Heliyon 10 (2024) e40522

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Review article

Rhizobacterial volatile organic compounds: Implications for agricultural ecosystems' nutrient cycling and soil health

Faryal Babar Baloch [a], Nan Zeng [a], Haiyang Gong [b], Zhiyong Zhang [a,**], Ning Zhang [b], Sadia Babar Baloch [c], Shahzaib Ali [c], Bingxue Li [a,*]

[a] *College of Land and Environment, Shenyang Agricultural University, Shenyang, 110866, China*
[b] *College of Bioscience and Biotechnology, Shenyang Agricultural University, Shenyang, 110866, China*
[c] *Faculty of Agriculture and Technology, University of South Bohemia in České Budějovice, Branišovská 1645/31a, 37005, Ceske Budejovice, Czech Republic*

ARTICLE INFO

Keywords:
Rhizobacterial VOCs
Plant-microbe interactions
Nutrient cycling
Agricultural sustainability
Soil health

ABSTRACT

Plant growth-promoting rhizobacteria (PGPR) have emerged as key players in sustainable agriculture due to their ability to enhance plant growth, nutrient uptake, and disease resistance. A significant aspect of PGPR is the emission of volatile organic compounds (VOCs), which serve as signaling molecules that influence various physiological processes in plants. This review article explores the complex interactions between rhizobacterial VOCs and soil health, focusing particularly on their role in nutrient cycling within agricultural ecosystems. By investigating the mechanism of production and release of VOCs by rhizobacteria, along with impacts on soil properties and microbial communities. We aim to highlight the potential of rhizobacterial volatile organic compounds (VOCs) for sustainable agricultural management. Additionally, we discuss the role of rhizobacterial VOCs in promoting root growth, nutrient uptake, and enhancing nutrient cycling processes. By providing insights into these mechanisms, this review offers tailored strategies for exploring the potential of rhizobacterial VOCs to optimize nutrient availability, enhance soil fertility, and address environmental challenges in agriculture. Exploring the potential of rhizobacterial VOCs presents an opportunity to establish sustainable and resilient agricultural systems that significantly enhance global food security and promote environmental stewardship.

1. Introduction

Plant growth-promoting rhizobacteria (PGPR), commonly known as rhizobacteria. They are beneficial microorganisms that form a symbiotic relationship with plant roots [1]. These microorganisms have demonstrated their abilities to enhance plant growth, improve nutrient uptake, and strengthen plant resistance to pathogens [2,3]. Moreover, rhizobacteria emit a diverse variety of volatile organic compounds (VOCs), low molecular weight compounds that readily vaporize at room temperature [4]. Additionally, the production of VOCs by rhizobacteria contributes to the complexity and diversity of the soil microbiome, influencing ecosystem functions such as nutrient cycling and soil health [5].

Research has highlighted the vital functions of rhizobacterial volatile organic compounds (VOCs) in facilitating plant-microbe

* Corresponding author.
** Corresponding author.
E-mail addresses: zhangzy@syau.edu.cn (Z. Zhang), libingxue@syau.edu.cn (B. Li).

https://doi.org/10.1016/j.heliyon.2024.e40522
Received 28 July 2024; Received in revised form 15 November 2024; Accepted 18 November 2024
Available online 20 November 2024

interactions and influencing soil microbial communities [4,6]. These compounds act as signaling molecules that regulate various physiological processes in plants, influencing their growth and development. Some specific VOCs, such as Aminocyclopropane-1-carboxylate (ACC) Deaminase, 2,3-butanediol, Indole-3-acetic acid (IAA), 2,4-diacetyl phloroglucinol (DAPG), and Dimethyl sulfide (DMS), have been discovered to encourage root development, improve nutrient acquisition efficiency, and improve overall plant growth [7,8]. Additionally, VOCs mediate plant-plant interactions, by exhibiting allelopathic effects that suppress the growth of neighboring plant species [9,10]. Furthermore, VOCs play a crucial role in facilitating communication with beneficial organisms, such as mycorrhizal fungi and other rhizobacteria. They enhance nutrient uptake [11], plant defense against pathogens [12], and induce stress tolerance [5].

Understanding the practical applications of utilizing rhizobacterial VOCs in agriculture is of great importance. These applications encompass crop protection, plant growth promotion, soil health improvement, stress tolerance induction, enhanced nutrient cycling, bioremediation, microbial community modulation, and promotion of greenhouse gas mitigation [13–15]. By utilizing the potential of rhizobacterial VOCs, sustainable agricultural practices can be developed, benefiting both the environment and long-term agricultural viability [16]. Fig. 1 explores the mechanisms of VOC production and emission by rhizobacteria, their impacts on soil properties and microbial communities, and their potential for sustainable agricultural practices. It emphasizes the effects of rhizobacterial VOCs on root growth, nutrient uptake, and enhancing nutrient cycling processes [17].

In this comprehensive review, we aim to explore the practical applications of rhizobacterial VOCs in sustainable agriculture. By examining the current scientific research, we will provide insights into how these VOCs can be utilized to enhance crop productivity, improve soil health, and mitigate environmental challenges. Incorporating rhizobacterial volatile organic compounds (VOCs) into agricultural practices. This is supported by effective policies and practices. It can improve the sustainability and resilience of agricultural systems.

1.1. Effects of R-VOCs on soil nutrients

Rhizobacteria are essential agents in the modulation of soil nutrients via diverse pathways. Research indicates that the application of PGPR through seed inoculation before sowing can mitigate the downward movement of biogenic nutrients and water-soluble

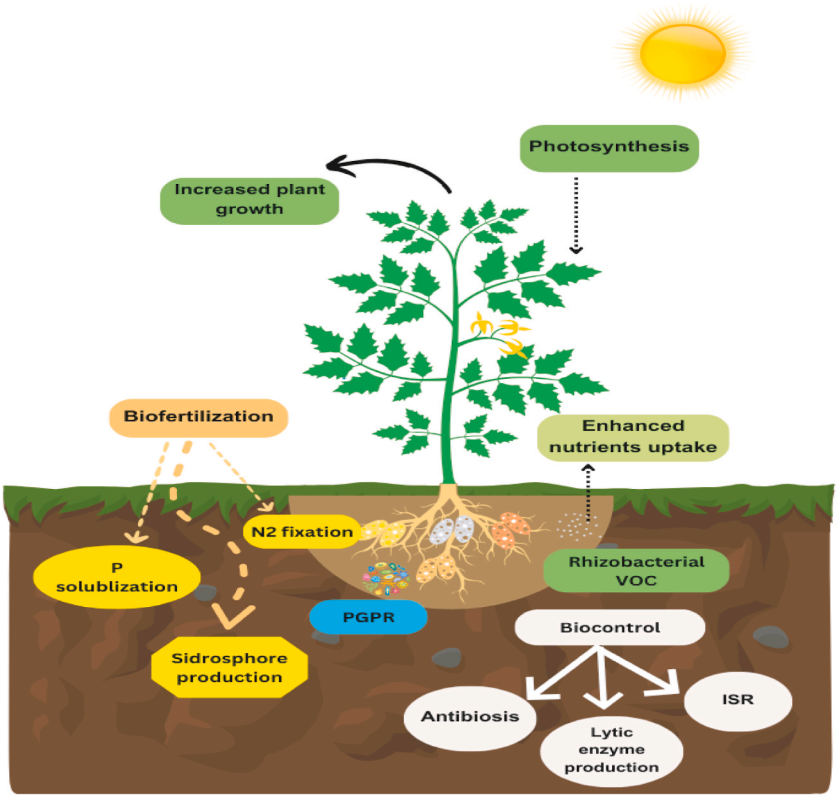

Fig. 1. Diagrammatic representations of the interactions and effects of Rhizobacteria. Rhizobacteria play a beneficial role in agricultural ecosystems by releasing volatile organic compounds (VOCs). These VOCs enhance soil health by promoting biological nitrogen fixation and phosphorus solubility, both essential for plant growth. Additionally, they enhance plants' resilience to pests and disease by supporting beneficial microbial communities, inducing systemic resistance (ISR), and utilizing available nutrients. Overall, rhizobacterial VOCs contribute to improved plant growth and nutrient availability in agricultural soils.

organic substances in the soil profile, thereby reducing nutrient depletion [18]. Schulz-Bohm et al. [19] highlighted the substantial impact of Rhizobacterial volatile organic compounds (R-VOCs) on soil nutrient dynamics. Their research revealed a significant restructuring of soil microbial communities, characterized by a reduction in alpha diversity and notable shifts in the relative abundance of key bacterial phyla, including *Proteobacteria* and *Firmicutes*. Furthermore, Wang et al. [20] demonstrated the synergistic effects of R-VOCs with nutrients, resulting in enhanced plant growth, increased enzymatic activity in the rhizosphere soil, and improved efficiency in the phytoextraction of heavy metals such as cadmium and zinc. Moreover, Yuan et al. [21] provided insights into the positive impact of rhizobacterial fertilizers on soil nitrogen ion concentrations, rice yields, and reduced reliance on chemical fertilizers, promoting sustainable agricultural practices. In summary, these studies collectively underscore the pivotal role of R-VOCs in shaping soil nutrient dynamics and enhancing plant growth in agricultural ecosystems.

1.2. Rhizobacteria and VOC emission

1.2.1. Rhizobacteria and their role in plant interactions

The presence of distinct volatiles in specific plant-soil ecosystems results from the interaction between bacteria and the metabolism of plants [22]. These volatiles, occurring in various concentrations in the biosphere, serve as ideal chemicals for conveying information over long distances [23]. Rhizobacteria, residing in the rhizosphere consume nutrient-rich substances released by plants, which helps enhance plant growth [24].

Dimethyl disulfide released by rhizobacteria has bacteriostatic effects on plant pathogens, such as *Agrobacteriumtumefaciens* and *Agrobacterium vitis* [25]. Rhizobacteria can induce systemic resistance in plants, activating defense mechanisms and enhancing resistance against pathogens [26]. Some rhizobacteria act as biocontrol agents by competing with pathogens for resources and producing antimicrobial compounds such as antibiotics and volatile organic compounds (VOCs) to suppress pathogen growth [27,28]. While numerous rhizobacteria provide beneficial outcomes, a few strains are dangerous, showing pathogenic developments and causing diseases in plant life [29]. Sustainable agriculture and disease control require an understanding of the specific relationships between rhizobacteria and plants, along with their influence on plant health and growth [30].

1.3. Mechanisms of VOCs production and emission by rhizobacteria

Recent advances have shown that rhizobacteria produce and release VOCs using multiple mechanisms. One key pathway for VOC production is terpene synthesis. This involves specific enzymatic reactions. For example, sesquiterpene synthase from *Streptomyces coelicolor* catalyzes the synthesis of epi-isozizaene by a carbocation-dependent process controlled by different amino acid residues [31]. The methylation pathway required for producing methyl-containing VOCs works through a methyltransferase-dependent mechanism. A well-studied example is S-adenosylmethionine (SAM) in halo-methane transfer in marine bacteria, which methylates halogen ions to form methyl halides [32]. Another noteworthy mechanism is the decarboxylation of amino acids, as shown by lysine decarboxylase in *Escherichia coli*, which uses a pyridoxal 5′-phosphate (PLP)-dependent reaction to convert lysine to cadaverine [33].

