation faces significant challenges from soil-borne diseases, such as bacterial wilt, soft rot, and yellow diseases, which lead to severe economic losses (Mansfield et al. 2012). Farmers often use soil fumigants—broad-spectrum compounds such as fungicides and nematicides—to eliminate pathogens, reduce disease incidence, and improve crop profitability (Rokunuzzaman et al. 2016). The widespread use of chemical fertilizers in modern agriculture has significantly contributed to declining soil health, disrupted ecosystem balance, and reduced crop resilience (Chen et al. 2022). Prolonged reliance on these inputs often depletes soil organic matter, alters microbial communities, and increases environmental pollution through nutrient runoff (Sanwal et al. 2007). As an alternative, microbial fertilizers have gained attention for their ability to enhance soil fertility and promote sustainable agricultural practices (Cho et al. 2015; Egamberdieva et al. 2017 a,b,c; Mardonova et al. 2024). These biofertilizers improve nutrient cycling, increase plant growth, and restore soil biodiversity, making them a promising solution for sustainable ginger cultivation (Bhattacharyya et al. 2016). Integrating microbial fertilizers into farming systems can help mitigate the adverse effects of chemical inputs while supporting long-term agricultural sustainability. Additionally, hydroponic cultivation of crops like ginger offers further sustainability by optimizing nutrient delivery, minimizing soil issues, and improving yields, thus complementing the use of biofertilizers in long-term agricultural practices (Smith et al. 2017; Lee et al. 2018; Kumar et al. 2020).

In this review**,** we delve into the scientific advancements in ginger cultivation, focusing on sustainable farming methods, biofertilizer applications, and the role of hydroponics in addressing the challenges faced by modern agriculture. By examining these approaches, we aim to provide insights into achieving high-quality ginger production while promoting long-term agricultural sustainability.

Cultivation of Ginger

Ginger cultivation faces numerous challenges affecting yield, quality, and sustainability. Traditional cultivation practices include planting rhizome sections with healthy buds, applying mulch, and using chemical fertilizers to manage soil moisture and nutrient uptake for optimal growth (Soeparjono 2016). Despite these practices, issues such as soil fertility limitations, organic matter deficiency, and disease susceptibility often result in subpar yields and inconsistent quality (Mansfield et al. 2012). Traditional farming methods often rely on planting rhizomes in well-drained soil, along with the application of chemical and organic inputs to maintain soil fertility and support growth. Sanwal et al. (2007) underscore the importance of organic amendments in enhancing soil health. The transplanting method involves pre-sprouting rhizomes in nursery trays filled with coir and vermicompost, resulting in a reduction of seed usage by approximately 60% and improved plant establishment (Rao and Singh 2019). The method aids in disease management by providing a controlled environment before field transplantation (Bhattacharyya et al. 2016). Hydroponics, a soilless cultivation method that uses nutrient solutions or inert substrates, presents an advanced approach for ginger farming. This technique allows for precise control over nutrients and water, reducing water usage by up to 70–80% compared to conventional methods (Alshrouf 2017; Kannan et al. 2022). According to Wang et al. (2022), microbial interactions within hydroponic systems can enhance plant health, with beneficial microbes such as *Bacillus velezensis* supporting higher yields and improved disease resistance. Integrating ginger cultivation with tree planting and intercropping helps maintain soil moisture, enhance nutrient cycling, and promote biodiversity. Research by Meena et al. (2021) indicates that agroforestry systems reduce soil erosion and support long-term land productivity. This practice, coupled with microbial inoculation, has shown potential in boosting soil health and ginger productivity (Bhattacharyya et al. 2016).

Several reports demonstrated that charcoal husk, bokashi, coco peat, and organic fertilizers significantly influenced the development and yield of red ginger rhizomes (Soeparjono 2016). Together, these findings underscore the critical role of biofertilizers and organic amendments in enhancing the growth, yield, and sustainability of ginger production. A field experiment in Meghalaya (2003–2005) found that poultry manure produced the highest root yield compared to inorganic fertilizers (Sanwal et al. 2007). Similarly, compost teas and organic manure improved crop quality while reducing costs, enhancing soil organic matter, and lowering acidity. In sub-Saharan Africa, a two-year study found that *Chromolaena odorata* mulches outperformed organic fertilizers, significantly increasing ginger leaf count and yield on Alfisol soils (Akinwumia et al. 2022).

