Review Article

Beneficial Role of soil microbiome in enhancing crop productivity, insight from recent study

Abstract

Reducing the use of synthetic fertilizers and pesticides is the goal of current agricultural practices, which calls for low-input technology to improve food production sustainability and restore ecosystem function. The geochemical cycles and plants function rely heavily on the contributions of the soil biota to many ecosystem endeavours. As a result of interactions between host plants roots and microbes in the rhizosphere, these beneficial microorganisms perform a variety of functions that promote plants growth, such as fixing, mineralizing, solubilizing, and mobilizing nutrients; producing siderophores, antagonistic substances, and antibiotics; and releasing hormones that promote plants growth, such as auxin and gibberellin. Microbes that are vital for agriculture and possess properties that may dissolve iron and zinc can be employed to biofortify micronutrients in various cereal crops. Our capacity to manage soil fertility and create a high-yield food production system will be sustained by our increased understanding of plants-microbe interactions in both natural and agroecosystems. Utilising the microbiome effectively contributes to a safe environment, which benefits human health. In an effort to increase soil productivity and fertility for future generations, soil microbiologists are working to analyse the diversity of soil niches and then try to characterise the roles of these soil residents at trophic levels.

Keywords:microbe, soil-plants interaction, crop productivity, sustainability

1. Introduction

By 2050, there will likely be 9.7 billion people on the planet, which will raise demand for food and water. According to this scenario, food production must rise by 70% by the year 2050 [1]. In order to fulfil the world's food demand, intensive cropping and extensive use of water, agrochemicals, and mineral fertilizers resulted in environmental contamination, soil degradation, and the loss of natural resources [2]. The negative effects of numerous anthropogenic activities, such as changing land uses and intensifying agricultural practices, are currently negatively affecting soils despite their ecological significance [3]. This is causing a decline in soil biodiversity worldwide [4-6]. Sustainable agriculture aims to produce food with as little of an impact on the environment and the food chain as possible from leftover chemical effects. Soil microbes are essential to agriculture since they enhance plants nutrition and health as well as soil quality [7,8]. Given its abundance of macro- and microbes, soil is home to the most varied biological population on the planet [9,10]. In order to maintain ecosystem services like food production and climate control, soil biodiversity is essential to many ecological processes, or ecosystem multifunctionality [11,12].

Soil-plants-microbial interactions have been a topic of study among scientists for a while given its close relationship to microbiologists, agronomists, soil scientists, botanists, and pathologists. Apart from its connection to fundamental scientific research, microbial interaction can have an applied impact on agricultural productivity. It is crucial to comprehend both the microbial population and the root architecture in order to have a comprehensive understanding of how these interactome associates, given the microbial diversification, speciation, structural complexity, and interactions that surround the root systems [13]. Soil microbes and plantss interact at high levels, leading to the observation of these components as holobionts or metaorganisms [14, 15]. Apart from the microbe-plants and microbe-microbe relationships, there are also the microbe–microbe and microbe–soil connections. The environment and other soil elements, in addition to plantss, increase the complexity of the bacteria in the soil. The microbiome is significantly influenced by the physical, chemical, and biological elements of the soil [16].

Beneficial microorganisms plays a crucial role in sustainable agriculture and has many roles such as can be added to soil or inoculated to enhance agricultural techniques. To improve crop health and yield while reducing the harmful effects of agrochemicals, microbial inoculants are injected into the soil or plantss. It may control diseases and pests, stabilize soil structure, and encourage plants growth—all of which make it a viable substitute for chemical treatment. These inputs might be used as biopesticides, biocontrol agents, bioherbicides, and biofertilizers. Considerable progress has been achieved in the production, distribution, and application of vaccines in the past several years [17]. Since there are now more high-quality, multipurpose strains on the market that increase production at a cheaper cost than synthetic fertilizers, the use of inoculants is becoming more prevalent. The most often used bacteria as inoculants are rhizobia [18]. The biological nitrogen fixation (BNF) process, which meets the plant's nitrogen requirements, is influenced by the legume-rhizobia symbiosis [17]. In a variety of settings, plants growth-promoting bacteria (PGPB) can assist a plants either by themselves or in conjunction with other elements. The creation of phytohormones and siderophores, the solubilization of phosphate, and the induction of a plant’s defense mechanism against biotic and abiotic stresses are all ways that PGPB affects plantss(Table 1) [19,20]. In agriculture, the use of different microorganisms forecological pest and disease management is growing [21]. Some of the factors are:

Biotic factor: Several factors, such as host genome, the developmental stage of the plants and its root architecture, are known to modulate the community structure and diversity of rhizospheric microbiome members. Plants when they are exposed to pathogens they activate a defense mechanisms such as ISR (induced systemic response) and SAR (systemic acquired response) which help them in alleviats the adverse effects of pathogens and viral attacks. Plants growth stages have a major impact on microbe interactions [115].

Abiotic factor: Soil pH, temperature, moisture and pesticide application also play important roles. Soil is a reservoir of diverse microbial communities with a range of functions that cause a significant impact on soil health. Continuous and non-judicious use of synthetic chemicals has led to soil contamination and degradation. Owing to these problems, soil faces functionality losses such as nutrient imbalance, nutrient deficiencies and biodiversity losses. Thus this affects the microbial diversity [115].

Table 1: Role of PGPM in alleviating biotic and abiotic stress

PGPM	Plants	Inoculation	Factor	Effect	Reference
Pseudomonas aeruginosa and *Bacillus subtilis*	*Brassica juncea*	Seed	Soil	Heavy metal tolerance and increase plants growth	[22]
Azotobacter chrococcum	*Glycin max*	Soil	Water	Improve plants growth and flood tolerance by	[23]

				inducing adventitious root	
Bacillus sp.	*Solanum lycopersicum*	Seed	Light	Under high light, PGPM increases growth and seed production	[24]
Pseudomonas sp.	*Triticum sp.*	Seed	Tempera ture	Increase low temperature tolerance by modification of carbohydrate metabolism	[25]
B. megaterium and *Glomus sp* .	*Trifolium*	Seed	Soil	Improved root system architecture, enlarged plants biomass, and increased photosynthetic capacity	[26]
Glomus sp.	*C. arietinum*	Seed	Drought	Growth, IAA production, ACCD activity, P solubilization, Siderophore activity	[27]
Pseudomonas otitidis	*P. vulgaris*	Seed	Disease	Inhibits pathogenss and growth promotion	[28]

2. Microbiome interaction

The soil is home to a wide range of phylogenetic groupings as well as important functional groups as producer, consumer, and decomposer microorganisms. Interestingly, each gram of soil has hundreds of genomes, which together make up genetic diversity [29]. Plantss and soil microorganisms can have mutualistic or harmful interactions (Fig. 1)[30]. The majority of terrestrial vegetation and the yearly nitrogen needs are ultimately the result of soil bacteria acting as decomposers. According to this hierarchy, the primary source of carbon fixed by photosynthesis in plantss is microorganisms [31]. In addition to competing for soil resources, microorganisms and plantss develop a mutualistic and competitive interaction concurrently [32].

Through the provision of mineral resources and defense against other pests, mycorrhizal fungi and PGPR improve the host plants's fitness [33,34]. Plantss are additionally protected from soil pathogenss by a variety of different nonmycorrhizal fungi, rhizospheric bacteria, protozoa, and nematodes [35,36]. These pathogenss include fungus, bacteria, actinobacteria, protozoa, nematodes, and viruses.