VOCs are primarily released through passive diffusion, with the release rate influenced by factors such as molecular weight and lipid composition [34]. Transport activity is a critical factor influencing VOC emission, as evidenced by the distinct emission patterns documented in previous studies [35]. Recent research indicates a porous secretion mechanism that facilitates the transport of microbial volatile organic compounds (VOCs), supported by findings showing microparticles capable of penetrating bacterial membranes [36]. The processes governing the production and secretion of these compounds are tightly regulated by intricate systems that respond to environmental signals and changes in population density. The GacS/GacA dual regulatory system in *Pseudomonas* species modulates the expression of VOC synthesis genes through a phosphorylation pathway that is activated by specific environmental signals [37]. The production of VOCs by rhizobacteria is influenced by various factors, including plant root exudates, which serve as a source of carbon and energy [38]. Environmental conditions, such as temperature and nutrient availability, play a role in regulating VOC emissions [39]. Despite these advances, further research is needed to fully explore the mechanisms and biological significance of VOC production by rhizobacteria [36,40].

1.4. Rhizobacterial VOCs and soil health

1.4.1. Microbial species and VOCs: shaping soil properties and plant health

Microbial species and VOCs significantly regulate soil properties and enhance plant health, offering sustainable alternatives for managing plant diseases. These VOCs cause soil swelling by inhibiting pathogens and increasing soil compaction [41]. They also modify soil properties, control the availability of nutrients, and influence the development of microbial communities [42]. VOCs' importance is highlighted while evaluating their function in facilitating beneficial interactions in the soil ecosystem. For instance, VOCs released by certain fungi, such as those in the genus *Fusarium*, have been shown to improve root architecture in plants such as *Arabidopsis*, thus significantly influencing plant development and general vigor [43]. This improvement in the root system facilitates greater absorption of nutrients, increases the ability to retain water, and enhances resilience to environmental stress. VOCs also act as important signaling molecules that facilitate communication between plants and their associated microbial communities. This interaction supports a collaborative relationship, increasing plant health and disease resilience [44].

Microbial VOCs are an environmentally sustainable alternative to chemical pesticides, which are often associated with adverse environmental effects and health risks. By exploring the natural properties of microbial VOCs, farmers can reduce their reliance on conventional agricultural inputs and adopt more sustainable practices [44]. Additionally, understanding the signaling pathways associated with VOCs can lead to innovative crop management strategies that enhance pathogen resilience while maintaining soil health [45]. Table 1 provides a comprehensive overview of the effects of different types of microbial species and Volatile Organic Compounds (VOCs) on soil characteristics, emphasizing their significance in maintaining soil quality, promoting plant development, and contributing to the overall functionality of ecosystems.

1.5. Soil health: Rhizobacteria and carbon dynamics

Rhizobacteria, particularly Plant Growth-Promoting Rhizobacteria (PGPR), are key players in maintaining soil health and agricultural productivity [46]. These beneficial bacteria contribute to nutrient cycling by promoting processes such as biological nitrogen fixation and phosphorus solubilization [58]. Moreover, they secrete antibiotics and siderophores to suppress harmful soil-borne pathogens, safeguarding plant health [59]. Additionally, rhizobacteria improve soil structure and water retention by producing extracellular polymeric substances (EPS) [60]. This microbial activity results in a range of positive effects on soil health, fertility, and plant growth.

Simultaneously, organic matter decomposition is essential for promoting stable soil organic carbon (SOC) and significantly contributes to addressing climate change. The stability of SOC is influenced by a variety of factors, including soil-forming processes, changes in land cover, and the method of tillage. These processes and land cover variations have significant impacts on both SOC stocks and stability [61]. Different tillage systems, including zero-tillage, can influence SOC concentration and stability within soil aggregates, affecting carbon retention and greenhouse gas emissions [62]. Furthermore, the application of highly stabilized organic amendments has been shown to increase SOC levels. This enhancement promotes soil health and productivity while reducing CO_2 emissions, supporting climate-smart agriculture practices [63]. Understanding the mechanisms underlying SOC formation and stability is crucial for implementing effective climate change mitigation strategies.

1.6. Mechanisms of VOCs: chemical communication in soil ecosystems

Volatile organic compounds (VOCs) play a crucial role in chemical communication within soil ecosystems, facilitating interactions between various organisms and influencing ecosystem processes [64]. This form of communication, often referred to as infochemicals or semiochemicals, allows soil inhabitants to interact, coordinate activities, and respond to environmental changes [65]. Plants, microorganisms, and soil fauna emit and secrete VOCs into the environment of the soil, while VOCs can diffuse through soil pores. This process facilitates long-distance communication between organisms that lack direct contact with one another [66].

In plant-microbe interactions, plants release root exudates containing VOCs, which attract beneficial microorganisms, repel plant pathogens, and influence microbial community composition in the rhizosphere [67]. Soil microorganisms use VOCs for quorum sensing, regulating gene expression, and coordinating group behaviors within microbial communities [64]. VOCs mediate plant-plant interactions, including competition and defense responses; for instance, plants under attack by herbivores may release VOCs that induce defense responses in neighboring plants [68].

1.7. Rhizobacterial VOCs and nutrient cycling

1.7.1. VOCs as signaling molecules for nutrient acquisition by plants

VOCs serve as crucial signaling molecules that facilitate nutrient acquisition by plants through complex interactions with soil microorganisms. Soil bacteria and fungi produce a diverse array of VOCs, which encompass various chemical classes, including alcohols, ketones, aldehydes, alkenes, aromatic compounds, and terpenes [69]. A research by Kai et al. [34] identified over 300 MVOCs

Table 1
Impacts of microbial species and VOCs on soil properties.

Microbial Species	Compound Name	Impact on soil properties	References
Pseudomonas putida	2,4-diacetylphloroglucinol (DAPG)	Biocontrol of plant pathogens	[47,48]
Bacillus subtilis	Surfactins, bacillomycin D, Fengicin	Enhanced nutrient uptake	[49]
*Streptomyces*spp.	Various antibiotics	Biocontrol of plant pathogens	[50]
*Trichoderma*spp.	6-phtyl-α-pyrone and chitinases	Biocontrol of plant pathogens, promotion of plant growth, and enhancement of nutrient availability	[51]
*Mycorrhizal Fungi (e.g., Glomus*spp.*)*	Not applicable- they form symbiotic associations with plants	Enhancement of nutrient uptake, soil structure, and plant resistance to pathogens	[52]
*Methonegenicarchaea (e.g., Glomus*spp.*)*	Methane	Production of methane	[53]
*Nitrosomonas*spp. *and Nitrobacter*spp.	Not applicable	Facilitation of the nitrification process	[54]
Acidobacteria	Not applicable- they are adiverse phylum with various functions	Impact on various soil properties	[55]
Actinobacteria	Not applicable- they are adiverse phylum with various functions	Play crucial roles in nutrient cycling, organic matter decomposition, and antibiotic production	[56]
Cyanobacteria	Not applicable- they are adiverse phylum with various functions	Play a critical role in soil nitrogen fixation	[57]

from soil bacteria, with 2,3-butanediol, acetoin, and indole being among the most abundant compounds. These MVOCs play a direct role in regulating plant physiology and promoting growth. Ryu et al. [4] demonstrated that 2,3-butanediol and acetoin, produced by *Bacillus subtilis* GB03 and *Bacillus amyloliquefaciens* IN937a, significantly enhance the growth of *Arabidopsis thaliana* by modulating the plant's ethylene signaling pathway. Ditengou et al. (2015) reported that volatile sesquiterpenes, such as β-caryophyllene produced by ectomycorrhizal fungi, promote lateral shoot formation in *Arabidopsis* and *Populus*, improving the plant's ability to absorb nutrients [68].

MVOC contributes to the rhizosphere environment and affects nutrient availability. Schulz-Bohm et al. [66] reviewed the effects of microbial compounds on nutrient availability in plants, emphasizing their role in nutrient metabolism and absorption. For example, dimethyl disulfide from Bacillus spp. promotes phosphate solubility, increasing the availability of essential nutrients for plants [70]. MVOC can increase nutrient availability indirectly by stimulating beneficial microbial communities in the rhizosphere. Cordovez et al. [71] observed that VOCs produced by *Streptomyces* spp. stimulate the growth of beneficial rhizobacteria while inhibiting pathogenic fungi, establishing an environment that promotes plant growth and nutrient acquisition. Several MVOCs exhibiting antimicrobial properties contribute to plant health by suppressing pathogens. Schmidt et al. [72] identified VOCs released by *Burkholderia ambifaria* that inhibit the growth of various plant pathogens, such as *Rhizoctonia solani* and *Fusarium solani*, which protect plants from these pathogens. Additionally, these MVOCs promote the absorption and utilization of nutrients.

1.8. VOCs in soil nutrient mobilization and immobilization

Nutrient cycling is facilitated by soil VOCs in two ways. They enhance nutrient mobilization through mineral solubilization, chelation of metal ions, or microbial activity [38], and they decrease nutrient immobilization through microbial uptake and the formation of stable organic compounds [73,74]. The interaction between these two factors determines total soil fertility and plant nutrient availability. Specific VOCs function as signaling molecules that activate the functions of soil microorganisms participating in the mobilization of nutrients. For example, the VOCs discharged by *Azospirillum brasilense*, a bacterium that fixes nitrogen, enhance nitrogen availability utilizing biological nitrogen fixation [75]. Similarly, the VOCs produced by species of *Bacillus* have been shown to stimulate the production of cellulases and phosphatases, facilitating the breakdown of complex organic compounds and releasing nutrients for plant absorption [5]. Nevertheless, it is essential to consider the impact of VOCs on nutrient immobilization processes. Certain VOCs can induce changes in the composition and activity of the soil microbial community, resulting in the immobilization of

Table 2
Rhizobacterial VOCs and nutrient cycling interactions.