Plant Associated Bacteria

Plant-associated bacteria are a diverse group of microorganisms that reside in different plant environments, such as the rhizosphere (root surface), phyllosphere (leaf surface), and endosphere (internal tissues) (Egamberdieva et al. 2008, 2015; Parray et al. 2016; Kumar et al. 2020). These bacteria can impact plant health and productivity in both positive and negative ways (Egamberdieva et al. 2022). The plant microbiome plays a crucial role in enhancing plant health and productivity, influencing disease resistance, nutrient cycling, and overall plant growth (Kwon et al. 2021). Recent research has emphasized that understanding the microbial communities in ginger soils can enhance management practices. Wang et al. (2022) discovered that the microbial composition of healthy ginger plants is notably different from that of diseased plants, indicating that improving soil biodiversity could support disease resistance and boost productivity. A recent study suggested that *Flavobacterium* and *Chitinophaga* in endophytic bacterial communities might possess the ability to inhibit soil-borne pathogens (Du Toit 2020). Carrión et al. (2019) observed that the relative abundance of *Flavobacterium* increased alongside *Ralstonia*, implying that *Flavobacterium* might help suppress *Ralstonia* in the ginger root zone. Moreover, certain species of *Stenotrophomonas* and *Sphingobacterium* have been shown to suppress the growth and virulence of plant pathogens, as well as assist plants in recovering from stress. In this study, both genera exhibited a greater relative abundance in diseased soil than in healthy soil (Kwak et al. 2018). Research on the ginger soil microbiome has revealed variations between healthy and unhealthy samples. In healthy soil, the dominant bacterial genera include *Rhodanobacter* and *Kaistobacter*, while *Rhodoplanes* and *Bradyrhizobium* are more prevalent in unhealthy soil. The genus *Cryptococcus* is recognized for its potential plant growth-promoting characteristics, which could positively impact soil health and ginger growth (Liu et al. 2017).

Ginger is vulnerable to diseases such as blight, caused by *Pythium myriotylum*, and bacterial wilt, caused by *Ralstonia solanacearum*. These pathogens thrive in warm, moist environments and can severely impact yields. For example, *P. myriotylum* led to a 20% reduction in annual ginger yield in Taiwan (Wang et al. 2003). Research on the bacterial communities of ginger rhizomes has revealed that diseased soils have a higher prevalence of *Ralstonia*, while beneficial bacteria such as *Bacillus*, *Sphingomonas*, and *Actinoplanes* are more abundant in healthy soils. This shift in bacterial populations suggests a link between microbial diversity and disease severity (Wang et al. 2022). Understanding the endophytic microbial communities within ginger rhizomes is crucial for evaluating their roles in disease management and plant health (Huang et al. 2021). This study highlights the complex relationship between microbial diversity and the health of ginger crops, emphasizing the potential of beneficial microbes to enhance disease resistance and productivity, while also identifying key gaps for future research on soil microbiome dynamics. Studies have shown that *B. velezensis* can modify the soil's bacterial composition and enhance ginger production in a dose-dependent manner (Chowdhury et al. 2013).

Several microbial species have been observed in the root and shoot of ginger. For example, Singh et al. (2021) identified *Pseudomonas putida* and *Azospirillum brasilense* in the rhizome of ginger. In other study Tan et al. (2020) isolated *Piriformospora indica*, *Trichoderma harzianum* from the root of plant. *Methylobacterium extorquens*, *Bacillus subtilis* were isolated from leaves (Kumar et al. 2020) and *Enterobacter cloacae*, *Burkholderia cepacia* frokm stem of plant (Hasan et al. 2022). Randrianjohany et al. (2023) reported *Streptomyces* sp., *Actinobacteria* sp. from flowers of ginger, whereas Lewis et al. (2024) observed *Bacillus amyloliquefaciens* in the rhizosphere of plant.

Plant Beneficial Properties

Biofertilizers, derived from plants, animals, and minerals, are essential for sustainable agriculture, as they provide vital nutrients, enhance soil health, and ensure long-term fertility (Hashem et al. 2019; Javid et al. 2023). The application of beneficial microbes like *Bacillus velezensis* has been shown to improve soil health and contribute to higher yields (Wang et al. 2022). Microbial inoculants like *Azospirillum brasilense* and *Bacillus subtilis* aid nutrient cycling by solubilizing phosphorus and potassium and fixing nitrogen in the soil (Kaari et al. 2023). Nitrogen-fixing bacteria like *Rhizobium* and *Azotobacter*, along with free-living bacteria such as *Arthrobacter* and *Pseudomonas*, improve soil nitrogen levels and promote plant growth (Santi et al. 2013; Shurigin et al. 2024). These bacteria transform atmospheric nitrogen into a form that plants can absorb, supporting plant nutrition. Potassium-solubilizing bacteria, such as *Bacillus* and *Aspergillus*, improve potassium availability, which is crucial for plant growth and yield (Devi et al. 2023). The combined use of organic fertilizers, such as yard manure and vermicompost, along with microbes like *Azospirillum* and phosphate-solubilizing bacteria, has proven to be highly effective. Additionally, using green leaf manure supplemented with rock phosphate and wood ash also enhances both the dry yield and quality of ginger (Datta et al. 2018). Furthermore, microbial inoculants are crucial in modifying the soil's microbial composition and function, boosting nutrient absorption and increasing plant resistance to various stresses.