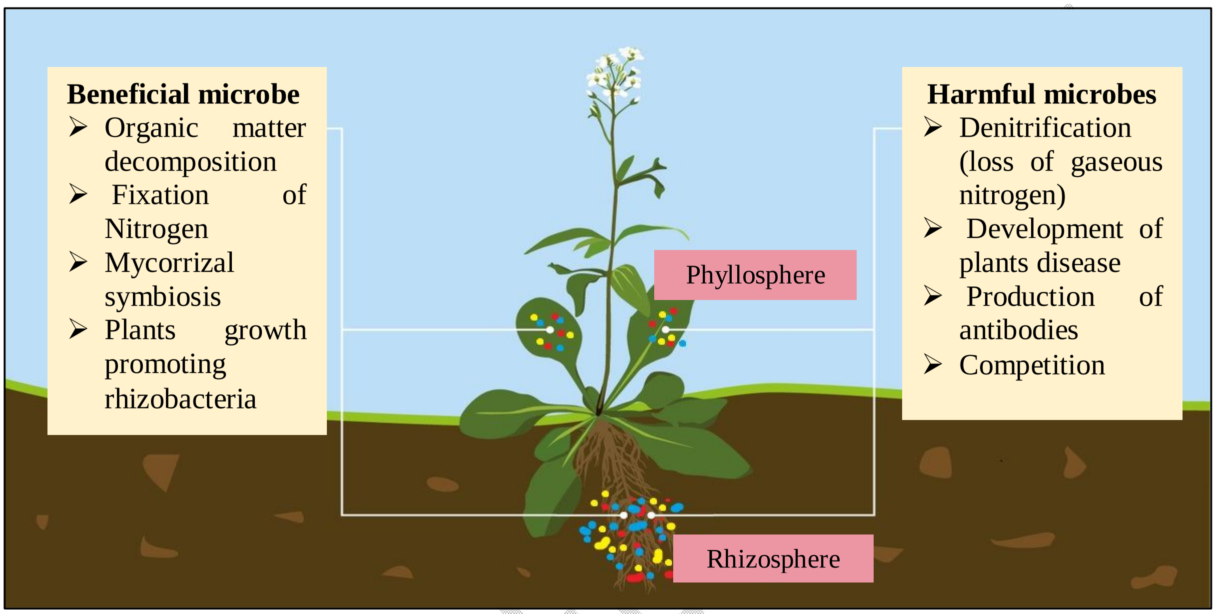

Fig. 1: Beneficial and harmful microbe's attribution to plants

2.1 Interaction between Soil Microbes and Plants

Plants get their nutrients from the soil, which is a complex ecosystem that is home to a wide range of protists, bacteria, fungus, and animals. According to Ratnadass et al. [37], plants exhibit a wide variety of interactions with these soil-dwelling microbes that cover the whole spectrum of environmental potentials, including competitive, exploitative, neutral, commemensal, and mutualistic relationships. While the ecological interactions have long-standing interest in characterization, a variety of interactions were observed that concentrated on enhancing the effects of pathogenss like herbivory and infection or tempering abiotic stress conditions through modern plants science [38]. When attacked by pathogens, plants activate a complex array of biochemical responses to prevent disease establishment and spread [116]. Immune receptors, antimicrobial proteins, and secondary metabolites have been widely investigated and characterized as key components of the plant immune system [117]. To reiterate the beneficial roles of microorganisms, research has shifted in the contemporary scenario towards assembling fairly planned, unimaginative clusters that form the strains of the dominant rhizospheric species.

Interactions that are advantageous to the host or the residing microorganisms in one or more ways are called beneficial interactions. Beneficial microbe interactions often aid in the solubilization and mobilization of inaccessible soil nutrients, promote plants growth promotion, defend against pests and diseases, and enable the partners tolerate abiotic stress.

2.1.1 Nitrogen-Fixing Microbes

Based on their interactions with their host plantss, nitrogen-fixing bacteria are classified as endophytes, symbiotic, associative symbiotic, and symbiotic/free dwelling [39]. The main source of nitrogen in the soil that is accessible to plantss is microbial symbiotic fixation of nitrogen. The bacterial genera *Rhizobium, Bradyrhizobium, Sinorhizobium, Mesorhizobium, Azorhizobium,* and *Photorhizobium*, which produce either root nodules or stem nodules and represent rod-shaped Proteobacteria, are included in the symbiotic nitrogen-fixing group [40]. Recent studies have demonstrated that various α-Proteobacteria, such as *Phyllobacterium, Methylobacterium, and Ochrobactrum*, and *β-Proteobacteria*, such as *Burkholderia, Cupriavidus*, and *Devosia*, also form nitrogen-fixing nodules in legume roots in addition to rhizobia [41]. Another significant source of nitrogen in certain agricultural plantss is actinobacterial symbiosis (Frankia) [42]. N_2-fixer genera that are both free-living and symbiotic include *Burkholderia, Azotobacter, Beijerinckia, Bacillus, Pantoea,* and *Klebsiella*. A small number of Cyanobacteria, such as *Nostoc, Anabaena, Calothrix*, etc., are also involved in asymbiotic N_2 fixation in addition to bacteria. According to Bashan and de-Bashan [43], the leading genus in associative symbiotic N_2 fixation is Azospirillum.

2.1.2 Mycorrhizae

The mutualistic relationship known as mycorrhizal symbiosis occurs between fungi and higher plantss, and it has been observed in of several terrestrial plantss[39]. Ecto- and endomycorrhiza are two different types of mycorrhiza based on their interactions and location in plants roots. Endo or arbuscular mycorrhizal fungal (AMF) relationships have been documented from a variety of crops, but ectomycorrhiza has primarily been researched in trees. The genera *Glomus, Gigaspora, Acaulospora, Scutellospora,* and*Entrophospora* are the most often seen AM fungal species. According to reports, nitrogen fixers, phosphate solubilizers, and other plants growth-promoting rhizobacteria (PGPRs) interact synergistically with AM fungi in the soil [44]. According to reports, mycorrhizal association in crop plantss offers numerous benefits to crops, including enhanced phosphorus mobilisation and uptake of macro- and micronutrients [45], as well as resistance to heavy metals, drought, and increased potential for biocontrol and disease suppression [46].

2.1.3 Plants Growth-Promoting Rhizobacteria (PGPRs)

Plants growth-promoting rhizobacteria (PGPRs) are microorganisms that have been the subject of research in the rhizosphere of agricultural plantss during the past 10 years due to their potential to enhance plants development and production [47]. According to Viveros et al. [48], there are two general categories of PGPR: extracellular and intracellular. The rhizosphere and rhizoplane are the primary locations for extracellular plants growth regulators (PGPRs) [49], whilst the specialised nodular structures inside root cells—also known as endophytes—are the home of internal PGPRs. According to Ahemad and Kibret[50], common extracellular PGPR are associated with bacterial taxa that include *Bacillus, Burkholderia, Agrobacterium, Erwinia, Arthrobacter, Azotobacter, Azospirillum, Caulobacter, Chromobacterium, Flavobacterium, Micrococcus, Pseudomonas,* and *Serratia*. These rhizospheric microbes enhance plants growth in two ways: either by secreting growth-promoting chemicals (IAA, GA, cytokinins, ethylene, etc.) or by inhibiting specific plantspathogenss through their biocontrol activity. Major, secondary, and micronutrients—nitrogen fixation, phosphorus and potassium solubilization, iron sequestration, etc.—are increased through increased nutrient uptake [51]. When inoculated alone or with bacterial or fungal partners, a number of cyanobacteria are involved in promoting plants growth, improving nutrient uptake, and enhancing soil fertility in crops [52].