Rhizobacterial Species	Volatile Organic Compounds (VOCs)	Nutrient Cycling Processes	Microbial Interactions	Associated Microbial Groups	References
Bacillus subtilis	Subtilin, Bacillomycin D	Phosphorus solubilization, Nitrogen fixation	Antibiosis, Plant growth promotion	Other beneficial rhizobacteria	[76–78]
Pseudomonas fluorescens	Pyrrolnitrin, Pyoluteorin	Siderophore production, Nitrate reduction	Antagonism, Mycorrhizal fungi	Beneficial nematodes, other bacteria	[48,79]
Rhizobium leguminosarum	Nod factors	Nitrogen fixation	Symbiotic nitrogen fixation	Other nitrogen-fixing bacteria	[80,81]
Streptomyces spp.	Geosmin, 2-methylisoborneol	Decomposition of organic matter	Mycorrhizal associations, Antibiosis	Actinomycetes, saprophytic fungi	[35,82]
Trichodermaharzianum	Trichodermin, Harzianum A	Biological control against plant pathogens	Plant growth promotion, Root development	Mycoparasitic fungi	[83,84]
Mycorrhizal fungi (e.g., Glomus spp.*)*	Mycotoxins, Glomalin	Enhanced nutrient uptake, especially phosphorus	Symbiotic association	Beneficial bacteria, other mycorrhizal species	[51,85]
Azospirillumbrasilense	Indole-3-acetic acid (IAA), Siderophores	Phytohormone production, Nitrogen fixation	Plant growth promotion, stress tolerance	Other plant growth-promoting bacteria	[86,87]
Methylobacterium spp.	Methanol, Formaldehyde	Methanol metabolism, Plant hormone modulation	Stress tolerance, Nitrogen fixation	Other methylotrophic bacteria	[88,89]
Clostridium pasteurianum	Acetone, Ethanol	Fermentation of organic matter	Synergistic interactions with cellulose-degrading bacteria	Other anaerobic microorganisms	[90]
Burkholderia spp.	Burkholderic acid, Burkholdines	Nitrogen fixation, Antagonism against pathogens	Plant root colonization, plant growth	Other rhizosphere bacteria	[91,92]
Azotobactervinelandii	Hydrogen cyanide (HCN)	Nitrogen fixation, HCN production	Promotes growth in non-leguminous plants	Other nitrogen-fixing bacteria	[93,94]
Clostridium acetobutylicum	Acetone, Butanol	Solvent production, Fermentation	Synergistic interactions with acetate-producing bacteria	Other anaerobic microorganisms	[95,96]
Actinomycetes (e.g., Streptomyces spp.*)*	Geosmin, Actinomycin D	Decomposition of organic matter	Antibiosis against soil pathogens, Promotes soil structure	Other soil bacteria	[35,82]
Lysobacter spp.	Lysobactin, HSAF	Antibiosis against plant pathogens	Plant growth promotion, Disease suppression	Other biocontrol bacteria	[42]

nutrients. Nutrients can be incorporated into microbial biomass or sequestered in soil organic matter, reducing their immediate availability for plant uptake [38].

1.9. *VOC-mediated interactions in rhizosphere nutrient cycling*

The volatile organic compounds (VOCs) emitted by rhizobacteria play a crucial role in influencing the dynamics of nutrient cycling in the rhizosphere. These interactions are multifaceted, involving various ecological relationships that profoundly impact nutrient availability and turnover. One crucial aspect of these VOC-mediated interactions is the attraction and cooperation between rhizobacteria and nutrient-mineralizing microbes Table 2. Bitas et al. [97] showed that rhizobacterial VOCs could attract nitrogen-cycling microbes and enhance the availability of soil nitrogen. These VOCs demonstrate antimicrobial activity, suppressing competing microorganisms and assisting rhizobacteria in securing nutrients and establishing ecological habitats [99–101]. VOCs influence microbial gene expression, regulating nutrient cycling. For instance, Vespermann et al. [35] found that VOCs produced by *Streptomyces* VOCs upregulated genes associated with phosphate solubilization leading to increased phosphate availability in the soil. Rhizobacterial VOCs also influence higher trophic levels such as nematodes and *mycorrhizal fungi*, impacting nutrient cycling and plant nutrient acquisition in the rhizosphere [98]. These interactions are essential in influencing nutrient availability, turnover, and the overall functioning of the soil ecosystem [4,99,100].

1.10. *Applications of rhizobacterial VOCs in agriculture*

Utilizing volatile organic compounds (VOCs) for sustainable agriculture and soil management involves considering both detrimental and advantageous microorganisms. Microbial emissions significantly enhance plant development by improving resilience and promoting overall growth [101,102]. The widely recognized plant hormone and VOC, ethylene, promotes the development of roots and the formation of branches in various plant species [103]. Fig. 2 Plant growth-promoting bacteria, such as *Pseudomonas* and *Bacillus* spp., produce volatile organic compounds (VOCs) that drive essential processes, including root development and nutrient uptake. These VOCs strengthen the plant's resilience to stress, attract beneficial soil organisms, reduce weed pressure, and decrease the need for chemical inputs, promoting environmentally friendly and efficient agricultural practices. This highlights the potential of microbial VOCs to support sustainable agriculture [104]. VOC-mediated microbial interactions in soil significantly influence nutrient availability and plant-microbe interactions [105].

VOCs contribute to plant defense mechanisms against pests and diseases. Herbivore-induced plant volatiles (HIPVs) attract

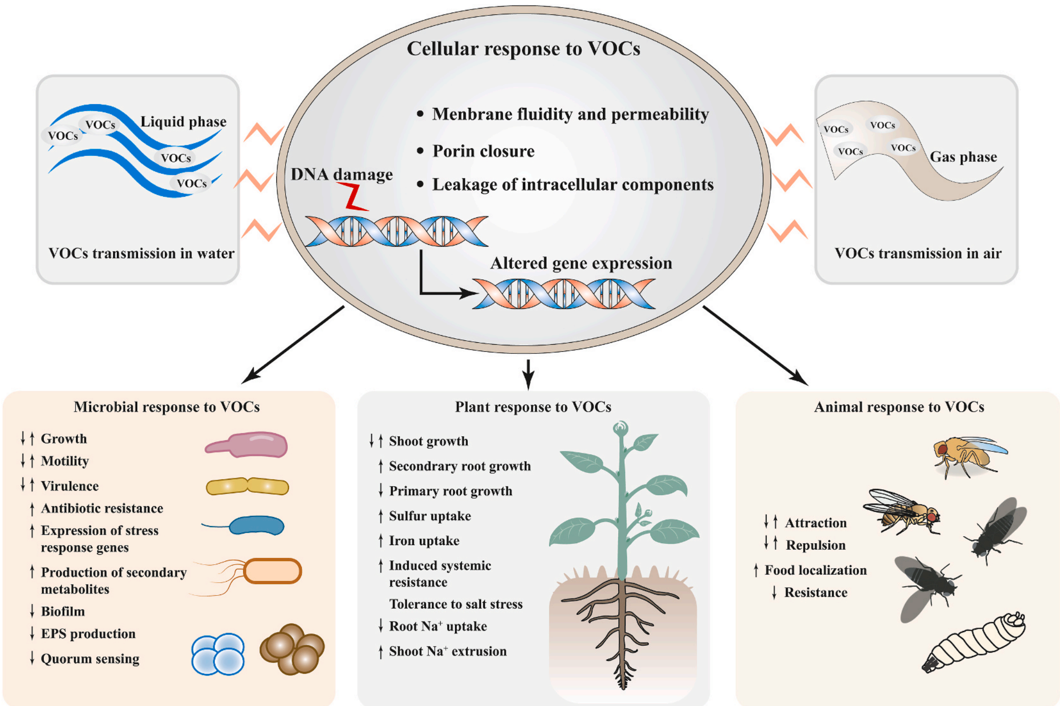

Fig. 2. Plant growth-promoting bacteria (PGPB), such as *Pseudomonas* and *Bacillus* spp., emit volatile organic compounds (VOCs) that play various roles in plant growth and stress responses. These VOCs influence root development, nutrient acquisition, and stress tolerance in plants. They attract beneficial soil microbes and can suppress weed growth. Understanding these functions of VOCs offers potential for sustainable agriculture by promoting plant growth, enhancing nutrient use efficiency, and reducing reliance on chemicals.

predators of herbivores, providing an indirect defense mechanism [106,107]. Specific VOCs emitted by plants directly inhibit the growth and development of pathogens, offering a natural defense against diseases [5]. These interactions can be utilized for sustainable pest control strategies in agriculture. Lazcano and Domínguez (2011) found that the use of VOCs in weed control and pest management reduced reliance on chemical herbicides among US organic growers, minimizing negative impacts on soil health and beneficial organisms. Furthermore, VOCs have the potential to improve soil fertility and overall health [108]. Some released by plant roots act as signaling molecules, attracting soil microorganisms involved in nutrient cycling, enhancing nutrient availability, and promoting soil fertility [109]. Certain cover crops and green manures release VOCs with allelopathic effects, inhibiting weed growth and reducing the need for chemical herbicides [110].

1.11. Rhizobacterial VOCs and plant growth promotion

Volatile organic compounds are essential components in a plant's response to environmental challenges. In response to biotic attacks, the release of VOCs initiates defensive strategies that enhance resilience against herbivores and pathogens [12,111,112]. These compounds are involved in the synthesis of protective agents, strengthening structural barriers, and stimulating protective proteins. Certain VOCs possess antimicrobial properties, suppressing pathogenic growth [113,114]. Regarding abiotic stressors, VOC emissions have been shown to regulate transpiration and modify protective layers to mitigate drought stress [115,116]. Additionally, isoprenoids, including isoprene protects photosystems under thermal stress. Moreover, VOCs contribute to the mitigation of heavy metal stress by chelating toxic metals, reducing their impact on plant systems [117].

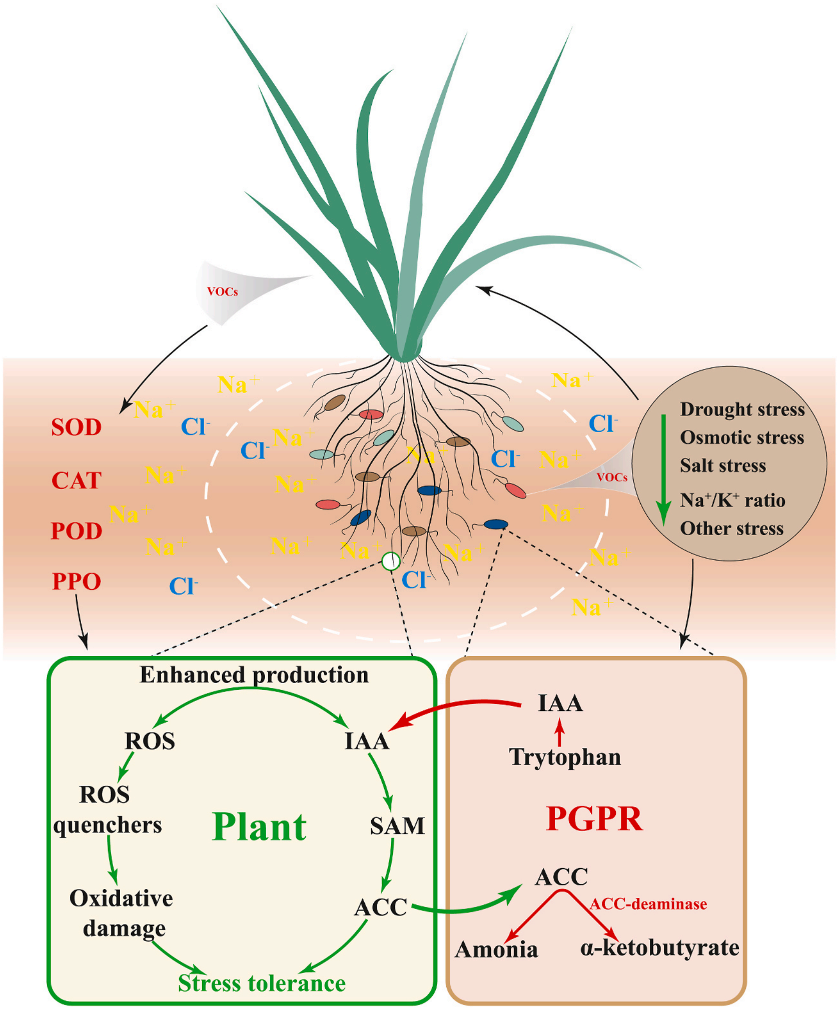

Fig. 3. Salinity stress impacts plant roots by raising sodium (Na^+) levels and lowering potassium (K^+) levels. Beneficial microbes, particularly plant growth-promoting rhizobacteria (PGPR), release microbial volatile organic compounds (MVOCs) that aid plants in stress management. These MVOCs enhance potassium uptake, decrease sodium accumulation, and increase antioxidant activity, leading to improved stress tolerance. Additionally, they induce changes in gene expression associated with stress responses, emphasizing the potential of MVOCs to enhance plant growth and resilience under salinity stress conditions.