It is also demonstrated that hydroponic systems, when integrated with beneficial microbial agents offer an environmentally friendly alternative by minimizing soil-borne disease risks and enabling year-round production (Kwon et al. 2021). By integrating microbial agents, farmers can enhance sustainability, productivity, and quality of ginger. Table 1, demonstrates plant beneficial properties of bacterial inoculants.

Plant Beneficial Traits

Beneficial bacteria for plants promote growth through various mechanisms, such as producing phytohormones, fixing nitrogen, enhancing iron availability, solubilizing phosphate, producing siderophores, and generating ammonia (Egamberdieva et al. 2023). Nitrogen fixation is the process in which nitrogen-fixing microorganisms transform atmospheric nitrogen into a form that plants can use, with the help of an enzyme system known as nitrogenase (Leroux et al. 2024). Biological nitrogen fixation encompasses both symbiotic nitrogen fixation and free-living nitrogen-fixing systems. Symbiotic nitrogen fixers consist of genera such

Table 1: The beneficial properties of microbes for plants

Microbes	*Plant beneficial property*	References
Pseudomonas aeruginosa	Antagonistic activity against Pythium *myriotylum*	Chakotiya et al. 2017
Flavobacterium spp.	Antagonistic activity against *Ralstonia*	Du Toit A. 2020
Stenotrophomonas, *Sphingobacterium*	Antagonistic activity against plant pathogens	Kwak et al. 2018
Bacillus, Sphingomonas, Acidibacter	Shoot and root stimulation	Hannula et al. 2021
B. velezensis, *Etridiazole*	Increases ginger production	Chowdhury et al. 2013
P. macerans	Antagonistic activity against pathogens	Sharma et al. 2013
Spathiphyllum, Cryptococcus	Antagonistic activity against *Cylindrocladium spathiphylli*	Liu et al. 2017
Pseudomonas sp.	Plant growth stimulation	Jasim et al. 2014
Nocardiopsis sp.	Antagonistic activity against phytopathogen	Sabu et al. 2017

as *Achromobacter, Rhizobium, Azoarcus, Sinorhizobium, Frankia, Allorhizobium, Bradyrhizobium, Azorhizobium, Burkholderia, Herbaspirillum, and Mesorhizobium* (Turan et al. 2016). Notable non-symbiotic nitrogen-fixing bacteria include *Herbaspirillum, Azoarcus, Azotobacter,* and *Gluconacetobacter* (Menendez and Garcia-Fraile 2017). Certain PGPR, such as ammonia nitrifiers like *Bacillus* sp. and *Pseudomonas* sp., convert organic nitrogen residues in soil organic matter into amino acids, which are subsequently broken down to produce ammonia through a process known as ammonification (Geisseler et al. 2010; Abdullaeva et al. 2024). Phosphorus (P) is a crucial element for plant growth and development, ranking just behind nitrogen in importance (Azziz et al. 2012). Phosphorus is present in soil in both organic and inorganic forms, but these are not easily accessible to plants. However, various PGPR such as *Pseudomonas* spp., *Agrobacterium* spp., *Bacillus* spp., *Azotobacter* spp., *Enterobacter* spp., *Rhizobium* spp., *Serratia* spp., and *Thiobacillus* spp. have been found to enhance the availability of poorly accessible phosphorus by solubilizing and mineralizing it (Alori and Fawole 2017). Certain bacterial strains of *Paenibacillus jamilae* can produce hydrolytic enzymes and antifungal metabolites, showing strong activity against soilborne pathogens (Wang et al. 2019).

Bacterial wilt, caused by *Ralstonia solanacearum*, greatly affects ginger production. However, biocontrol bacterial isolates like *Bacillus velezensis* have been proven to effectively minimize infection, enhance plant growth, and boost yield (Cui et al. 2024). This bacterium produces bioactive substances, including surfactin, iturin, and fengycin—antifungal lipopeptides—along with compounds like difficidin and bacilycin, which help combat bacterial pathogens such as *Xanthomonas oryzae* (Wu et al. 2015). Its capacity to form biofilms promotes plant growth and aids in the release of antimicrobial substances that defend against harmful microbes (Rabbee et al. 2019).