2.1.4 Endophytes

Endophytes are microorganisms, such as bacteria or fungi, that reside inside plants cells or tissues without negatively impacting them. Endophytes are beneficial to plantss in a variety of ways and often rely on the host plants for sustenance and protection. Numerous endophytes have been shown to improve nutrient cycling, hasten seedling emergence, encourage plants development, increase yield, aid in bioremediation, and lessen disease proliferation. According to Arnold [53], endophytes generate phytohormones and hence improve resistance to abiotic stressors. Nearly all plants tissues, including the roots, stem, bark, leaves, floral parts, and seeds, are susceptible to endophyte colonisation. The microbiome of plantss is home to a variety of endophytes that exhibit significant levels of abundance [54]. These endophytes modulate gene expression to benefit plants nutrition and elicit defense mechanisms. Actinomycetes such as Streptomyces and Microbiospora, and genera such as *Azospirillum, Gluconacetobacter, Herbaspirillum, Azoarcus, Achromobacter, Acinetobacter, Pseudomonas*, etc. are some of the often reported bacterial endophytes [55]. It was discovered that the Basidiomycetes group of fungi was the most prevalent endophyte. Unknown taxa *Exophyla, Cladophialophora, Harpophora, Periconiamacrospinosa,* and *Ceratobasidium/Rhizoctonia* complex are examples of other fungal endophytes that have been linked to improved plants development and nutrient uptake [56].

3. Microbe (Plants Growth Promoting Microorganisms) as a bioinoculants/biofertilizers

The rhizosphere's bacterial and fungal communities may be home to PGPMs, or helpful microbes. In more environmentally friendly and sustainable agricultural systems, the application of PGPM as microbial inoculants, or biofertilizers is a potentially beneficial strategy for increasing crop yield, food quality, and security [57]. PGPM functions as a biofertilizer by solubilizing soil minerals like phosphorus and potassium and bio-fixing atmospheric nitrogen, boosting the availability of nutrients. According to Bhat et al. [58], some rhizobacteria can aid in the synthesis of siderophores that improve iron updating. Additionally, they act as a direct phytostimulator, increasing the synthesis of auxin, cytokinins, abscisic acid, gibberellins, and ethylene reduction while also impacting the metabolism of phytohormones [58,59]. Indirect effects of PGPM as biopesticides or biocontrol agents include boosting resistance to phytopathogenss through antagonistic interactions, competition for nutrients, and the induction of systemic resistance [58,59].

Beneficial bacteria's ability to thrive in roots is demonstrated by their ability to colonise seeds [60]. The direct distribution of microorganisms in the rhizosphere, where they may form associations with plantss, is a benefit of this microbial consortium seed-inoculation approach [61]. Microorganisms can be injected into plantss to increase their nutrient availability and aid in efficient carbon sequestration below ground [62]. Leguminous plantss that have had their seeds inoculated have a high incidence of rhizobia in the rhizosphere. These microorganisms then proceed to colonize, form nodules, and fix nitrogen [63] to maximise yield and production.

Formulation type and method often dictate the mode of application of the inoculant. As to Khandelwal et al. [64], solid formulations are primarily delivered by broadcasting across the field or seed dressing, whereas liquid formulations can be supplied through several methods. The most widely employed liquid carriers are water and/or organic solvents (such as glycerol and carboxymethyl cellulose, excluding microbiological media); these chemicals are used to enhance properties like stickiness and dispersion capacities [65]. According to Babalola and Glick [66], there are many different types of solid carriers, such as clay, vermiculite, peat, and charcoal. It's important to choose microbiological carriers carefully to ensure they won't damage the environment or the microbe [67]. Further, the microbe with its carrier base can be applied to the plants for improving growth and productivity.

3.1 Microbes for enhancing crop growth and productivity

3.1.2 Microbes for crop growth

Plants growth-promoting microorganisms (PGPMs) have long been known to enhance plants health and increase yield [68]. It is possible to supplement soil, seeds, leaves, seedling roots, or a combination of these using microbial inoculants. PGPM directly stimulates plants development via enhancing nutrient availability [69], controlling phytohormones, and indirectly inducing systemic resistance [59]. *Pseudomonas*, *Bacillus*, and *Mycobacterium* inoculation is often more effective in encouraging plants development in nutrient-poor soils [70]. Beneficial microorganisms improve the availability of nutrients, control phytohormones, and boost a plants's resistance to biotic and abiotic stresses. Each of these procedures helps to enhance the development of plantss [71]. The actions previously mentioned indicate that PGPM increases the levels of auxin, gibberellin, cytokinin, and ACC-deaminase. Furthermore, advantageous microbes can produce volatile metabolites (VOC), which can increase resistance to illness and abiotic stress. Additionally, by increasing exopolysaccharides, osmo-regulants, and antioxidants while decreasing oxidative stress, PGPM can reduce stress [72]. Studies have been conducted on PGPM as a possible biofertilizer that might increase the availability of macro- and micronutrients, promote plants growth, and reduce the need for chemical fertilization [73].

Plants height, biomass production, seed germination, seedling vigour, chlorophyll content, and photosynthetic rates are all enhanced by PGPM. Using microbial compounds could also be a better choice because seed inoculation of PGPM (*PSB* and *Aspergillus awamori*) has been demonstrated to significantly increase the growth characteristics, yield, and yield attributes of mungbean [74]. To help with plants growth and development, a range of phytohormones are secreted into the soil by plants growth promoters. Lipochitooligosaccharides (LCOs) are one example; they may be employed in both stressed and non-stressed contexts [75] to encourage the growth of non-leguminous crops and legumes [76].

3.1.3 Microbes for crop productivity

Plantss associated with microbial diversity are the result of ecological and evolutionary processes [77]. The fact that PGPMs are a specialist group of microorganisms that support and protect plantss—which in turn provide bacteria with food—is one of their shared traits. Using PGPM increases fertiliser usage efficiency by solubilizing insoluble phosphates in the soil and fixing biological nitrogen. Consortia of *Bacillus sp*. (BPR7), *Pseudomonas sp*. (PPR8), and *Rhizobium leguminosarum* (RPN5) have been shown to considerably increase *P. vulgaris* production in an experiment carried out by Kumar et al. [78]. This might result from using B. subtilis and *Pseudomonas species*, which along with other phosphate-solubilizers have significant phosphate-solubilizing activity and increase yield. Ojuederie and Babalola [79] found that the biomass and nutrient intake of Sorghum plantss increased after PGPM inoculation in a soil-based medium, either by itself or in combination with mycorrhiza. PGPM (*Trichoderma viride*) bio-inoculation significantly increases rice yield and yield-related traits [80]. The results demonstrate how *Trichoderma* colonises roots and communicates with plantss to produce growth regulators, develop systemic resistance to infections, and solubilize P to increase the amount of nutrients available to the plantss—all actions that support plants development and productivity.