Microbial Volatile Organic Compounds (MVOCs) influence plant tolerance to abiotic stress, with limited attention given to their role in salinity stress. Fig. 3 depicts a plant root system under salt stress, highlighting the challenges posed by increased sodium (Na^+) influx and reduced potassium (K^+) uptake [118]. Studies have demonstrated the effectiveness of MVOCs from various PGPR strains in alleviating salt stress in plants. For example, MVOCs from *Trichoderma* fungi enhance salt tolerance in *Arabidopsis thaliana*, while *Pseudomonas simiae*-derived MVOCs mitigate Na^+ accumulation and enhance K^+ and P content in soybean roots [119,120]. These findings highlight the potential of PGPR-derived MVOCs as biocontrol agents to improve plant growth and stress tolerance in saline environments.

1.12. Rhizobacterial (VOCs) opportunities and challenges in agriculture

Rhizobacterial VOCs represent a promising advancement in sustainable agriculture, offering the potential to improve crop yields while enhancing environmental sustainability. These microbial metabolites play a crucial role in mediating plant-microbe interactions and significantly contribute to soil health by increasing nutrient availability and improving soil structure [121]. Significantly, specific VOCs produced by rhizobacteria have been found to solubilize phosphate and enhance nitrogen fixation, leading to more efficient nutrient uptake by plants [122]. Additionally, these compounds contribute to the formation of soil aggregates, which aid in water retention and reduce soil erosion. In addition to their role in nutrient cycling, rhizobacterial VOCs have been shown to directly influence plant growth by promoting root development, increasing shoot biomass, and enhancing overall plant vigor [103]. Moreover, research indicates that plants exposed to certain VOCs exhibit enhanced resilience to biotic and abiotic stressors, improving both stress tolerance and systemic resistance against pathogens [123,124]. Fig. 4 illustrates the role of microbial communities in promoting plant growth and resilience by enhancing nutrient availability, reducing greenhouse gas emissions, and enabling resistance to environmental stressors. It highlights the importance of quorum sensing and the release of VOCs in regulating these beneficial interactions [125–128].

Utilizing VOC-producing bacteria into agricultural systems requires a comprehensive evaluation of their environmental implications. Long-term studies are crucial to assess potential risks, ensuring that these interventions maintain the stability of native microbial communities and prevent any adverse environmental impacts on agroecosystems [129]. Despite these concerns, research is actively investigating novel VOCs, elucidating their mechanisms of action, and developing sustainable application methods. Collaborative initiatives among microbiologists, agronomists, and environmental scientists are crucial for fully realizing the potential of rhizobacterial VOCs in current agricultural practices [36,130]. Table 3 summarizes the various applications and opportunities of

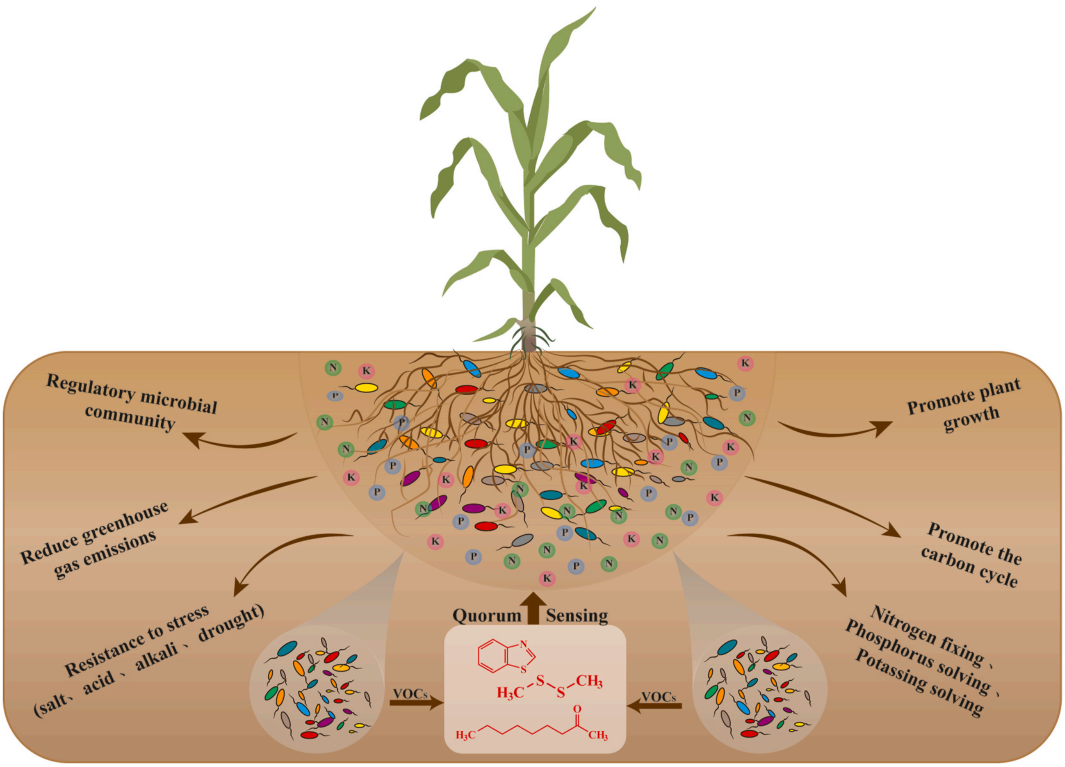

Fig. 4. Illustration of the role of rhizobacterial VOCs on plants and in soil. Essential functions of microbial volatile organic compounds (VOCs) in the rhizosphere. It is emphasized that these compounds contribute to plant growth. Nutrient cycling and stress resistance under adverse conditions such as salinity, acidity, and drought. The main processes include nitrogen fixation. Dissolving phosphorus, potassium, and nutrition of beneficial microbial communities helps reduce greenhouse gas emissions. The figure also highlights quorum sensing mechanisms. This shows the complex interactions between microbial populations and plants, increasing agricultural sustainability.

rhizobacterial volatile organic compounds (VOCs) in agriculture. It highlights their benefits, such as reduced pesticide use, improved yield and quality, enhanced soil structure and fertility, increased stress tolerance, improved nutrient availability, bioremediation of pollutants, and modulation of microbial communities.

Although rhizobacterial VOCs offer significant advantages, several challenges remain regarding their practical application. VOC production is highly variable and influenced by environmental conditions such as soil type, temperature, and moisture levels, complicating their consistent use in agricultural practices [132]. Moreover, due to the volatile nature of these compounds, ensuring consistent concentrations in soil environments remains a significant challenge. Innovative approaches, such as encapsulation methods and slow-release formulations, are being explored to address this issue; however, further optimization is required for large-scale applications [133,134]. Ongoing research into these strategies is essential for overcoming current limitations and maximizing the benefits of rhizobacterial VOCs in agricultural practices.

1.13. Environmental implications of rhizobacterial VOCs

1.13.1. Mitigation strategies to minimize potential environmental risks

The application of rhizobacterial volatile organic compounds (VOCs) contributes to growth promotion and increased stress resistance in agriculture while presenting environmental challenges. To mitigate these risks, a diverse approach is needed, incorporating sustainable practices, advanced biotechnology, and relevant policy measures. Sustainable soil management enhances soil resilience to VOCs by increasing soil organic matter, which improves soil structure and microbial diversity, thereby buffering against potential negative impacts [135]. Diverse microbial communities can balance VOC production and degradation, reducing off-target effects [136], while mycorrhizal fungi enhance nutrient uptake and may modulate VOC effects [137]. Metagenomics can elucidate the genetic basis for VOC production, enabling regulation at the gene level to minimize environmental risks without compromising benefits [138].

Effective monitoring of VOC emissions is crucial for mitigating environmental risks, particularly in agricultural systems. Utilizing advanced technologies such as remote sensing, precision agriculture, and sensor networks allows for the collection of critical data, facilitating targeted interventions to minimize VOC-related impacts and enhance sustainable agricultural practices. Hyperspectral Imaging (HSI) captures high-resolution spectral information to monitor soil and crop health, indicating VOC accumulation [139]. Additionally, HSI and LiDAR measure vegetation and soil conditions, providing further insights into plant health and environmental changes [140]. In precision agriculture, site-specific management utilizing sensor data can effectively deploy beneficial rhizobacterial VOCs to enhance crop yields while minimizing adverse effects on soil health [139]. Implementing sensor networks in agricultural fields allows for continuous monitoring of soil VOCs, enabling rapid identification of emerging issues and facilitating improved risk management through predictive modeling [140,141].

2. Conclusions and future prospective

Exploring the complex mechanisms of rhizobacterial VOC emissions and the environmental factors that regulate their production represents a crucial area of research for maximizing their potential in sustainable agriculture. This in-depth knowledge will contribute to the formulation of targeted interventions to modify VOC biosynthesis and optimize their effects on nutrient cycling and soil health. The integration of powerful tools such as metagenomics, which elucidate the taxonomic and functional characteristics of soil microbial communities, along with real-time VOC monitoring through advanced sensor technology, presents a novel approach. This synergistic strategy will enable researchers to precisely regulate VOC production and achieve tailored outcomes within agricultural ecosystems. Future research holds considerable promise for developing specialized groups of rhizobacteria specifically tailored for distinct crops and soil conditions, maximizing their beneficial effects on plant growth, nutrient acquisition, and stress tolerance. Additionally, exploring the potential for immobilization or controlled-release technologies for VOCs could result in novel biofertilizers with enhanced stability and targeted application in the field. By investigating rhizobacterial VOCs, we can promote sustainable agriculture that emphasizes environmental responsibility, optimized resource utilization, and increased crop yields.

Table 3
Applications and opportunities of rhizobacterial volatile organic compounds.

Application Area	Benefits	Challenges	Opportunities	References
Crop Protection	Reduced pesticide use	Variable efficacy	Sustainable agriculture	[131]
Plant Growth Promotion	Improved yield and quality	Compatibility with other treatments	Increased productivity	[87,89]
Soil Health Improvement	Enhanced structure and fertility	Limited shelf-life of VOCs	Sustainable practices	[35,91]
Stress Tolerance	Enhanced resilience	Variable responses	Improved crop resilience	[86,88]
Enhanced Nutrient Cycling	Improved nutrient availability	Dependency on plant host	Reduced fertilizer use	[80,81]
Bioremediation	Degradation of pollutants	Specificity of VOCs	Sustainable cleanup	[35,88,89]
Microbial Community Modulation	Tailored microbial communities	Potential disruption of native ecosystems	Enhanced plant health and nutrient cycling	[35,90]
Sustainable Agriculture	Environmentally friendly and economically viable	Adoption and economic feasibility	Transition to sustainable agriculture	[86,91]

CRediT authorship contribution statement

Faryal Babar Baloch: Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Nan Zeng:** Writing – review & editing, Conceptualization. **Haiyang Gong:** Investigation. **Zhiyong Zhang:** Supervision, Project administration, Funding acquisition. **Ning Zhang:** Investigation. **Sadia Babar Baloch:** Investigation. **Shahzaib Ali:** Investigation. **Bingxue Li:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials

No data was used for the research described in the article.