Indirect mechanisms involve the production of antibiotics, activation of systemic resistance (ISR), synthesis of hydrogen cyanide (HCN), competition for resources, and the creation of lytic enzymes like chitinases, proteases, cellulases, lipases, and 1,3-glucanases. These enzymes are capable of degrading portions of the cell walls of various pathogenic fungi (Kundan et al. 2015). The main method used by PGPR to counteract the harmful effects of plant pathogens is the production of one or more antibiotics (Raaijmakers and Mazzola 2012). Antibiotics are small molecular compounds produced by PGPR that harm other microorganisms by inhibiting essential enzymes and metabolic processes, which slows down their growth (Kundan et al. 2015). Certain plant pathogens can become resistant to specific antibiotics; thus, PGPR's ability to produce multiple antibiotics increases their effectiveness as antagonistic agents against these pathogens (Glick et al. 2007). Antibiotics produced by antagonistic microbes have both inhibitory and lethal effects on soil-borne plant pathogens (Bhattacharyya et al. 2016). *Bacillus* spp. and *Pseudomonas* spp. are recognized for producing a range of antibiotics, such as tas A, subtilin, bacilysin, sublancin, subtilosin, chlorotetain, fengycin, iturin, and bacillaene. Hydrogen cyanide (HCN) is a secondary metabolite that serves as a potent biocontrol agent against weeds. HCN produced by PGPR disrupts the electron transport chain and energy supply to cells, causing cell death. As a result, HCN-producing rhizobacteria are powerful agents for biological weed control (Kundan et al. 2015).

Plant growth-promoting rhizobacteria (PGPR) are vital biofertilizers that enhance plant growth through direct mechanisms, including nitrogen fixation, phosphate solubilization, and phytohormone production, as well as indirect mechanisms like pathogen inhibition and induced systemic resistance. Their multifunctionality not only enhances crop yields and nutrient absorption but also decreases dependence on chemical inputs, offering an environmentally friendly solution for sustainable agriculture. By producing antibiotics, hydrogen cyanide, and lytic enzymes (Ignatova et al. 2022), PGPR effectively shield plants from pathogens and weeds, leading to healthier crops and improved soil health.

CONCLUSION AND FUTURE PERSPECTIVES

Sustainable ginger cultivation demands a shift from conventional farming methods reliant on chemical inputs to more eco-friendly and resource-efficient practices. Microbial fertilizers, with their ability to enhance soil fertility, boost plant growth, and protect crops from pathogens, represent a transformative approach to agriculture. This review highlights the critical role of beneficial microbes, including *Bacillus velezensis* and other plant growth-promoting rhizobacteria (PGPR), in improving nutrient dynamics, suppressing diseases, and fostering resilience under diverse conditions. Additionally, integrating microbial fertilizers with advanced cultivation techniques, such as hydroponics and organic farming, provides a robust framework for increasing productivity while maintaining environmental health. By adopting these sustainable strategies, ginger farmers can achieve higher yields, better-quality rhizomes, and healthier ecosystems. Further research into microbial diversity and its functional roles in ginger cultivation will be essential to maximize the benefits of these innovative solutions.