4. Soil-beneficial microorganisms for sustainable agriculture

The symbiotic relationships between nitrogen-fixing bacteria, primarily rhizobia, arbuscular mycorrhizal fungi, and phosphate-solubilizing bacteria, among other benefits of the microbiome for plantss, also aid in stress and heavy metal tolerance internally, improve soil microbial and enzymatic activity, and helps in enhancing the soil ecosystem services. Additionally, the microbiome is crucial for a plants's ability to withstand harsh environmental factors such as salt, drought, and heavy metal exposure [81]. Salinity in the soil has slowed plants development and decreased productivity. However, the generation of phytohormones by the microbiome can reduce the detrimental effects of high salt levels in the soil, increasing plants tolerance to these harsh conditions [81]. According to a Miller et al.[82], the rhizosphere microbiota can encourage *Hibiscus hamabo* germination and development in salinity-prone environments. In the rhizosphere of contaminated soil plantss, a model was recently suggested by Kumar et al. [83] to explain the formation and maintenance of the degrading and beneficial microbiome. To maintain the microbial population under control in contaminated environments, four techniques were identified: feeding of supply lines, root exudate interference, disturbance, and plants selection depending on the microbiome. The microbiome is essential to the survival, development, and biomass production of plantss in oil-contaminated soils [84].

The most recent developments in PGPM applications in various agroecosystems have made it clear that further understanding of how these systems work is needed. While rhizospheric bacteria for horticulture and agriculture are still being commercially exploited, reports suggest that there is a global market with potential development of 10% annually [85]. Numerous microorganisms, such as fungi and bacteria, have already been made commercially available. Consequently, studies have demonstrated that low-input technology for managing microbial interactions in the rhizosphere can enhance sustainable farming methods [86]. All potential interactions in the rhizosphere mediated by plantss, either directly or indirectly. Gaining fresh insight into the relationship between microbiomes and plantss is essential to reducing the effects of climate change and ensuring food security and agricultural sustainability. A thorough comprehension of the functional ecological processes of soil microorganisms in the rhizosphere is essential for their successful use. Furthermore, significant advancements in yield with fewer chemical inputs will come from the introduction of crop types aimed at augmenting certain phyto-beneficial activities in soil microbial communities. Our understanding of sensing, signalling, and secretion in soil microbial populations linked with plants has to be expanded in order to improve plants health and nutrient absorption.

5. Future Challenges and Way Forward

Research on the functional profile of the rhizosphere, which is important for activities like nutrient mobilization and plants disease control, will be facilitated by future advancements in functional genomics. One of the main goals of practical research in the future should be the precise regulation of soil microbial associations through the creation of appropriate mycorrhizospheres. In this way, the optimization and acclimatization of the soil microbiome may also lead to additional improvements in its efficiency. They are expected to replace artificial growth regulators, herbicides, and chemical fertilizersshortly. Improved competent isolates that are effective in a variety of agroecological settings would be made possible by more studies on microbe-mediated phytostimulation. The field of ecological engineering, which will investigate the practical significance of microbial ecology, could help from advancements in metagenomics and metaproteomics.

Diverse research methodologies are now being employed to investigate the possibility of engineering the rhizosphere to promote beneficial organisms while inhibiting the presence of diseases. Numerous difficulties with research methods are presented by the associated study subjects. Gaining a biased rhizosphere unquestionably creates new possibilities for agricultural advancements in the future that rely on the utilization of advantageous microbial services to lower pesticide inputs and achieve sustainable economic and environmental objectives. Moreover, developing plans to create innovative biotechnological interventions that combine sustainable technology with restoring of microbial diversity in local and regional agroecosystems may provide major advantages. Communities that have managed to hold onto their regional knowledge bases will be in a good position to start new business initiatives that entail teaching nearby farmers how to grow food with less pesticide input. A new generation of customers who are more interested in organic and locally farmed foods is demanding such items. Lastly, in addition to the scientific methods, the administrative role in formulating policies and practices that support the integration of environmental sciences, nutrition, agroecology, crop development, socioeconomics, and extension with microbial ecology will support the development of robust, adaptive, and sustainable agroecosystems that have enhanced potential to mitigate the effects of globalisation and climate change.

6. Scientific relevance

The scientific relevance of the review lies in its detailed exploration of how soil microbiomes can be leveraged to improve agricultural productivity and sustainability. This review underscores the critical functions that soil biota perform, particularly in the rhizosphere, where they engage in nutrient cycling, disease suppression, and growth promotion. The paper highlights how these relationships can be harnessed to reduce dependency on synthetic fertilizers and pesticides by focusing on the beneficial interactions between plant roots and microbes. Such insights are particularly pertinent as they offer viable low-input technological solutions to enhance food production while restoring ecosystem functions, a key goal in modern sustainable agriculture.

In the context of soil quality and crop productivity studies, this review presents a significant comparison to current scientific production in developing countries such as Colombia [87, 88], Panama [89, 90], and Venezuela [91, 92, 93]. These nations face unique agricultural challenges, including soil degradation [94, 95], limited access to synthetic inputs, and the need for sustainable practices to support food security. The review's findings align well with the ongoing research in these countries that aims to optimize the use of native soil microbiomes to enhance soil fertility and crop yields [96, 97]. Moreover, the emphasis on the biofortification of crops through microbial interventions resonates with regional priorities to improve nutritional outcomes and support smallholder farmers. This approach offers a path to not only boost agricultural productivity but also to maintain ecological balance and improve human health [98, 99, 100].

Artificial intelligence (AI) techniques are increasingly being integrated into agricultural research and practices in developing countries, and this review complements such efforts by providing a biological foundation that AI can build upon. In Colombia, Panama, and Venezuela, AI is being employed to analyze soil health [101, 102], predict crop yields [103, 104], and optimize resource use [105, 106]. The detailed understanding of soil microbiome functions provided by this review can enhance these AI applications by offering precise biological data that can be integrated into predictive models and decision-support systems [107, 108]. This interdisciplinary synergy between soil microbiome research and AI can drive innovative solutions tailored to the specific agro-ecologicalagroecological conditions of these countries [109, 110], thereby advancing sustainable agricultural practices and improving food security in the region [111, 112, 113].

7. Conclusion

The intricacy of the soil system facilitates the development of a varied microbial community because of stratification and a variety of microhabitats. Understanding the functional categories of bacterial taxa and the dynamics of the bacterial community structure is crucial for comprehending the functioning of soil ecosystems, even beyond taxonomy. PGPM plays an important role in enhancing plants nutrition, productivity as well as ecological stability. Soil microbes improve the physical, chemical and biological properties of soil and have immense potential as biocontrol agents. Various interacting microbes also protect plants against biotic and abiotic stress and improve plants health. Good quality organic inputs with lower doses of chemical fertilizers have the potential to augment sustaining crop productivity and soil fertility. It can be concluded that the interacting microbes strive to optimize diverse biological processes in the soil to create a healthy, fertile environment that ensures adequate nutrition for the crop. Hence, it was evident that the application of PGPM is absolutely indispensable not only to sustain productivity but also to maintain soil health and the ecosystem. However, it is necessary to educate the public about the use of PGPM in agriculture and more widespread utilization of PGPM.

Disclaimer (Artificial intelligence)

Option 1:

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

References

1. Poveda J. Insect frass in the development of sustainable agriculture. A review. Agron Sustain Dev. (2021) 41:1–10. doi: 10.1007/s13593-020-00656-x.
2. Suman J, Rakshit A, Ogireddy SD, Singh S, Gupta C and Chandrakala J (2022) Microbiome as a Key Player in Sustainable Agriculture and Human Health. Front. Soil Sci. 2:821589. doi: 10.3389/fsoil.2022.821589.
3. Winkler, K., Fuchs, R., Rounsevell, M., et al., 2021. Global land use changes are four times greater than previously estimated. Nat Commun 12, 2501. https://doi.org/10.1038/s41467-021-22702-2.