Funding

This research was funded by the National Natural Science Foundation of China (31271818); International Cooperation Project of Universities in Liaoning Province (2023–01); Liaoning Province Rural Science and Technology Special Action Project (2022030673-JH5/104); Shenyang Science and Technology Project (22-319-2-13), and supported by the China Scholarship Council (CSC202208850002).

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Bingxue Li reports financial support and writing assistance were provided by Shenyang Agricultural University. Faryal Babar Baloch reports financial support and writing assistance were provided by Shenyang Agricultural University. Nan Zeng reports financial support and writing assistance were provided by Shenyang Agricultural University. Haiyang Gong reports financial support and writing assistance were provided by Shenyang Agricultural University. Zhiyong Zhang reports financial support and writing assistance were provided by Shenyang Agricultural University. Ning Zhang reports financial support and writing assistance were provided by Shenyang Agricultural University. Sadia Babar Baloch reports financial support and writing assistance were provided by University of South Bohemia in České Budějovice, Branišovská. Shahzaib Ali reports financial support and writing assistance were provided by University of South Bohemia in České Budějovice, Branišovská. Bingxue Li reports a relationship with Shenyang Agricultural University that includes: employment. Faryal Babar Baloch reports a relationship with Shenyang Agricultural University that includes: non-financial support. Nan Zeng reports a relationship with Shenyang Agricultural University that includes: non-financial support. Haiyang Gong reports a relationship with Shenyang Agricultural University that includes: employment. Zhiyong Zhang reports a relationship with Shenyang Agricultural University that includes: non-financial support. Ning Zhang reports a relationship with Shenyang Agricultural University that includes: employment. Sadia Babar Baloch reports a relationship with University of South Bohemia in České Budějovice that includes: employment. Shahzaib Ali reports a relationship with University of South Bohemia in České Budějovice that includes: employment. Bingxue Li has patent licensed to HELIYON-D-24-48005R2. Not applicable If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to express their gratitude to the National Natural Science Foundation of China (31271818), the Liaoning Province Rural Science and Technology Special Action Project (2022030673-JH5/104), and the China Scholarship Council (CSC202208850002) for their support. Special thanks to Prof. Bingxue Li for invaluable insights and contributions throughout the study.

Abbreviations

PGPR	Plant Growth-Promoting Rhizobacteria
VOCs	Volatile Organic Compounds
ACC	Aminocyclopropane-1-carboxylate
IAA	Indole-3-acetic acid
DAPG	2,4-Diacetylphloroglucinol

DMS Dimethyl sulfide
R-VOCs Rhizobacterial Volatile Organic Compounds
R-SOC Soil Organic Carbon
EPS Extracellular Polymeric Substances
MVOCs Microbial Volatile Organic Compounds
ISR Induced Systemic Resistance
IST Induced Systemic Tolerance
HIPVs Herbivore-Induced Plant Volatiles
TMV Tobacco Mosaic Virus

References

[1] R. Backer, J.S. Rokem, G. Ilangumaran, J. Lamont, D. Praslickova, E. Ricci, S. Subramanian, D.L. Smith, Plant growth-promoting rhizobacteria: context, mechanisms of action, and roadmap to commercialization of biostimulants for sustainable agriculture, Front. Plant Sci. 9 (2018) 1473, https://doi.org/10.3389/fpls.2018.01473.

[2] A. Zaidi, M.S. Khan, M. Ahemad, M. Oves, Plant growth promotion by phosphate solubilizing bacteria, Acta Microbiol. Immunol. Hung. 56 (2009) 263–284, https://doi.org/10.1556/AMicr.56.2009.3.6.

[3] A.L. Khan, M. Waqas, S.-M. Kang, A. Al-Harrasi, J. Hussain, A. Al-Rawahi, S. Al-Khiziri, I. Ullah, L. Ali, H.-Y. Jung, I.-J. Lee, Bacterial endophyte Sphingomonas sp. LK11 produces gibberellins and IAA and promotes tomato plant growth, J. Microbiol. 52 (2014) 689–695, https://doi.org/10.1007/s12275-014-4002-7.

[4] C.-M. Ryu, M.A. Farag, C.-H. Hu, M.S. Reddy, H.-X. Wei, P.W. Paré, J.W. Kloepper, Bacterial volatiles promote growth in Arabidopsis, Proc. Natl. Acad. Sci. U.S.A. 100 (2003) 4927–4932, https://doi.org/10.1073/pnas.0730845100.

[5] U. Effmert, J. Kalderás, R. Warnke, B. Piechulla, Volatile mediated interactions between bacteria and fungi in the soil, J. Chem. Ecol. 38 (2012) 665–703, https://doi.org/10.1007/s10886-012-0135-5.

[6] H. Zhang, M.-S. Kim, V. Krishnamachari, P. Payton, Y. Sun, M. Grimson, M.A. Farag, C.-M. Ryu, R. Allen, I.S. Melo, P.W. Paré, Rhizobacterial volatile emissions regulate auxin homeostasis and cell expansion in Arabidopsis, Planta 226 (2007) 839–851, https://doi.org/10.1007/s00425-007-0530-2.

[7] K. Gomi, M. Matsuoka, Gibberellin signalling pathway, Curr. Opin. Plant Biol. 6 (2003) 489–493, https://doi.org/10.1016/s1369-5266(03)00079-7.

[8] S. Yamaguchi, Gibberellin metabolism and its regulation, Annu. Rev. Plant Biol. 59 (2008) 225–251, https://doi.org/10.1146/annurev.arplant.59.032607.092804.

[9] W.M. Ridenour, R.M. Callaway, The relative importance of allelopathy in interference: the effects of an invasive weed on a native bunchgrass, Oecologia 126 (2001) 444–450, https://doi.org/10.1007/s004420000533.

[10] Y. Xu, X. Chen, L. Ding, C.H. Kong, Allelopathy and allelochemicals in grasslands and forests, Forests 14 (2023), https://doi.org/10.3390/f14030562.

[11] K. Akiyama, K.-I. Matsuzaki, H. Hayashi, Plant sesquiterpenes induce hyphal branching in arbuscular mycorrhizal fungi, Nature 435 (2005) 824–827, https://doi.org/10.1038/nature03608.

[12] M. Heil, R. Karban, Explaining evolution of plant communication by airborne signals, Trends Ecol. Evol. 25 (2010) 137–144, https://doi.org/10.1016/j.tree.2009.09.010.

[13] M.A. Altieri, C.I. Nicholls, A. Henao, M.A. Lana, Agroecology and the design of climate change-resilient farming systems, Agron. Sustain. Dev. 35 (2015) 869–890, https://doi.org/10.1007/s13593-015-0285-2.

[14] A. Vaishnav, S. Kumari, S. Jain, A. Varma, N. Tuteja, D.K. Choudhary, PGPR-mediated expression of salt tolerance gene in soybean through volatiles under sodium nitroprusside: PGPR-mediated amelioration of soybean under salt stress, J. Basic Microbiol. 56 (2016) 1274–1288, https://doi.org/10.1002/jobm.201600188.

[15] C. Wang, J. Zhao, Y. Feng, M. Shang, X. Bo, Z. Gao, F. Chen, Q. Chu, Optimizing tillage method and irrigation schedule for greenhouse gas mitigation, yield improvement, and water conservation in wheat–maize cropping systems, Agric. Water Manag. 248 (2021) 106762, https://doi.org/10.1016/j.agwat.2021.106762.

[16] U. Niinemets, A. Kännaste, L. Copolovici, Quantitative patterns between plant volatile emissions induced by biotic stresses and the degree of damage, Front. Plant Sci. 4 (2013) 262, https://doi.org/10.3389/fpls.2013.00262.

[17] R. Prakash, R. Subramani, C.V. Berde, T. Chandrasekhar, A.M. Prathyusha, E. Kariali, P.V. Bramhachari, Rhizobacteriome: plant growth-promoting traits and its functional mechanism in plant growth, development, and defenses, in: InUnderstanding the Microbiome Interactions in Agriculture and the Environment, Springer Nature, Singapore; Singapore, 2022.

[18] V.V. Volkogon, L.V. Potapenko, M.V. Volkogon, Vertical migration of nutrients and water-soluble organic matter in the soil profile under pre-sowing seed treatment with plant growth promoting rhizobacteria, Front. Sustain. Food Syst. 6 (2023).

[19] K. Schulz-Bohm, H. Zweers, W. de Boer, P. Garbeva, A fragrant neighborhood: volatile mediated bacterial interactions in soil, Front. Microbiol. 6 (2015) 1212, https://doi.org/10.3389/fmicb.2015.01212.

[20] L. Wang, N. Wang, D. Guo, Z. Shang, Y. Zhang, S. Liu, Y. Wang, Rhizobacteria helps to explain the enhanced efficiency of phytoextraction strengthened by Streptomyces pactum, J. Environ. Sci. (China) 125 (2023) 73–81, https://doi.org/10.1016/j.jes.2022.01.022.

[21] J. Yuan, M. Zhao, R. Li, Q. Huang, W. Raza, C. Rensing, Q. Shen, Microbial volatile compounds alter the soil microbial community, Environ. Sci. Pollut. Res. Int. 24 (2017) 22485–22493, https://doi.org/10.1007/s11356-017-9839-y.

[22] R. Kaiser, Flowers and fungi use scents to mimic each other, Science 311 (2006) 806–807, https://doi.org/10.1126/science.1119499.

[23] P.K. Misztal, Measuring rapid changes in plant volatiles at different spatial levels, Deciphering chemical language of plant communication (2016) 95–114.

[24] R. Wihlborg, D. Pippitt, R. Marsili, Headspace sorptive extraction and GC-TOFMS for the identification of volatile fungal metabolites, J. Microbiol. Methods 75 (2008) 244–250, https://doi.org/10.1016/j.mimet.2008.06.011.

[25] N. Dandurishvili, N. Toklikishvili, M. Ovadis, P. Eliashvili, N. Giorgobiani, R. Keshelava, M. Tediashvili, A. Vainstein, I. Khmel, E. Szegedi, L. Chernin, Broad-range antagonistic rhizobacteria Pseudomonas fluorescens and Serratia plymuthica suppress Agrobacterium crown gall tumours on tomato plants: biocontrol of Agrobacterium by bacterial antagonists, J. Appl. Microbiol. 110 (2011) 341–352, https://doi.org/10.1111/j.1365-2672.2010.04891.x.

[26] C.M.J. Pieterse, C. Zamioudis, R.L. Berendsen, D.M. Weller, S.C.M. Van Wees, P.A.H.M. Bakker, Induced systemic resistance by beneficial microbes, Annu. Rev. Phytopathol. 52 (2014) 347–375, https://doi.org/10.1146/annurev-phyto-082712-102340.

[27] P.R. Hardoim, L.S. van Overbeek, J.D. van Elsas, Properties of bacterial endophytes and their proposed role in plant growth, Trends Microbiol. 16 (2008) 463–471, https://doi.org/10.1016/j.tim.2008.07.008.