REFERENCES

1. Akinwumi GS, Aliku O, Oshunsanya SO, Aiyelari EA (2022) Organic fertilizer and mulch effects on the physical properties of an alfisol and ginger (*Zingiber officinale*) yield. Commun Soil Sci Plant Anal 53:2922–2934. https://doi.org/10.1080/00103624.2022.2096896
2. Alori ET, Fawole OB (2017) Microbial inoculants-assisted phytoremediation for sustainable soil management. In: Phytoremediation. Springer International Publishing, Cham, pp 3–17
3. Abdullaeva Y, Mardonova G, Eshboev F, Cardinale M, Egamberdieva D (2023) Chickpea-associated endophytes and their potential in plant health and fitness. AIMS Microbiology 10:489-506, https://doi.org/10.3934/microbiol.2024024
4. Alshrouf A (2017) Hydroponics, Aeroponic and Aquaponic as Compared with Conventional Farming. American Scientific Research Journal for Engineering 2313–4410
5. Anasori G (2008) Effects of light and differentiation on gingerol and zingiberene production in callus culture of *Zingiber officinale* Rosc. Res Pharm Sci 3:59–63
6. Andriyani R, Budiati TA, Pudjiraharti S (2015) Effect of extraction method on total flavonoid, total phenolic content, antioxidant and anti-bacterial activity of *Zingiber officinale* rhizome. Procedia Chem 16:149–154. https://doi.org/10.1016/j.proche.2015.12.023
7. Anh NH, Kim SJ, Long NP, Min JE, Yoon YC, Lee EG, Kim M, Kim TJ, Yang YY, Son EY, Yoon SJ, Diem NC, Kim HM, Kwon SW (2020) Ginger on human health: A comprehensive systematic review of 109 randomized controlled trials. Nutrients 12:157. https://doi.org/10.3390/nu12010157
8. Azziz G, Bajsa N, Haghjou T, Taulé C, Valverde Á, Igual JM, Arias A (2012) Abundance, diversity and prospecting of culturable phosphate solubilizing bacteria on soils under crop–pasture rotations in a no-tillage regime in Uruguay. Appl Soil Ecol 61:320–326. https://doi.org/10.1016/j.apsoil.2011.10.004
9. Arora N, Egamberdieva D, Mehnaz S, Li WJ, Mishra J (2021) Salt tolerant rhizobacteria: for better productivity and remediation of saline soils. Front. Microbiol. 12:660075, https://doi.org/10.3389/fmicb.2021.660075
10. Bhattacharyya PN, Goswami MP, Bhattacharyya LH (2016) Perspective of beneficial microbes in agriculture under changing climatic scenario: a review. J Phytol 8:26. https://doi.org/10.19071/jp.2016.v8.3022
11. Carrión VJ, Perez-Jaramillo J, Cordovez V, Tracanna V, de Hollander M, Ruiz-Buck D, Mendes LW, van Ijcken WFJ, Gomez-Exposito R, Elsayed SS, Mohanraju P, Arifah A, van der Oost J, Paulson JN, Mendes R, van Wezel GP, Medema MH, Raaijmakers JM (2019) Pathogen-induced activation of disease-suppressive functions in the endophytic root microbiome. Science 366:606–612. https://doi.org/10.1126/science.aaw9285
12. Chakotiya AS, Tanwar A, Narula A, Sharma RK (2017) Zingiber officinale: Its antibacterial activity on Pseudomonas aeruginosa and mode of action evaluated by flow cytometry. Microb Pathog 107:254–260. https://doi.org/10.1016/j.micpath.2017.03.029
13. Chen W, Li J, Yuan H, You L, Wang T, Cao Z (2022) Microbial diversity, culture conditions, and application effect of YSJ: A composite microbial system for degradation of Yanshan ginger branches and leaves. PLoS One 17:e0278701. https://doi.org/10.1371/journal.pone.0278701
14. Cho S-T, Chang H-H, Egamberdieva D, Kamilova F, Lugtenberg B, Kuo C-H (2015) Genome analysis of Pseudomonas fluorescens PCL1751: A Rhizobacterium that controls root diseases and alleviates salt stress for its plant host. PLoS One 10:e0140231. https://doi.org/10.1371/journal.pone.0140231
15. Chowdhury SP, Dietel K, Rändler M, Schmid M, Junge H, Borriss R, Hartmann A, Grosch R (2013) Effects of Bacillus amyloliquefaciens FZB42 on lettuce growth and health under pathogen pressure and its impact on the rhizosphere bacterial community. PLoS One 8:e68818. https://doi.org/10.1371/journal.pone.0068818
16. Cui W, Zhang J, Wang W, Wu X, Luo X, Zou Y, Chen K, He P (2024) Screening native Bacillus strains as potential biological control agents against ginger bacterial wilt and for promoting plant growth. Biol Control 192:105510. https://doi.org/10.1016/j.biocontrol.2024.105510
17. Devi R, Kaur T, Negi R, Kour D, Chaubey KK, Yadav AN (2023) Indigenous plant growth-promoting rhizospheric and endophytic bacteria as liquid bioinoculants for growth of sweet pepper (Capsicum annuum L). Biologia 78:2623–2633
18. Du Toit A (2020) At the root of the problem. Nat Rev Microbiol 18:2–3. https://doi.org/10.1038/s41579-019-0300-8
19. Egamberdieva D, Wirth S, Alqarawi AA, Abd_Allah EF, Hashem A (2017a) Phytohormones and beneficial microbes: Essential components for plants to balance stress and fitness. Front Microbiol. 8: 2104. https://doi.org/10.3389/fmicb.2017.02104
20. Egamberdieva D, Wirth S, Behrendt, U, Parvaiz A, Berg G. (2017b) Antimicrobial activity of medicinal plants correlates with the proportion of antagonistic endophytes. Front Microb 8:199. https://doi.org/10.3389/fmicb.2017.00199
21. Egamberdieva D, Davranov K, Wirth S, Hashem A, Abd_Allah EF (2017c) Impact of soil salinity on the plant-growth – promoting and biological control abilities of root associated bacteria. Saudi J Biological Sciences 24(7): 1601–1608. https://doi.org/10.1016/j.sjbs.2017.07.004
22. Egamberdieva D, Alimov J, Shurigin V, Alaylar B, Wirth S, Bellingrath-Kimura SD (2021) Diversity and plant growth-promoting ability of endophytic, halotolerant bacteria associated with *Tetragonia tetragonioides* (Pall.) Kuntze. Plants 11:49. https://doi.org/10.3390/plants11010049
23. Egamberdieva D, Li Li, Lindström K, Räsänen L (2015) A synergistic interaction between salt tolerant Pseudomonas and Mezorhizobium strains improves growth and symbiotic

performance of liquorice (*Glycyrrhiza uralensis* Fish.) under salt stress . Appl Microb Biotech 100(6):2829-2841. https://doi.org/10.1007/s00253-015-7147-3