4. Carmona, C.P., Guerrero, I., Peco, B., et al., 2020. Agriculture intensification reduces plants taxonomic and functional diversity across European arable systems. Funct Ecol. 34, 1448–1454. https://doi.org/10.1111/1365-2435.13608.
5. Tsiafouli, M.A., Thébault, E., Sgardelis, S.P., de Ruiter, P.C., van der Putten, W.H., Birkhofer, K., Hemerik, L., de Vries, F.T., Bardgett, R.D., Brady, M.V., Bjornlund, L., Jørgensen, H.B., Christensen, S., Hertefeldt, T.D., Hotes, S., Gera Hol, W.H., Frouz, J., Liiri, M., Mortimer, S.R., Setälä, H., Tzanopoulos, J., Uteseny, K., Pižl, V., Stary, J., Wolters, V., Hedlund, K., 2015. Intensive agriculture reduces soil biodiversity across Europe. Glob Change Biol 21, 973–985. https://doi.org/10.1111/gcb.12752.
6. Zhou, Z.,Wang, C., Luo, Y., 2020. Meta-analysis of the impacts of global change factors on soil microbial diversity and functionality. Nat Commun 11, 3072. https://doi.org/10.1038/s41467-020-16881-7.
7. Barea JM, Pozo MJ, Azcón R, Azcón Aguilar C (2013) Microbial interactions in the rhizosphere. In: de Bruijn FJ (ed) Molecular microbial ecology of the rhizosphere. Wiley, Hoboken, pp 29–44.
8. Lugtenberg B (2015) Life of microbes in the rhizosphere. In: Lugtenberg B (ed) Principles of plants-microbe interactions. Springer, Heidelberg, pp 7–15. doi:10.1007/978-3-319-08575-3_3.
9. Crowther, T.W., van den Hoogen, J., Wan, J., Mayes, M.A., Keiser, A.D., Mo, L., Averill, C., Maynard, D.S., 2019. The global soil community and its influence on biogeochemistry. Science 365 (1979), eaav0550. https://doi.org/10.1126/science.aav0550.
10. Fierer, N., 2017. Embracing the unknown: disentangling the complexities of the soil microbiome. Nat. Rev. Microbiol. 15, 579–590. https://doi.org/10.1038/nrmicro.2017.87.
11. Banerjee, S., van der Heijden, M.G.A., 2023. Soil microbiomes and one health. Nat Rev Microbiol 21, 6–20. https://doi.org/10.1038/s41579-022-00779-w.
12. Byrnes, J.E.K., Gamfeldt, L., Isbell, F., Lefcheck, J.S., Griffin, J.N., Hector, A., Cardinale, B.J., Hooper, D.U., Dee, L.E., Emmett Duffy, J., 2014. Investigating the relationship between biodiversity and ecosystem multifunctionality: challenges and solutions. Methods Ecol. Evol. 5, 111–124. https://doi.org/10.1111/2041-210X.12143.

13. Pascale, A.; Proietti, S.; Pantelides, I.S.; Stringlis, I.A. Modulation of the root microbiome by plants molecules: The basis for targeted disease suppression and plants growth promotion. Front. Plants Sci. 2020, 10, 1741.
14. Hacquard, S.; Schadt, C.W. Towards a holistic understanding of the beneficial interactions across the Populus microbiome. New Phytol. 2015, 205, 1424–1430.
15. Hacquard, S. Disentangling the factors shaping microbiota composition across the plants holobiont. New Phytol. 2016, 209, 454–457.
16. Rahman, N.S.N.A.; Hamid, N.W.A.; Nadarajah, K. Effects of abiotic stress on soil microbiome. Int. J. Mol. Sci. 2021, 22, 9036.
17. Santos, M.S.; Nogueira, M.A.; Hungria, M. Microbial inoculants: Reviewing the past, discussing the present and previewing an outstanding future for the use of beneficial bacteria in agriculture. AMB Express 2019, 9, 205.
18. Backer, R.; Rokem, J.S.; Ilangumaran, G.; Lamont, J.; Praslickova, D.; Ricci, E.; Subramanian, S.; Smith, D.L. Plants growth promoting rhizobacteria: Context, mechanisms of action, and roadmap to commercialization of biostimulants for sustainable agriculture. Front. Plants Sci. 2018, 9, 1473.
19. Bhattacharyya, P.N.; Jha, D.K. Plants growth-promoting rhizobacteria (PGPR): Emergence in agriculture. World J. Microbiol. Biotechnol. 2011, 28, 1327–1350.
20. Malusá, E.; Vassilev, N. A contribution to set a legal framework for biofertilizers. Appl. Microbiol. Biotechnol. 2014, 98, 6599–6607.
21. Berg, G.; Köberl, M.; Rybakova, D.; Müller, H.; Grosch, R.; Smalla, K. Plants microbial diversity is suggested as the key to future biocontrol and health trends. FEMS Microbiol. Ecol. 2017, 93, 50.
22. Aka, N.R.J. and Babalola, O.O. (2016) Effect of bacterial inoculation of strains of *Pseudomonas aeruginosa, Alcaligenes feacalis* and *Bacillus subtilis* on germination, growth and heavy metal (Cd, Cr, and Ni) uptake of *Brassica juncea*. *International Journal of Phytoremediation*, **18**: 200–209.
23. Kim, A.Y., Shahzad, R., Kang, S.M., Seo, C.W., Park, Y.G., Park, H.J. and Lee, I.J. (2017) IAA-producing Klebsiella variicola AY13 reprograms soybean growth during flooding stress. Journal of Crop Science and Biotechnology, 20: 235–242.

24. Verma, M.; Mishra, J.; Arora, N.K. Plants Growth-Promoting Rhizobacteria: Diversity and Applications. In Environmental Biotechnology: For Sustainable Future; Springer: Berlin/Heidelberg, Germany, 2018; pp. 129–173.
25. Fernandez, O., Theocharis, A., Bordiec, S., Feil, R., Jacquens, L. and Clément, C. (2012) BurkholderiaphytofirmansPsJN acclimates grapevine to cold by modulating carbohydrate metabolism. Molecular Plants-Microbe Interactions, 5: 496–504.
26. Zhou, C., Ma, Z., Zhu, L., Xiao, X., Xie, Y. and Zhu, J. (2016). Rhizobacterial Strain *Bacillus megaterium* BOFC15 induces cellular polyamine changes that improve plants growth and drought resistance. International Journal of Molecular Sciences, **17**: 976.
27. Kuffner, M.; Puschenreiter, M.; Wieshammer, G.; Gorfer, M.; Sessitsch, A. Rhizosphere bacteria affect growth and metal uptake of heavy metal accumulating willows. Plants Soil 2008, 304, 35–44.
28. Kumar, P., Pandey, P., Dubey, R.C. and Maheshwaria, D.K. (2016) Bacteria consortium optimization improves nutrient uptake, nodulation, disease suppression and growth of the common bean (Phaseolus vulgaris) in both pot and field studies. Rhizosphere, 2: 13–23.
29. Bardgett RD, Freeman C, Ostle NJ (2008) Microbial contributions to climate change through carbon cycle feedbacks. ISME J 2:805–814.
30. Reynolds HL, Packer A, Bever JD, Clay K (2003) Grassroots ecology: plants–microbe-soil interactions as drivers of plants community structure and dynamics. Ecology 84:2281–2291.
31. Gougoulias C, Clark JM, Shaw LJ (2014) The role of soil microbes in the global carbon cycle: tracking the below-ground microbial processing of plants-derived carbon for manipulating carbon dynamics in agricultural systems. J Sci Food Agric 94:2362–2371.
32. Van Der Heijden MG, Bardgett RD, Van Straalen NM (2008) The unseen majority: soil microbes as drivers of plants diversity and productivity in terrestrial ecosystems. Ecol Lett 11:296–310.
33. Parnell JJ, Berka R, Young HA, Sturino JM, Kang Y, Barnhart DM, DiLeo MV (2016) From the lab to the farm: an industrial perspective of plants beneficial microorganisms. Front Sci 7:1–12.