[28] R.L. Berendsen, C.M.J. Pieterse, P.A.H.M. Bakker, The rhizosphere microbiome and plant health, Trends Plant Sci. 17 (2012) 478–486, https://doi.org/10.1016/j.tplants.2012.04.001.

[29] P. Bhadrecha, S. Singh, V. Dwibedi, "A plant's major strength in rhizosphere": the plant growth promoting rhizobacteria, Arch. Microbiol. 205 (2023) 165, https://doi.org/10.1007/s00203-023-03502-2.

[30] G. Berg, Plant-microbe interactions promoting plant growth and health: perspectives for controlled use of microorganisms in agriculture, Appl. Microbiol. Biotechnol. 84 (2009) 11–18, https://doi.org/10.1007/s00253-009-2092-7.

[31] Y. Yamada, T. Kuzuyama, M. Komatsu, K. Shin-Ya, S. Omura, D.E. Cane, H. Ikeda, Terpene synthases are widely distributed in bacteria, Proc. Natl. Acad. Sci. U.S.A. 112 (2015) 857–862, https://doi.org/10.1073/pnas.1422108112.

[32] I. Mármol, C. Sánchez-de-Diego, N. Jiménez-Moreno, C. Ancín-Azpilicueta, M. Rodríguez-Yoldi, Therapeutic applications of Rose hips from different Rosa species, Int. J. Mol. Sci. 18 (2017) 1137, https://doi.org/10.3390/ijms18061137.

[33] H. Massalha, E. Korenblum, S. Malitsky, O.H. Shapiro, A. Aharoni, Live imaging of root–bacteria interactions in a microfluidics setup, Proc. Natl. Acad. Sci. U.S.A. 114 (2017) 4549–4554, https://doi.org/10.1073/pnas.1618584114.

[34] M. Kai, M. Haustein, F. Molina, A. Petri, B. Scholz, B. Piechulla, Bacterial volatiles and their action potential, Appl. Microbiol. Biotechnol. 81 (2009) 1001–1012, https://doi.org/10.1007/s00253-008-1760-3.

[35] A. Vespermann, M. Kai, B. Piechulla, Rhizobacterial volatiles affect the growth of fungi and Arabidopsis thaliana, Appl. Environ. Microbiol. 73 (2007) 5639–5641, https://doi.org/10.1128/AEM.01078-07.

[36] V. Bitas, H.-S. Kim, J.W. Bennett, S. Kang, Sniffing on microbes: diverse roles of microbial volatile organic compounds in plant health, Mol. Plant Microbe Interact. 26 (2013) 835–843, https://doi.org/10.1094/MPMI-10-12-0249-CR.

[37] L. Weisskopf, S. Schulz, P. Garbeva, Microbial volatile organic compounds in intra-kingdom and inter-kingdom interactions, Nat. Rev. Microbiol. 19 (2021) 391–404, https://doi.org/10.1038/s41579-020-00508-1.

[38] K. Schulz-Bohm, L. Martín-Sánchez, P. Garbeva, Microbial volatiles: small molecules with an important role in intra-and inter-kingdom interactions, Front. Microbiol. 8 (2017), https://doi.org/10.3389/fmicb.2017.02484.

[39] M. Kai, B. Piechulla, Plant growth promotion due to rhizobacterial volatiles-an effect of CO2? FEBS (Fed. Eur. Biochem. Soc.) Lett. 583 (2009) 3473–3477, https://doi.org/10.1016/j.febslet.2009.09.053.

[40] D.T. Nagrale, S.P. Gawande, V. Shah, P. Verma, N.S. Hiremani, T. Prabhulinga, N. Gokte-Narkhedkar, V.N. Waghmare, Correction: biocontrol potential of volatile organic compounds (VOCs) produced by cotton endophytic rhizobacteria against Macrophomina phaseolina, Eur. J. Plant Pathol. 163 (2022), https://doi.org/10.1007/s10658-022-02503-z, 511–511.

[41] V.P. Campos, R.S.C. de Pinho, E.S. Freire, Volatiles produced by interacting microorganisms potentially useful for the control of plant pathogens, Ciênc, Agrotecnologia 34 (2010) 525–535, https://doi.org/10.1590/s1413-70542010000300001.

[42] W. Raza, Z. Wei, A. Jousset, Q. Shen, V.-P. Friman, Extended plant metarhizobiome: understanding volatile organic compound signaling in plant-microbe metapopulation networks, mSystems 6 (2021) e0084921, https://doi.org/10.1128/mSystems.00849-21.

[43] D. Schenkel, J.G. Maciá-Vicente, A. Bissell, R. Splivallo, Fungi indirectly affect plant root architecture by modulating soil volatile organic compounds, Front. Microbiol. 9 (2018) 1847, https://doi.org/10.3389/fmicb.2018.01847.

[44] C.P. Enespa, Microbial volatiles as chemical weapons against pathogenic fungi. Volatiles and Food Security: Role of Volatiles in Agro-Ecosystems, 2017, pp. 227–254.

[45] C. Hw, Microbial volatile organic compounds: generation pathways and mass spectrometric detection, China Biotechnol. 28 (2008) 124–133.

[46] R.D. Bardgett, W.H. van der Putten, Belowground biodiversity and ecosystem functioning, Nature 515 (2014) 505–511, https://doi.org/10.1038/nature13855.

[47] D.M. Weller, J.M. Raaijmakers, B.B.M. Gardener, L.S. Thomashow, Microbial populations responsible for specific soil suppressiveness to plant pathogens, Annu. Rev. Phytopathol. 40 (2002) 309–348, https://doi.org/10.1146/annurev.phyto.40.030402.110010.

[48] H.P. Bais, R. Fall, J.M. Vivanco, Biocontrol of Bacillus subtilis against infection of Arabidopsis roots by Pseudomonas syringae is facilitated by biofilm formation and surfactin production, Plant Physiol. 134 (2004) 307–319, https://doi.org/10.1104/pp.103.028712.

[49] J. Bérdy, Thoughts and facts about antibiotics: where we are now and where we are heading, J. Antibiot. (Tokyo) 65 (2012) 441, https://doi.org/10.1038/ja.2012.54.

[50] H.A. Contreras-Cornejo, L. Macías-Rodríguez, C. Cortés-Penagos, J. López-Bucio, Trichoderma virens, a plant beneficial fungus, enhances biomass production and promotes lateral root growth through an auxin-dependent mechanism in Arabidopsis, Plant Physiol. 149 (2009) 1579–1592, https://doi.org/10.1104/pp.108.130369.

[51] S.E. Smith, D.J. Read, Mycorrhizal Symbiosis, Academic Press, 2010.

[52] R. Conrad, Microbial ecology of methane production and oxidation in rice soils, Soil Biol. Biochem. 39 (2007) 859–870.

[53] G.W. Nicol, C. Schleper, Ammonia-oxidising Crenarchaeota: important players in the nitrogen cycle? Trends Microbiol. 14 (2006) 207–212, https://doi.org/10.1016/j.tim.2006.03.004.

[54] R.I. Adams, M. Miletto, J.W. Taylor, T.D. Bruns, Erratum: dispersal in microbes: fungi in indoor air are dominated by outdoor air and show dispersal limitation at short distances, ISME J. 7 (2013), https://doi.org/10.1038/ismej.2013.84, 1460–1460.

[55] A. Checcucci, E. Azzarello, M. Bazzicalupo, M. Galardini, A. Lagomarsino, S. Mancuso, L. Marti, M.C. Marzano, S. Mocali, A. Squartini, M. Zanardo, A. Mengoni, Mixed nodule infection in Sinorhizobium meliloti-Medicago sativa symbiosis suggest the presence of cheating behavior, Front. Plant Sci. 7 (2016) 835, https://doi.org/10.3389/fpls.2016.00835.

[56] W. Elbert, B. Weber, S. Burrows, J. Steinkamp, B. Büdel, M.O. Andreae, U. Pöschl, Contribution of cryptogamic covers to the global cycles of carbon and nitrogen, Nat. Geosci. 5 (2012) 459–462, https://doi.org/10.1038/ngeo1486.

[57] R. Mendes, P. Garbeva, J.M. Raaijmakers, The rhizosphere microbiome: significance of plant beneficial, plant pathogenic, and human pathogenic microorganisms, FEMS Microbiol. Rev. 37 (2013) 634–663, https://doi.org/10.1111/1574-6976.12028.

[58] A.A. Parlin, M. Kondo, N. Watanabe, K. Nakamura, J. Wang, Y. Sakamoto, T. Komai, Role of water in unexpectedly large changes in emission flux of volatile organic compounds in soils under dynamic temperature conditions, Sci. Rep. 12 (2022) 4418, https://doi.org/10.1038/s41598-022-08270-5.

[59] J.M. Oades, Soil organic matter and structural stability: mechanisms and implications for management, Plant Soil 76 (1984) 319–337, https://doi.org/10.1007/bf02205590.

[60] Ł. Musielok, M. Stolarczyk, A. Rudnik, K. Buczek, The role of soil-forming processes and changes in land cover in the storage and stabilization of soil organic carbon-preliminary results from the Carpathians (Southern Poland), in: InEGU General Assembly Conference Abstracts, 2023.

[61] H. Cooper, M. Lark, S. Sjogersten, S. Mooney, The role of zero-tillage in mitigating climate change in tropical soils, in: InEGU General Assembly Conference Abstracts, 2023.

[62] G. Tian, C.-Y. Chiu, O. Oladeji, T. Johnston, B. Morgan, A. Cox, T. Granato, H. Zhang, E. Podczerwinski, JumpStart of soil organic matter with highly stabilized organic amendment: implication for climate-smart agriculture, Environmental Challenges 12 (2023) 100726, https://doi.org/10.1016/j.envc.2023.100726.

[63] H. Insam, M.S.A. Seewald, Volatile organic compounds (VOCs) in soils, Biol. Fertil. Soils 46 (2010) 199–213, https://doi.org/10.1007/s00374-010-0442-3.

[64] K. Wenke, M. Kai, B. Piechulla, Belowground volatiles facilitate interactions between plant roots and soil organisms, Planta 231 (2010) 499–506, https://doi.org/10.1007/s00425-009-1076-2.

[65] K. Schulz-Bohm, S. Gerards, M. Hundscheid, J. Melenhorst, W. de Boer, P. Garbeva, Calling from distance: attraction of soil bacteria by plant root volatiles, ISME J. 12 (2018) 1252–1262, https://doi.org/10.1038/s41396-017-0035-3.

[66] B.M. Delory, P. Delaplace, M.-L. Fauconnier, P. du Jardin, Root-emitted volatile organic compounds: can they mediate belowground plant-plant interactions? Plant Soil 402 (2016) 1–26, https://doi.org/10.1007/s11104-016-2823-3.

[67] F.A. Ditengou, A. Müller, M. Rosenkranz, J. Felten, H. Lasok, M.M. van Doorn, V. Legué, K. Palme, J.-P. Schnitzler, A. Polle, Volatile signalling by sesquiterpenes from ectomycorrhizal fungi reprogrammes root architecture, Nat. Commun. 6 (2015) 6279, https://doi.org/10.1038/ncomms7279.