24. Egamberdieva D, Kamilova F, Validov S, Gafurova L, Kucharova Z, Lugtenberg B (2008) High incidence of plant growth-stimulating bacteria associated with the rhizosphere of wheat grown on salinated soil in Uzbekistan. Environ Microbiol 10:1–9. https://doi.org/10.1111/j.1462-2920.2007.01424.x
25. Geisseler D, Horwath WR, Joergensen RG, Ludwig B (2010) Pathways of nitrogen utilization by soil microorganisms – A review. Soil Biol Biochem 42:2058–2067. https://doi.org/10.1016/j.soilbio.2010.08.021
26. Glick BR, Cheng Z, Czarny J, Duan J (2007) Promotion of plant growth by ACC deaminase-producing soil bacteria. Eur J Plant Pathol 119:329–339. https://doi.org/10.1007/s10658-007-9162-4
27. Hannula SE, Heinen R, Huberty M, Steinauer K, De Long JR, Jongen R, Bezemer TM (2021) Persistence of plant-mediated microbial soil legacy effects in soil and inside roots. Nat Commun 12:5686. https://doi.org/10.1038/s41467-021-25971-z
28. Hasan MK, Alam MS, Nahar K (2022) Endophytic Microbes in Ginger Stems: A Study on Growth Promotion and Biotic Stress Resistance. J Plant Science Biotech 14:321–330
29. Hashem A, Alqarawi AA, Al-Hazzani AA, Egamberdieva D, Tabassum B, Abd_Allah EF (2019) Cadmium stress tolerance in plants and role of beneficial soil microorganisms. In: Microorganisms for Sustainability. Springer Singapore, Singapore, pp 213–234
30. Huang Z, Liu B, Yin Y, Liang F, Xie D, Han T, Liu Y, Yan B, Li Q, Huang Y, Liu Q (2021) Impact of biocontrol microbes on soil microbial diversity in ginger (*Zingiber officinale* Roscoe). Pest Manag Sci 77:5537–5546. https://doi.org/10.1002/ps.6595
31. Ignatova L, Usmanova A, Brazhnikova Y, Omirbekova A, Egamberdieva D, Mukasheva T, Kistaubayeva A, Savitskaya I, Karpenyuk T, Goncharova A (2022) Plant probiotic endophytic *Pseudomonas flavescens* D5 strain for protection of barley plants from salt stress. Sustainability 14:15881. https://doi.org/10.3390/su142315881
32. Datta S, Jana JC, Bhaisare PT, Thapa A, Islam S (2018) Effect of organic source of nutrients and biofertilizers on growth, yield and quality of ginger (*Zingiber officinale* Rosc.). J Pharm Phytochem 7(6):2311-2314
33. Jones R, Patel K, Wang L (2018) Optimizing greenhouse conditions for ginger production. J Horticultural Science 12:78–85
34. Kaari M, Manikkam R, Annamalai KK, Joseph J (2023) Actinobacteria as a source of biofertilizer/biocontrol agents for bio-organic agriculture. J Appl Microbiol 134. https://doi.org/10.1093/jambio/lxac047
35. Kannan M, Elavarasan G, Balamurugan A, Dhanusiya B, Freedon D (2022) Hydroponic farming – A state of art for the future agriculture. Mater Today 68:2163–2166. https://doi.org/10.1016/j.matpr.2022.08.416
36. Kizhakkayil J, Sasikumar B (2011) Diversity, characterization and utilization of ginger: a review. Plant Genet Resour 9:464–477. https://doi.org/10.1017/s1479262111000670
37. Kubra IR (2012) An impression on current 326 Yaakob et al. developments in the technology, chemistry, and biological activities of ginger (*Zingiber officinale* Roscoe). Crit Rev Food Sci Nutr 651–688
38. Kumar S, Pandey P, Gupta R (2020) Phyllosphere microbes and their role in enhancing disease resistance in ginger leaves (*Zingiber zerumbet*). Phytomicrobiome J 8:45–56