34. Prasad R, Kumar M, Varma A (2015) Role of PGPR in soil fertility and plants health. In: Egamberdieva D, Shrivastava S, Varma A (eds) Plants growth-promoting rhizobacteria (PGPR) and medicinal plantss. Springer International, Switzerland, pp 247–260.
35. Igiehon NO, Babalola OO (2018) Below-ground-above-ground plants-microbial interactions: focusing on soybean, rhizobacteria and mycorrhizal fungi. Microbiol J 12:261–279.
36. Singh D, Raina TK, Kumar A, Singh J, Prasad R (2019) Plants microbiome: a reservoir of novel genes and metabolites. Plants Gene. https://doi.org/10.1016/j.plgene.2019.100177.
37. Ratnadass A, Blanchart É, Lecomte P (2013) Ecological interactions within the biodiversity of cultivated systems. In: Cultivating biodiversity to transform agriculture. Springer, Dordrecht, pp 141–179.
38. Shoresh M, Harman GE, Mastouri F (2010) Induced systemic resistance and plants responses to fungal biocontrol agents. Annu Rev Phytopathol 48:21–43.
39. Devi OR, Ojha N, Laishram B, Dutta S, Kalita P. Roles of Nano-fertilizers in sustainable agriculture and biosafety. Environment and Ecology. 2023;41(1B):457—463.
40. Deaker R, Roughley RJ, Kennedy IR (2004) Legume seed inoculation technology – a review. Soil BiolBiochem 36:1275–1288.
41. Moreira FMS (2008) Nitrogen fixing Leguminosae-nodulating bacteria. In: Moreira FMS, Huising EJ, Bignell DEA (eds) Hand book of tropical soil biology. Earthscan, London, pp 107–130.
42. Daniel G, Jaffre T, Prin Y (2007) Abundance of Frankia from Gymnostoma spp. in the rhizosphere of Alphitonianeocaledonica, a non nodulated Rhamnaceae endemicto New Caledonia. Eur J Soil Biol 36:169–175.
43. Bashan Y, De-Bashan LE (2010) How the plants growth-promoting bacterium Azospirillum promotes plants growth-a critical assessment. Adv Agron 108:77–136.
44. Bagyaraj DJ (2011) Microbial biotechnology for sustainable agriculture, horticulture and forestry. New India Publishing Agency, New Delhi.

45. Bago NB, Pfeffer PE, Abubakar J et al (2003) Carbon export from arbuscular mycorrizal roots involves the translocation of carbohydrate as well as lipid. PlantsPhysiol 13:1496–1507.
46. Buee M, Rossignol M, Januneau A et al (2000) The pre-symbiotic growth of arbuscular mycorrhizal fungi is induced by a branching factor partially purified from the plants root exudates. Mol Plants-Microbe Interact 13:693–698.
47. Bloemberg GV, Lugtenberg BJ (2001) Molecular basis of plants growth promotion and biocontrol by rhizobacteria. Curr OpinPlantsBiol 4:343–350.
48. Viveros OM, Jorquera MA, Crowley DE et al (2010) Mechanisms and practical considerations involved in plants growth promotion by rhizobacteria. J Soil Sci PlantsNutr 10:293–319.
49. Laishram B, Singh TB, Kalpana A, Wangkheirakpam M, Chongtham SK and Singh W. Effect of Salicylic Acid and Potassium Nitrate on Growth and Yield of Lentil (Lens culinaris L.) under Rainfed Condition. International Journal of Current Microbiology and Applied Sciences. 2020; 9(11):2779–2791. https://doi.org/10.20546/ijcmas.2020.911.337
50. Ahemad M, Kibret M (2014) Mechanisms and applications of plants growth promoting rhizobacteria: current perspective. J King Saud Univ Sci 26:1–20.
51. Singh R, Behl RK, Jain P et al (2007) Performance and gene effects for root characters and micronutrients uptake in wheat under inoculation of arbuscular mycorrhiza fungi and Azotobacter chroococcum. Acta Agron Hung 55:325–330.
52. Bidyarani N, Prasanna R, Chawla G et al (2015) Deciphering the factors associated with the colonization of rice plantss by cyanobacteria. J Basic Microbiol 55:407–419.
53. Arnold EA (2007) Understanding the diversity of foliar endophytic fungi: progress, challenges, and frontiers. Fungal Biol Rev 21:51–66.
54. Ganley R, Brunsfeld S, Newcombe G (2004) A community of unknown, endophytic fungi in western white pine. Proc Natl Acad Sci U S A 101:10107–10112.
55. Coombs JT, Franco CMM (2003) Isolation and identification of actinobacteria isolated from surface-sterilized wheat roots. Appl Environ Microbiol 69:5303–5308.
56. Jumpponen A (2001) Dark septate endophytes – are they mycorrhizal? Mycorrhiza 11:207–211.

57. Asghari, B., Khademian, R., and Sedaghati, B. (2020). Plants growth promoting rhizobacteria (PGPR) confer drought resistance and stimulate biosynthesis of secondary metabolites in pennyroyal (Mentha pulegium L.) under water shortage condition. Sci. Hort. 263, 1–10. doi: 10.1016/j.scienta.2019.109132.
58. Bhat, M. A., Rasool, R., and Ramzan, S. (2019). Plants growth promoting rhizobacteria (PGPR) for sustainable and eco-friendly agriculture. Acta Sci. Agric. 3, 23–25.
59. Khan, N., Bano, A., Ali, S., and Babar, M.d., A. (2020). Crosstalk amongst phytohormones from plantsa and PGPR under biotic and abiotic stresses. Plants Growth Regul. 90, 189–203. doi: 10.1007/s10725-020-00571-x.
60. Ahmad, M., Pataczek, L., Hilger, T. H., Zahir, Z. A., Hussain, A., Rasche, F., et al. (2018). Perspectives of microbial inoculation for sustainable development and environmental management. Front.Microbiol. 9:2992. doi: 10.3389/fmicb.2018.02992.
61. Philippot, L., Raaijmakers, J. M., Lemanceau, P., and Van Der Putten, W. H. (2013). Going back to the roots: the microbial ecology of the rhizosphere. Nat. Rev. Microbiol. 11, 789–799. doi: 10.1038/nrmicro3109.
62. Vishwakarma, K., Sharma, S., Kumar, N., Upadhyay, N., Devi, S., and Tiwari, A. (2016). “Contribution of microbial inoculants to soil carbon sequestration and sustainable agriculture,” in Microbial Inoculants in Sustainable Agricultural Productivity, Vol. 2, eds D. P. Singh, H. B. Singh, and R. Prabha (Singapore: Springer), 101–113. doi: 10.1007/978-81-322-2644-4_7.
63. Devi OR, Ojha N, Laishram B and Devi OB. Opportunities and Challenges of Soil Fertility Management in Organic Agriculture. Vigyan Varta. 2023; 4(8): 228-232.
64. Khandelwal, S.R.; Manwar, A.V.; Chaudhari, B.L.; Chincholkar, S.B. Siderophorogenic brady-rhizobia boost yield of soybean. Appl. Biochem. Biotechnol. 2002, 102, 155–168, doi:10.1385/ABAB:102□103:1□6:155.
65. Bashan, Y.; de□Bashan, L.E.; Prabhu, S.R.; Hernandez, J. Advances in plants growth□promoting bacterial inoculant technology: Formulations and practical perspectives (1998–2013). Plants Soil 2014, 378, 1–33, https://doi.org/10.1007/s11104□013□1956□x.
66. Babalola, O.O.; Glick, B.R. The use of microbial inoculants in African agriculture: Current practice and future prospects. J. Food Agric. Environ. 2012, 10, 540–549.