[68] J. Peñuelas, D. Asensio, D. Tholl, K. Wenke, M. Rosenkranz, B. Piechulla, J. Schnitzler, Biogenic vol atile emissions from the soil, Plant Cell Environ. 37 (2014) 1866–1891.

[69] D.G. Meldau, S. Meldau, L.H. Hoang, S. Underberg, H. Wünsche, I.T. Baldwin, Dimethyl disulfide produced by the naturally associated bacterium bacillus sp B55 promotes Nicotiana attenuata growth by enhancing sulfur nutrition, Plant Cell 25 (2013) 2731–2747, https://doi.org/10.1105/tpc.113.114744.

[70] V. Cordovez, V.J. Carrion, D.W. Etalo, R. Mumm, H. Zhu, G.P. van Wezel, J.M. Raaijmakers, Diversity and functions of volatile organic compounds produced by Streptomyces from a disease-suppressive soil, Front. Microbiol. 6 (2015) 1081, https://doi.org/10.3389/fmicb.2015.01081.

[71] R. Schmidt, V. Cordovez, W. de Boer, J. Raaijmakers, P. Garbeva, Volatile affairs in microbial interactions, ISME J. 9 (2015) 2329–2335, https://doi.org/10.1038/ismej.2015.42.
[72] R. Adeleke, C. Nwangburuka, B. Oboirien, Origins, roles and fate of organic acids in soils: a review, South Afr. J. Bot. 108 (2017) 393–406, https://doi.org/10.1016/j.sajb.2016.09.002.
[73] P. Garbeva, C. Hordijk, S. Gerards, W. de Boer, Volatile-mediated interactions between phylogenetically different soil bacteria, Front. Microbiol. 5 (2014) 289, https://doi.org/10.3389/fmicb.2014.00289.
[74] B. Drogue, H. Sanguin, S. Borland, C. Prigent-Combaret, F. Wisniewski-Dyé, Genome wide profiling of Azospirillum lipoferum 4B gene expression during interaction with rice roots, FEMS Microbiol. Ecol. 87 (2014) 543–555, https://doi.org/10.1111/1574-6941.12244.
[75] C.-M. Ryu, M.A. Farag, C.-H. Hu, M.S. Reddy, J.W. Kloepper, P.W. Paré, Bacterial volatiles induce systemic resistance in Arabidopsis, Plant Physiol. 134 (2004) 1017–1026, https://doi.org/10.1104/pp.103.026583.
[76] M. Ahemad, M. Kibret, Mechanisms and applications of plant growth promoting rhizobacteria: current perspective, J. King Saud Univ. Sci. 26 (2014) 1–20, https://doi.org/10.1016/j.jksus.2013.05.001.
[77] M. Naveed, B. Mitter, T.G. Reichenauer, K. Wieczorek, A. Sessitsch, Increased drought stress resilience of maize through endophytic colonization by Burkholderia phytofirmans PsJN and Enterobacter sp. FD17, Environ. Exp. Bot. 97 (2014) 30–39, https://doi.org/10.1016/j.envexpbot.2013.09.014.
[78] S.P. Chowdhury, A. Hartmann, X. Gao, R. Borriss, Biocontrol mechanism by root-associated Bacillus amyloliquefaciens FZB42-a review, Front. Microbiol. 6 (2015), https://doi.org/10.3389/fmicb.2015.00780.
[79] I.A. Siddiqui, S.S. Shaukat, I.H. Sheikh, A. Khan, Role of cyanide production by Pseudomonas fluorescens CHA0 in the suppression of root-knot nematode, Meloidogyne javanica in tomato, World J. Microbiol. Biotechnol. 22 (2006) 641–650, https://doi.org/10.1007/s11274-005-9084-2.
[80] G.E.D. Oldroyd, J.D. Murray, P.S. Poole, J.A. Downie, The rules of engagement in the legume-rhizobial symbiosis, Annu. Rev. Genet. 45 (2011) 119–144, https://doi.org/10.1146/annurev-genet-110410-132549.
[81] A. García-Salamanca, M.A. Molina-Henares, P. van Dillewijn, J. Solano, P. Pizarro-Tobías, A. Roca, E. Duque, J.L. Ramos, Bacterial diversity in the rhizosphere of maize and the surrounding carbonate-rich bulk soil: biodiversity in adjacent niches, Microb. Biotechnol. 6 (2013) 36–44, https://doi.org/10.1111/j.1751-7915.2012.00358.x.
[82] S.D. Schrey, M. Schellhammer, M. Ecke, R. Hampp, M.T. Tarkka, Mycorrhiza helper bacterium Streptomyces AcH 505 induces differential gene expression in the ectomycorrhizal fungus Amanita muscaria, New Phytol. 168 (2005) 205–216, https://doi.org/10.1111/j.1469-8137.2005.01518.x.
[83] M. Shoresh, G.E. Harman, F. Mastouri, Induced systemic resistance and plant responses to fungal biocontrol agents, Annu. Rev. Phytopathol. 48 (2010) 21–43, https://doi.org/10.1146/annurev-phyto-073009-114450.
[84] I.S. Druzhinina, V. Seidl-Seiboth, A. Herrera-Estrella, B.A. Horwitz, C.M. Kenerley, E. Monte, P.K. Mukherjee, S. Zeilinger, I.V. Grigoriev, C.P. Kubicek, Trichoderma: the genomics of opportunistic success, Nat. Rev. Microbiol. 9 (2011) 749–759, https://doi.org/10.1038/nrmicro2637.
[85] N.C. Johnson, G.W.T. Wilson, M.A. Bowker, J.A. Wilson, R.M. Miller, Resource limitation is a driver of local adaptation in mycorrhizal symbioses, Proc. Natl. Acad. Sci. U.S.A. 107 (2010) 2093–2098, https://doi.org/10.1073/pnas.0906710107.
[86] O. Steenhoudt, J. Vanderleyden, Azospirillum, a free-living nitrogen-fixing bacterium closely associated with grasses: genetic, biochemical and ecological aspects, FEMS Microbiol. Rev. 24 (2000) 487–506, https://doi.org/10.1016/s0168-6445(00)00036-x.
[87] Y. Bashan, G. Holguin, L.E. de-Bashan, Azospirillum-plant relationships: physiological, molecular, agricultural, and environmental advances (1997-2003), Can. J. Microbiol. 50 (2004) 521–577, https://doi.org/10.1139/w04-035.
[88] A. Sy, E. Giraud, P. Jourand, N. Garcia, A. Willems, P. de Lajudie, Y. Prin, M. Neyra, M. Gillis, C. Boivin-Masson, B. Dreyfus, Methylotrophic Methylobacterium bacteria nodulate and fix nitrogen in symbiosis with legumes, J. Bacteriol. 183 (2001) 214–220, https://doi.org/10.1128/JB.183.1.214-220.2001.
[89] C. Knief, A. Ramette, L. Frances, C. Alonso-Blanco, J.A. Vorholt, Site and plant species are important determinants of the Methylobacterium community composition in the plant phyllosphere, ISME J. 4 (2010) 719–728, https://doi.org/10.1038/ismej.2010.9.
[90] O.V. Berezina, N.V. Zakharova, A. Brandt, S.V. Yarotsky, W.H. Schwarz, V.V. Zverlov, Reconstructing the clostridial n-butanol metabolic pathway in Lactobacillus brevis, Appl. Microbiol. Biotechnol. 87 (2010) 635–646, https://doi.org/10.1007/s00253-010-2480-z.
[91] P. Estrada-De Los Santos, R. Bustillos-Cristales, J. Caballero-Mellado, Burkholderia, a genus rich in plant-associated nitrogen fixers with wide environmental and geographic distribution, Appl. Environ. Microbiol. 67 (2001) 2790–2798, https://doi.org/10.1128/AEM.67.6.2790-2798.2001.
[92] P. Gyaneshwar, E.K. James, P.M. Reddy, J.K. Ladha, Herbaspirillum colonization increases growth and nitrogen accumulation in aluminium-tolerant rice varieties, New Phytol. 154 (2002) 131–145, https://doi.org/10.1046/j.1469-8137.2002.00371.x.
[93] V.A. Cavalcante, J. Dobereiner, A new acid-tolerant nitrogen-fixing bacterium associated with sugarcane, Plant Soil 108 (1988) 23–31, https://doi.org/10.1007/bf02370096.
[94] Y. Bashan, L.E. de-Bashan, How the plant growth-promoting bacterium Azospirillum promotes plant growth—a critical assessment, in: Advances in Agronomy, Elsevier, 2010, pp. 77–136, https://doi.org/10.1016/S0065-2113(10)08002-8.
[95] J. Nölling, G. Breton, M.V. Omelchenko, K.S. Makarova, Q. Zeng, R. Gibson, H.M. Lee, J. Dubois, D. Qiu, J. Hitti, Y.I. Wolf, R.L. Tatusov, F. Sabathe, L. Doucette-Stamm, P. Soucaille, M.J. Daly, G.N. Bennett, E.V. Koonin, D.R. Smith, Genome sequence and comparative analysis of the solvent-producing bacterium Clostridium acetobutylicum, J. Bacteriol. 183 (2001) 4823–4838, https://doi.org/10.1128/JB.183.16.4823-4838.2001.
[96] P. Dürre, Biobutanol: an attractive biofuel, Biotechnol. J. 2 (2007) 1525–1534, https://doi.org/10.1002/biot.200700168.
[97] V. Bitas, N. McCartney, N. Li, J. Demers, J.-E. Kim, H.-S. Kim, K.M. Brown, S. Kang, Fusarium oxysporum volatiles enhance plant growth via affecting auxin transport and signaling, Front. Microbiol. 6 (2015) 1248, https://doi.org/10.3389/fmicb.2015.01248.
[98] M.I. Mhlongo, L.A. Piater, I.A. Dubery, Profiling of volatile organic compounds from four plant growth-promoting rhizobacteria by SPME-GC-MS: a metabolomics study, Metabolites 12 (2022) 763, https://doi.org/10.3390/metabo12080763.
[99] L.S. Ribeiro, M.L. de Souza, J.M.S. Lira, R.F. Schwan, L.R. Batista, C.F. Silva, Volatile compounds for biotechnological applications produced during competitive interactions between yeasts and fungi, J. Basic Microbiol. 63 (2023) 658–667, https://doi.org/10.1002/jobm.202200409.
[100] R. Razo-Belman, C. Ozuna, Volatile organic compounds: a review of their current applications as pest biocontrol and disease management, Horticulturae 9 (2023), https://doi.org/10.3390/horticulturae9040441.
[101] T.T. Le, S.E. Jun, G.T. Kim, Current perspectives on the effects of plant growth-promoting Rhizobacteria, J. Life Sci. 29 (2019) 1281–1293, https://doi.org/10.5352/JLS.2019.29.11.1281.
[102] S. Rasmann, T.G. Köllner, J. Degenhardt, I. Hiltpold, S. Toepfer, U. Kuhlmann, J. Gershenzon, T.C.J. Turlings, Recruitment of entomopathogenic nematodes by insect-damaged maize roots, Nature 434 (2005) 732–737, https://doi.org/10.1038/nature03451.
[103] A. Bailly, L. Weisskopf, The modulating effect of bacterial volatiles on plant growth: current knowledge and future challenges: current knowledge and future challenges, Plant Signal. Behav. 7 (2012) 79–85, https://doi.org/10.4161/psb.7.1.18418.
[104] P.N. Bhattacharyya, D.K. Jha, Plant growth-promoting rhizobacteria (PGPR): emergence in agriculture, World J. Microbiol. Biotechnol. 28 (2012) 1327–1350, https://doi.org/10.1007/s11274-011-0979-9.
[105] K. Schulz-Bohm, S. Geisen, E.J. Wubs, C. Song, W. De Boer, P. Garbeva, The prey's scent-volatile organic compound mediated interactions between soil bacteria and their protist predators, ISME J. 11 (2017) 817–820.
[106] A. Canale, S. Geri, G. Benelli, Associative learning for host-induced fruit volatiles in Psyttalia concolor (Hymenoptera: braconidae), a koinobiont parasitoid of tephritid flies, Bull. Entomol. Res. 104 (2014) 774–780, https://doi.org/10.1017/S0007485314000625.
[107] M. de Rijk, V. Cegarra Sánchez, H.M. Smid, B. Engel, L.E.M. Vet, E.H. Poelman, Associative learning of host presence in non-host environments influences parasitoid foraging: associative learning in parasitoid foraging, Ecol. Entomol. 43 (2018) 318–325, https://doi.org/10.1111/een.12504.
[108] C. Lazcano, J. Domínguez, The use of vermicompost in sustainable agriculture: impact on plant growth and soil fertility, Soil Nutrients 10 (2011).
[109] R. Hung, S. Lee, J.W. Bennett, Fungal volatile organic compounds and their role in ecosystems, Appl. Microbiol. Biotechnol. 99 (2015) 3395–3405, https://doi.org/10.1007/s00253-015-6494-4.