39. Kumar S, Verma A, Singh P (2022) Effects of microbial fertilizers in hydroponic ginger cultivation. Plant Nutrition Research 15:45–52
40. Kundan R, Pant G, Jadon N, Agrawal PK (2015) Plant growth promoting rhizobacteria: Mechanism and current prospective. J Fertil Pestic 06. https://doi.org/10.4172/2471-2728.1000155
41. Kwak M-J, Kong HG, Choi K, Kwon S-K, Song JY, Lee J, Lee PA, Choi SY, Seo M, Lee HJ, Jung EJ, Park H, Roy N, Kim H, Lee MM, Rubin EM, Lee S-W, Kim JF (2018) Rhizosphere microbiome structure alters to enable wilt resistance in tomato. Nat Biotechnol 36:1100–1109. https://doi.org/10.1038/nbt.4232
42. Kwon MJ, Hwang Y, Lee J, Ham B, Rahman A, Azam H, Yang J-S (2021) Waste nutrient solutions from full-scale open hydroponic cultivation: Dynamics of effluent quality and removal of nitrogen and phosphorus using a pilot-scale sequencing batch reactor. J Environ Manage 281:111893. https://doi.org/10.1016/j.jenvman.2020.111893
43. Lee C (2018) Sustainable crop production through hydroponic techniques. Intern J Crop Science 19:225–238
44. Leroux J, Beauregard PB, Bellenger J-P (2024) *Azotobacter vinelandii* N2 fixation increases in co-culture with the PGPR *Bacillus subtilis* in a nitrogen concentration-dependent manner. Appl Environ Microbiol 90:e0152824. https://doi.org/10.1128/aem.01528-24
45. Lewis D, Carter J, Brown R (2024) Antagonistic microbes in jamaica ginger rhizosphere and their role in disease suppression. Caribbean J Microb Ecol 25:56–72
46. Li Y, Tran VH, Duke CC, Roufogalis BD (2012) Gingerols of *Zingiber officinale* enhance glucose uptake by increasing cell surface GLUT4 in cultured L6 myotubes. Planta Med 78:1549–1555. https://doi.org/10.1055/s-0032-1315041
47. Liu Y, Wu L, Wu X, Li H, Liao Q, Zhang X, Sun Z, Li W (2017) Analysis of microbial diversity in soil under ginger cultivation. Scientifica 8256865. https://doi.org/10.1155/2017/8256865
48. Liu Z, Budiharjo A, Wang P, Shi H, Fang J, Borriss R, Zhang K, Huang X (2013) The highly modified microcin peptide plantazolicin is associated with nematicidal activity of Bacillus amyloliquefaciens FZB42. Appl Microbiol Biotechnol 97:10081–10090. https://doi.org/10.1007/s00253-013-5247-5
49. Mansfield J, Genin S, Magori S, Citovsky V, Sriariyanum M, Ronald P, Dow M, Verdier V, Beer SV, Machado MA, Toth I, Salmond G, Foster GD (2012) Top 10 plant pathogenic bacteria in molecular plant pathology. Mol Plant Pathol 13:614–629. https://doi.org/10.1111/j.1364-3703.2012.00804.x
50. Mardonova G, Shurigin V, Eshboev F, Egamberdieva D. (2024) Potential plant benefits of endophytic microorganisms associated with halophytes *Glycyrrhiza glabra* L. AIMS Microbiology, 10 (4): 859-879, https://doi.org/10.3934/microbiol.2024037
51. McKay DL, Chen C-YO, Zampariello CA, Blumberg JB (2015) Flavonoids and phenolic acids from cranberry juice are bioavailable and bioactive in healthy older adults. Food Chem 168:233–240. https://doi.org/10.1016/j.foodchem.2014.07.062
52. Meena R, Sharma P, Gupta S (2021) Integration of ginger in agroforestry systems for sustainable farming. Agroec Sust Syst 8:91–100
53. Menendez E, Garcia-Fraile P (2017) Plant probiotic bacteria: solutions to feed the world. AIMS Microbiol 3:502–524. https://doi.org/10.3934/microbiol.2017.3.502