67. Alori, E.T.; Babalola, O.O. Microbial Inoculants for Improving Crop Quality and Human Health in Africa. Front. Microbiol. 2018, 9, 2213, https://doi.org/10.3389/fmicb.2018.0221338.
68. Conlon R., Wang M., Germaine X.L., Mali R., Dowling D., Germaine K.J. Ecopiling: Beneficial Soil Bacteria, Plantss, and Optimized Soil Conditions for Enhanced Remediation of Hydrocarbon Polluted Soil. Good Microbes Med. Food Prod. Biotechnol. Bioremediat. Agric. 2022:337–347. doi: 10.1002/9781119762621.ch27.
69. Laishram B, Devi OR and Ngairangbam H. Insight into Microbes for Climate Smart Agriculture. Vigyan Varta. 2023; 4(4):53-56.
70. Egamberdiyeva, D. (2007). The effect of plants growth promoting bacteria on growth and nutrient uptake of maize in two different soils. Appl. Soil Ecol. 36, 184–189. doi: 10.1016/j.apsoil.2007.02.005.
71. Devi OR, Sarma A, Borah K, Prathibha RS, Tamuly G, Maniratnam K and Laishram B. Importance of zinc and molybdenum for sustainable pulse production in India. Environment and Ecology. 2023; 41(3C): 1853–1859. https://doi.org/10.60151/envec/lcch4556.
72. Varma, A.; Tripathi, S.; Prasad, R. Plants Biotic Interactions: State of the Art; Sprigner: Berlin/Heidelberg, Germany, 2019.
73. Lopes, M. J. D. S., Dias□Filho, M. B., & Gurgel, E. S. C. (2021). Successful Plants Growth Promoting Microbes: Inoculation methods and abiotic Factors. Frontiers in Sustainable Food Systems, 5. https://doi.org/10.3389/fsufs.2021.606454.
74. Venkatarao, C.H., Naga, S.R., Yadav, B.L., Shivran, A.C. and Singh, S.P. (2017) Influence of Phosphorus and Biofertilizers on Soil Fertility and Enzyme Activity of Soils Grown under Mungbean [Vigna radiata (L.)Wilczek]. International Journal of Current Microbiology and Applied Sciences, 6(12): 737-741.
75. Babalola, O.O.; Glick, B.R. Indigenous African agriculture and plants associated microbes: Current practice and future transgenic prospects. Sci. Res. Essays 2012, 7, 2431–2439.
76. Chen, C.; Mciver, J.; Yang, Y.; Bai, Y.; Schultz, B.; Mciver, A. Foliar application of lipochitooligosaccharides (Nod factors) to tomato (Lycopersicon esculentum) enhances

flowering and fruit production. Can. J. Plants Sci. 2007, 87, 365–372, doi:10.4141/P06□164.

77. Zilber-Rosenberg I., Rosenberg E. Role of microorganisms in the evolution of animals and plantss: The hologenome theory of evolution. FEMS Microbiol. Rev. 2008;32:723–735.
78. Kumar, P., Pandey, P., Dubey, R.C. and Maheshwaria, D.K. (2016) Bacteria consortium optimization improves nutrient uptake, nodulation, disease suppression and growth of the common bean (Phaseolus vulgaris) in both pot and field studies. Rhizosphere, 2: 13–23.
79. Ojuederie O.B., Babalola O.O. Microbial and plants-assisted bioremediation of heavy metal polluted environments: A review. Int. J. Environ. Res. Public Health. 2017;14:1504. doi: 10.3390/ijerph14121504.
80. Khadka, R.B. and Uphoff, N. (2019) Effects of Trichoderma seedling treatment with System of Rice Intensification management and with conventional management of transplantsed rice. Peer Journal of Life and Environment, 7: 5877.
81. GaieroJR,McCall CA, Thompson KA, Day NJ, Best AS, Dunfield KE. Inside the root microbiome: bacterial root endophytes and plants growth promotion. Am J Bot. (2013) 100:1738–50. doi: 10.3732/ajb.1200572.
82. Müller DB, Vogel C, Bai Y, Vorholt JA. The plants microbiota: systems-level insights and perspectives. Annu Rev Genet. (2016) 50:211–34. doi: 10.1146/annurev-genet-120215-034952.
83. Kumar I, Mondal M, Gurusamy R, Balakrishnan S, Natarajan S. Plants-microbiome interaction and the effects of biotic and abiotic components in agroecosystem. MicrobInterv Agric Environ. (2019) 2:517–46. doi: 10.1007/978-981-13-8383-0_18.
84. Stringlis IA, Zhang H, Pieterse CM, Bolton MD, de Jonge R. Microbial small molecules-weapons of plants subversion. Nat Prod Rep. (2018) 35:410–33. doi: 10.1039/C7NP00062F.
85. Berg, G.; Grube, M.; Schloter, M.; Smalla, K. Unraveling the plants microbiome: Looking back and future perspectives. Front. Microbiol. 2014, 5, 148.
86. Armada, E.; Portela, G.; Roldán, A.; Azcón, R. Combined use of beneficial soil microorganism and agrowaste residue to cope with plants water limitation under semiarid conditions. Geoderma 2014, 232, 640–648.

87. Armada, E.; Portela, G.; Roldán, A.; Azcón, R. Combined use of beneficial soil microorganism and agrowaste residue to cope with plant water limitation under semiarid conditions. Geoderma 2014, 232, 640–648.
88. Rodríguez-Yzquierdo, G.; Olivares, B.O.; González-Ulloa, A.; León-Pacheco, R.; Gómez-Correa, J.C.; Yacomelo-Hernández, M.; Carrascal-Pérez, F.; Florez-Cordero, E.; Soto-Suárez, M.; Dita, M.; et al.. Soil Predisposing Factors to Fusarium oxysporumf.spCubense Tropical Race 4 on Banana Crops of La Guajira, Colombia. Agronomy, 2023 13, 2588. https://doi.org/10.3390/agronomy13102588
89. Rodríguez-Yzquierdo, G.; Olivares, B.O.; Silva-Escobar, O.; González-Ulloa, A.; Soto-Suarez, M.; Betancourt-Vásquez, M. Mapping of the Susceptibility of Colombian Musaceae Lands to a Deadly Disease: Fusarium oxysporum f. sp. cubense Tropical Race 4. Horticulturae 2023. 9, 757. https://doi.org/10.3390/horticulturae9070757
90. Montenegro, E., Pitti-Rodríguez, J, Olivares-Campos, B. Identification of the main subsistence crops of Teribe: a case study based on multivariate techniques. Idesia (Arica), 2021. 39(3), 83-94. https://dx.doi.org/10.4067/S0718-34292021000300083
91. Rodríguez, J. E. P., Olivares, B. O., Montenegro, E. J., Miller, L., &Ñango, Y. The role of agriculture in the Changuinola District: A case of applied economics in Panama. Tropical and Subtropical Agroecosystems, 2021. 25(1). http://dx.doi.org/10.56369/tsaes.3815
92. Olivares, B.O.; Rey, J.C.; Perichi, G.; Lobo, D. Relationship of Microbial Activity with Soil Properties in Banana Plantations in Venezuela. Sustainability 2022. 14, 13531. https://doi.org/10.3390/su142013531
93. Olivares B, Rey JC, Lobo D, Navas-Cortés JA, Gómez JA, Landa BB. Machine Learning and the New Sustainable Agriculture: Applications in Banana Production Systems of Venezuela. Agricultural Research Updates. 2022. 42, 133 - 157. Nova Science Publishers, Inc
94. Olivares, B. Description of soil management in agricultural production systems in the Hamaca de Anzoátegui sector, Venezuela. La Granja: Revista de Ciencias de la Vida. 2016. 23(1): 14–24. https://n9.cl/ycp08