[110] L.A. Weston, Utilization of allelopathy for weed management in agroecosystems, Agron. J. 88 (1996) 860–866, https://doi.org/10.2134/agronj1996.00021962003600060004x.
[111] G.-I. Arimura, R. Ozawa, T. Nishioka, W. Boland, T. Koch, F. Kühnemann, J. Takabayashi, Herbivore-induced volatiles induce the emission of ethylene in neighboring lima bean plants, Plant J. 29 (2002) 87–98, https://doi.org/10.1046/j.1365-313x.2002.01198.x.
[112] M. Dicke, I.T. Baldwin, The evolutionary context for herbivore-induced plant volatiles: beyond the "cry for help,", Trends Plant Sci. 15 (2010) 167–175, https://doi.org/10.1016/j.tplants.2009.12.002.
[113] M. Kai, U. Effmert, G. Berg, B. Piechulla, Volatiles of bacterial antagonists inhibit mycelial growth of the plant pathogen Rhizoctonia solani, Arch. Microbiol. 187 (2007) 351–360, https://doi.org/10.1007/s00203-006-0199-0.
[114] R. Sharifi, C.-M. Ryu, Sniffing bacterial volatile compounds for healthier plants, Curr. Opin. Plant Biol. 44 (2018) 88–97, https://doi.org/10.1016/j.pbi.2018.03.004.
[115] T.D. Sharkey, F. Loreto, Water stress, temperature, and light effects on the capacity for isoprene emission and photosynthesis of kudzu leaves, Oecologia 95 (1993) 328–333, https://doi.org/10.1007/bf00320984.
[116] V. Velikova, P. Pinelli, S. Pasqualini, L. Reale, F. Ferranti, F. Loreto, Isoprene decreases the concentration of nitric oxide in leaves exposed to elevated ozone: rapid report, New Phytol. 166 (2005) 419–425, https://doi.org/10.1111/j.1469-8137.2005.01409.x.
[117] M. Krzesłowska, The cell wall in plant cell response to trace metals: polysaccharide remodeling and its role in defense strategy, Acta Physiol. Plant. 33 (2011) 35–51, https://doi.org/10.1007/s11738-010-0581-z.
[118] D.M. Ha-Tran, T.T.M. Nguyen, S.-H. Hung, E. Huang, C.-C. Huang, Roles of plant growth-promoting rhizobacteria (PGPR) in stimulating salinity stress defense in plants: a review, Int. J. Mol. Sci. 22 (2021) 3154, https://doi.org/10.3390/ijms22063154.
[119] M. Kottb, T. Gigolashvili, D.K. Großkinsky, B. Piechulla, Trichoderma volatiles effecting Arabidopsis: from inhibition to protection against phytopathogenic fungi, Front. Microbiol. 6 (2015) 995, https://doi.org/10.3389/fmicb.2015.00995.
[120] A. Vaishnav, S. Kumari, S. Jain, A. Varma, D.K. Choudhary, Putative bacterial volatile-mediated growth in soybean (Glycine max L. Merrill) and expression of induced proteins under salt stress, J. Appl. Microbiol. 119 (2015) 539–551, https://doi.org/10.1111/jam.12866.
[121] W. Raza, N. Ling, D. Liu, Z. Wei, Q. Huang, Q. Shen, Volatile organic compounds produced by Pseudomonas fluorescens WR-1 restrict the growth and virulence traits of Ralstonia solanacearum, Microbiol. Res. 192 (2016) 103–113, https://doi.org/10.1016/j.micres.2016.05.014.
[122] P. Vejan, R. Abdullah, T. Khadiran, S. Ismail, A. Nasrulhaq Boyce, Role of plant growth promoting rhizobacteria in agricultural sustainability-A review, Molecules 21 (2016) 573, https://doi.org/10.3390/molecules21050573.
[123] C.N. Kanchiswamy, M. Malnoy, M.E. Maffei, Chemical diversity of microbial volatiles and their potential for plant growth and productivity, Front. Plant Sci. 6 (2015) 151, https://doi.org/10.3389/fpls.2015.00151.
[124] C.-M. Ryu, M.A. Farag, P.W. Pare, J.W. Kloepper, Invisible signals from the underground: bacterial volatiles elicit plant growth promotion and induce systemic resistance, Plant Pathol. J. 21 (2005) 7–12, https://doi.org/10.5423/ppj.2005.21.1.007.
[125] S. Gouda, R.G. Kerry, G. Das, S. Paramithiotis, H.-S. Shin, J.K. Patra, Revitalization of plant growth promoting rhizobacteria for sustainable development in agriculture, Microbiol. Res. 206 (2018) 131–140, https://doi.org/10.1016/j.micres.2017.08.016.
[126] E.J. Gray, D.L. Smith, Intracellular and extracellular PGPR: commonalities and distinctions in the plant-bacterium signaling processes, Soil Biol. Biochem. 37 (2005) 395–412, https://doi.org/10.1016/j.soilbio.2004.08.030.
[127] D. Kang, D.R. Kirienko, P. Webster, A.L. Fisher, N.V. Kirienko, Pyoverdine, a siderophore from Pseudomonas aeruginosa, translocates into C. elegans, removes iron, and activates a distinct host response, Virulence 9 (2018) 804–817, https://doi.org/10.1080/21505594.2018.1449508.
[128] M.D. Mashabela, L.A. Piater, I.A. Dubery, F. Tugizimana, M.I. Mhlongo, Rhizosphere tripartite interactions and PGPR-mediated metabolic reprogramming towards ISR and plant priming: a metabolomics review, Biology 11 (2022) 346, https://doi.org/10.3390/biology11030346.
[129] O. Tyc, C. Song, J.S. Dickschat, M. Vos, P. Garbeva, The ecological role of volatile and soluble secondary metabolites produced by soil bacteria, Trends Microbiol. 25 (2017) 280–292, https://doi.org/10.1016/j.tim.2016.12.002.
[130] C.O. Dimkpa, J. Zeng, J.E. McLean, D.W. Britt, J. Zhan, A.J. Anderson, Production of indole-3-acetic acid via the indole-3-acetamide pathway in the plant-beneficial bacterium Pseudomonas chlororaphis O6 is inhibited by ZnO nanoparticles but enhanced by CuO nanoparticles, Appl. Environ. Microbiol. 78 (2012) 1404–1410, https://doi.org/10.1128/AEM.07424-11.
[131] K.P. Smith, J. Handelsman, R.M. Goodman, Genetic basis in plants for interactions with disease-suppressive bacteria, Proc. Natl. Acad. Sci. U.S.A. 96 (1999) 4786–4790, https://doi.org/10.1073/pnas.96.9.4786.
[132] M. Kai, U. Effmert, B. Piechulla, Bacterial-plant-interactions: approaches to unravel the biological function of bacterial volatiles in the rhizosphere, Front. Microbiol. 7 (2016) 108, https://doi.org/10.3389/fmicb.2016.00108.
[133] J.-H. Chung, G.C. Song, C.-M. Ryu, Sweet scents from good bacteria: case studies on bacterial volatile compounds for plant growth and immunity, Plant Mol. Biol. 90 (2016) 677–687, https://doi.org/10.1007/s11103-015-0344-8.
[134] M.I. Mhlongo, L.A. Piater, N.E. Madala, N. Labuschagne, I.A. Dubery, The chemistry of plant-microbe interactions in the rhizosphere and the potential for metabolomics to reveal signaling related to defense priming and induced systemic resistance, Front. Plant Sci. 9 (2018) 112, https://doi.org/10.3389/fpls.2018.00112.
[135] A.-K.J. Tahir, Enhancing plant resistance to biotic stresses through rhizobacteria for sustainable agriculture, Not. Bot. Horti Agrobot. Cluj-Napoca 52 (2024), https://doi.org/10.15835/nbha52213650.
[136] N. Rafique, S. Khalil, M. Cardinale, A. Rasheed, Z.H. Fengliang, Z. Abideen, A comprehensive evaluation of the potential of plant growth-promoting rhizobacteria for applications in agriculture in stressed environments, Pedosphere (2024), https://doi.org/10.1016/j.pedsph.2024.02.005.
[137] M. Mondal, J.K. Biswas, T. Roychowdhury, Rhizobacteria that boost plant growth while lowering abiotic stress—a profitable solution, in: Biotechnology of Emerging Microbes, Elsevier, 2024, pp. 45–59, https://doi.org/10.1016/B978-0-443-15397-6.00004-8.
[138] S. Chakraborty, A. Hooi, S. Mahapatra, Amelioration of biotic stress by using rhizobacteria: sustainable Crop Production. InMicrobiome Drivers of Ecosystem Function, Academic Press, 2024, https://doi.org/10.1016/B978-0-443-19121-3.00006-5.
[139] C. Vairavan, B.M. Kamble, A.G. Durgude, S.R. Ingle, K. Pugazenthi, Hyperspectral imaging of soil and crop: a review, review, Journal of Experimental Agriculture International 46 (2024) 48–61, https://doi.org/10.9734/jeai/2024/v46i12290.
[140] Z. Jiao, The application of remote sensing techniques in ecological environment monitoring, highlights in science, Eng. Technol. 81 (2024) 449–455, https://doi.org/10.54097/7dqegz64.
[141] L. Wang, Y. Cheng, G. Parekh, R. Naidu, Real-time monitoring and predictive analysis of VOC flux variations in soil vapor: integrating PID sensing with machine learning for enhanced vapor intrusion forecasts, Sci. Total Environ. 924 (2024) 171616, https://doi.org/10.1016/j.scitotenv.2024.171616.