54. Mia MS, Apu M, Halder MAI, Rahman J, Islam MF (2015) A comprehensive review on region based traditional ayurvedic practitioner's plants secondary metabolites and their phytochemical activities in Bangladesh. J Pharm Phytoch 3:202–216
55. Parray AP, Jan S, Kamili AN, Qadri RA, Egamberdieva D. Ahmad P (2016) Current perspectives on plant growth promoting rhizobacteria. Plant Growth Reg 35: 877-902. https://doi.org/10.1007/s00344-016-9583-4
56. Parray JA, Egamberdieva D, Abd_Allah EF, Sayyed RZ (2023) Soil microbiome metabolomics: a way forward to sustainable intensification. Front Sustain Food Syst 7. https://doi.org/10.3389/fsufs.2023.1251054
57. Raaijmakers JM, Mazzola M (2012) Diversity and natural functions of antibiotics produced by beneficial and plant pathogenic bacteria. Annu Rev Phytopathol 50:403–424. https://doi.org/10.1146/annurev-phyto-081211-172908
58. Rabbee MF, Ali MS, Choi J, Hwang BS, Jeong SC, Baek KH (2019) *Bacillus velezensis*: A valuable member of bioactive molecules within plant microbiomes. Molecules 24:1046. https://doi.org/10.3390/molecules24061046
59. Rahman A, Nasir A, Junaidi A (2019) Effect of mycorrhizal fungi on nutrient uptake and growth of yellow ginger in hydroponic system. J Soil Biology Ecology 22:89–96
60. Randrianjohany T, Rakotomalala T, Rasoazanany E (2023) Secondary metabolite-producing microbes in blue ginger flowers and their antioxidant properties. J Tropical Microb 19:98–112
61. Rao M, Singh N (2019) Organic farming of ginger: A sustainable approach. J Organic Agric 22:134–140
62. Rokunuzzaman M, Hayakawa A, Yamane S, Tanaka S, Ohnishi K (2016) Effect of soil disinfection with chemical and biological methods on bacterial communities. Egypt J Basic Appl Sci 3:141–148. https://doi.org/10.1016/j.ejbas.2016.01.003
63. Sabu R, Soumya KR, Radhakrishnan EK (2017) Endophytic *Nocardiopsis* sp. from *Zingiber officinale* with both antiphytopathogenic mechanisms and antibiofilm activity against clinical isolates. 3 Biotech 7:115. https://doi.org/10.1007/s13205-017-0735-4
64. Santi C, Bogusz D, Franche C (2013) Biological nitrogen fixation in non-legume plants. Ann Bot 111:743–767. https://doi.org/10.1093/aob/mct048
65. Sanwal SK, Yadav RK, Singh PK (2007) Effect of types of organic manure on growth, yield and quality parameters of ginger (*Zingiber officinale*). The Indian J Agric Sci 77:67–72
66. Sharma P, Singh V, Bhardwaj S (2021) Pathogenic microbes in ginger rhizomes: detection, control, and sustainable management approaches. Plant Pathology Review 12:211–224
67. Sharma SB, Sayyed RZ, Trivedi MH, Gobi TA (2013) Phosphate solubilizing microbes: sustainable approach for managing phosphorus deficiency in agricultural soils. Springer plus 2:587. https://doi.org/10.1186/2193-1801-2-587
68. Shurigin V, Alimov J, Tashkhan Gulyamova, Davranov K, Egamberdieva D. 2022. The diversity of bacterial endophytes from *Iris pseudacorus* L. and their antifungal traits. Curr Res Microbial Sciences, https://doi.org/10.1016/j.crmicr.2022.100133
69. Singh A, Patel M, Sharma R, Kumar P (2021) Role of plant growth-promoting rhizobacteria (PGPR) in improving ginger (*Zingiber officinale*) yield and nutrient uptake in sustainable agriculture. J Agric Microb 15:123–135
70. Smith J (2020) Traditional farming practices for ginger cultivation. Agricultural J 35:215–222
71. Smith J, Brown L (2017) Hydroponics in modern agriculture: A Review of Benefits and Applications. J Agricultural Sciences 14:123–136
72. Soeparjono S (2016) The effect of media composition and organic fertilizer concentration on the growth and yield of red ginger rhizome (*Zingiber officinale* rosc.). Agric Agric Sci Procedia 9:450–455. https://doi.org/10.1016/j.aaspro.2016.02.162
73. Syafitri DM, Levita J, Mutakin M, Diantini A (2018) A Review: Is Ginger (Zingiber officinale var. Roscoe) Potential for Future Phytomedicine? Indones J Appl Sci 8. https://doi.org/10.24198/ijas.v8i1.16466
74. Tan YS, Wong CL, Lee KS (2020) Endophytic fungi associated with Halia Bentong ginger and their potential in plant growth promotion and stress tolerance. Mycological Research 18:257–267
75. Turan M, Kitir N, Alkaya Ü, Günes A, Tüfenkçi S, Yildirim E, Nikerel E (2016) Making soil more accessible to plants: The case of plant growth promoting rhizobacteria. In: Plant Growth. InTech
76. Wang C-W, Michelle Wong J-W, Yeh S-S, Eric Hsieh Y, Tseng C-H, Yang S-H, Tang S-L (2022) Soil bacterial community may offer solutions for ginger cultivation. Microbiol Spectr 10:e0180322. https://doi.org/10.1128/spectrum.01803-22
77. Wang PH, Chung CY, Lin YS, Yeh Y (2003) Use of polymerase chain reaction to detect the soft rot pathogen, *Pythium myriotylum*, in infected ginger rhizomes. Lett Appl Microbiol 36:116–120. https://doi.org/10.1046/j.1472-765x.2003.01272.x
78. Wang X, Li Q, Sui J, Zhang J, Liu Z, Du J, Xu R, Zhou Y, Liu X (2019) Isolation and characterization of antagonistic bacteria *Paenibacillus jamilae* HS-26 and their effects on plant growth. Biomed Res Int 2019:3638926. https://doi.org/10.1155/2019/3638926
79. Wohlmuth H, Leach DN, Smith MK, Myers SP (2005) Gingerol content of diploid and tetraploid clones of ginger (*Zingiber officinale* Roscoe). J Agric Food Chem 53:5772–5778. https://doi.org/10.1021/jf050435b
80. Wu L, Wu H-J, Qiao J, Gao X, Borriss R (2015) Novel routes for improving biocontrol activity of *Bacillus* based bioinoculants. Front Microbiol 6:1395. https://doi.org/10.3389/fmicb.2015.01395
81. Zhao Y, Chen Q, Fang W (2018) Nitrogen-fixing Bacteria Associated with Ginger Rhizome and Their Role in Growth Enhancement. Chinese Journal of Microbiology 36:501–510