95. Olivares, B., Verbist, K., Lobo, D., Vargas, R. y Silva, O. Evaluation of the USLE model to estimate water erosion in an Alfisol. Journal of Soil Science and Plant Nutrition of Chile. 2011. 11 (2):71-84. http://dx.doi.org/10.4067/S0718-95162011000200007
96. Araya-Alman, M., Olivares, B., Acevedo-Opazo, C. et al. (2020). Relationship Between Soil Properties and Banana Productivity in the Two Main Cultivation Areas in Venezuela. J Soil Sci Plant Nutr.; 20 (3): 2512-2524. https://doi.org/10.1007/s42729-020-00317-8
97. Olivares, B.O., Calero, J., Rey, J.C., Lobo, D., Landa, B.B., Gómez, J. A. (2022a). Correlation of banana productivity levels and soil morphological properties using regularized optimal scaling regression. Catena,; 208: 105718. https://doi.org/10.1016/j.catena.2021.105718
98. Lobo, D; Olivares, B; Rey, J.C; Vega, A; Rueda-Calderón, A. Relationships between the Visual Evaluation of Soil Structure (VESS) and soil properties in agriculture: A meta-analysis. Scientia agropecuaria, 2023; 14 - 1, 67 - 78. https://doi.org/10.17268/sci.agropecu.2023.007
99. Campos, B. O. Banana Production in Venezuela: Novel Solutions to Productivity and Plant Health. 2023. Springer Nature. https://doi.org/10.1007/978-3-031-34475-6
100. Campos, B. O. O., Araya-Alman, M., & Marys, E. E. Sustainable Crop Plants Protection: Implications for Pest and Disease Control (p. 200). MDPI-Multidisciplinary Digital Publishing Institute. 2023. https://doi.org/10.3390/books978-3-0365-9150-6
101. Olivares B, Vega A, Calderón MAR, Rey JC, Lobo D, Gómez JA, Landa BB. Identification of Soil Properties Associated with the Incidence of Banana Wilt Using Supervised Methods. Plants, 2022. 11(15):2070. https://doi.org/10.3390/plants11152070
102. Martínez, G.; Olivares, B.O.; Rey, J.C.; Rojas, J.; Cardenas, J.; Muentes, C.; Dawson, C. The Advance of Fusarium Wilt Tropical Race 4 in Musaceae of Latin America and the Caribbean: Current Situation. Pathogens, 2023. 12, 277. https://doi.org/10.3390/pathogens12020277
103. Olivares, B.O.; Vega, A.; Rueda Calderón, M.A.; Montenegro-Gracia, E.; Araya-Almán, M.; Marys, E. Prediction of Banana Production Using Epidemiological Parameters of Black Sigatoka: An Application with Random Forest. Sustainability 2022. 14, 14123. https://doi.org/10.3390/su142114123

104. Olivares, B., Hernández, R. Application of multivariate techniques in the agricultural land's aptitude in Carabobo, Venezuela. Tropical and Subtropical Agroecosystems, 2020. 23(2):1-12. http://dx.doi.org/10.56369/tsaes.3233

105. Olivares B, Rey JC, Lobo D, Navas-Cortés JA, Gómez JA, Landa BB. Fusarium Wilt of Bananas: A Review of Agro-Environmental Factors in the Venezuelan Production System Affecting Its Development. Agronomy, 2021. 11(5):986. https://doi.org/10.3390/agronomy11050986

106. Campos, B. O. O., Calderón, A. R., & Rey, J. C. Clasificación de zonas afectadaspor la marchitezenbanano: unaaplicación con algoritmos de Machine Learning en Venezuela. REICIT: Revistaespecializada de ingeniería y ciencias de la tierra, 2021. 1(1), 1-17.

107. Olivares, B., Paredes, F., Rey, J., Lobo, D., Galvis-Causil, S. The relationship between the normalized difference vegetation index, rainfall, and potential evapotranspiration in a banana plantation of Venezuela. SAINS TANAH - Journal of Soil Science and Agroclimatology, 2021. 18(1), 58-64. http://dx.doi.org/10.20961/stjssa.v18i1.50379

108. Rodríguez, M.F, Olivares, B., Cortez, A., Rey, J.C. and Lobo, D. Natural physical characterization of the indigenous community of Kashaama for the purposes of sustainable land management. Acta Nova. 2015. 7 (2):143-164. https://n9.cl/hakdx

109. Olivares, B. O., & Franco, E. Diagnósticoagrosocial de la comunidadindígena de Kashaama: Un estudioempíricoenelestado de Anzoátegui, Venezuela. Revista Guillermo de Ockham, 2015. 13(1), 87-95.

110. Hernández, R., Olivares, B., Application of multivariate techniques in the agricultural land's aptitude in Carabobo, Venezuela. Tropical and Subtropical Agroecosystems, 2020. 23(2):1-12. https://n9.cl/zeedh

111. Hernández, R; Olivares, B. Arias, A; Molina, JC., Pereira, Y. Agroclimatic zoning of corn crop for sustainable agricultural production in Carabobo, Venezuela. RevistaUniversitaria de Geografía. 2018. 27 (2): 139-159. https://n9.cl/l2m83

112. Hernandez, R., Olivares, B., Arias, A, Molina, JC., Pereira, Y. Eco-territorial adaptability of tomato crops for sustainable agricultural production in Carabobo,

Venezuela. Idesia. 2020. 38(2):95-102. http://dx.doi.org/10.4067/S0718342920200002000095

113. Hernández, R; Olivares, B., Arias, A; Molina, JC., Pereira, Y. Identification of potential agroclimatic zones for the production of onion (Allium cepa L.) in Carabobo, Venezuela. Journal of the Selva Andina Biosphere., 2018. 6 (2): 70-82. http://www.scielo.org.bo/pdf/jsab/v6n2/v6n2_a03.pdf

114. Hernández, R. Olivares, B. Ecoterritorial sectorization for the sustainable agricultural production of potato (Solanum tuberosum L.) in Carabobo, Venezuela. Agricultural Science and Technology. 2019. 20(2): 339-354. https://doi.org/10.21930/rcta.vol20_num2_art:1462.

115. Agler, M. T., Ruhe, J., Kroll, S., Morhenn, C., Kim, S. T., Weigel, D., & Kemen, E. M. (2016). Microbial hub taxa link host and abiotic factors to plant microbiome variation. PLoS biology, 14(1), e1002352.

116. Jones, J. D., & Dangl, J. L. (2006). The plant immune system. nature, 444(7117), 323-329.

117. Zhou, J. M., & Zhang, Y. (2020). Plant immunity: danger perception and signaling. *Cell*, *181*(5), 978-989.