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SOIL MICROBIAL SERVICES: BACTERIA-FUNGI SYNERGY AS A DRIVER OF CROP RESILIENCE

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Abstract. *In the context of agroecological sustainability, this paper analyses the role of soil microorganisms as critical providers of ecosystem services in the absence of conventional chemical inputs. Bacteria and fungi govern the productivity of agricultural systems through fundamental biogeochemical processes, such as biological nitrogen fixation, solubilization of phosphorus and sequestration of atmospheric carbon in stable humus fractions. The resilience of the agroecosystems is supported by high-precision microbial mechanisms: arbuscular mycorrhizal fungi structure the edaphic matrix through the production of glomalin, a hydrophobic glycoprotein essential for aggregate stability and soil structural stability, while bacteria from the plant growth promotion group regulate plant physiological homeostasis through complex hormonal modulation. A central role in mitigating abiotic stress is played by the activity of the enzyme ACC-deaminase, which functions as a metabolic drain for the ethylene precursor, preventing the inhibition of root growth under drought or salinity stress. The novelty of the current research lies in the conceptual transition from inoculation with isolated strains to the assembly of complex microbial consortia. This microbial approach uses principles of functional complementarity and metabolic cross-feeding phenomena to ensure efficient rhizosphere flows and increased biofilm stability under natural field conditions. The integration of microbial complex consortia transforms soil management from an interventionist practice into a predictive and self-sustaining system, capable of optimizing ecosystem health and ensuring global food security.*

Keywords*: Ecosystem Services, Stress Resilience, Synergy, Plant growth promotion*

INTRODUCTION

Modern agriculture is a production model that is based on ecological processes, biodiversity and cycles adapted to local conditions, eliminating dependence on synthetic fertilizers and pesticides (Kazemi et al., 2018). In this system, the soil microbiome becomes the main engine of fertility, being responsible for transforming unavailable forms of nutrients into forms that can be assimilated by plants. The success of these sustainable ecosystems depends on the complex interaction between soil, climate and microbial communities (Philippot et al., 2024). The microbiome not only sustains the plant growth and development, but also actively structures the soil matrix, preventing erosion and compaction.

However, the use of biofertilizers and biopesticides faces challenges such as the pressure of native microbiomes and fluctuations in pH or humidity, which requires a deep understanding of microbial ecology to ensure efficient colonization of the rhizosphere (Pathma et. al., 2020). In recent years, there has been considerable interest in studies involving plant growth-promoting bacteria (PGPB), derived from the hope that they will be widely used in sustainable agricultural practices, allowing partial or complete replacement of chemicals. This evolution marks the shift towards a new paradigm in agriculture, where understanding genetic and biochemical mechanisms allows the use of microbial technology at a global scale (Riaz et al., 2025).

Integrated nutrient management through biofertilizers is not limited to nitrogen and phosphorus, but also includes specialized bacterial groups, such as sulfur-oxidizing bacteria or zinc-solubilizing bacteria, essential elements for oilseed crops and beyond (Maheshwari, 2011). These microorganisms are capable of synthesizing volatile compounds and siderophores that improve the acquisition of iron and other micronutrients, while providing a competitive advantage in the rhizosphere by inhibiting the development of pathogens (Desai and Archana, 2011; Osorio, 2011). Thus, the functional diversity of soil bacteria supports a balanced growth of plant biomass even in degraded soils.

In addition to nutritional functions, biological disease control through volatile organic compounds (VOCs) of bacterial and fungal origin represents a critical frontier in reducing pathogen inoculum without toxic residues (Fernando and Nawalage, 2011). The use of microbial biopesticides is rigorously regulated to ensure ecosystem safety, with notable successes demonstrated in suppressing soil diseases such as root rot or fusarium wilt (Ayaz et la., 2023; Bakr et al., 2025). The integration of these agents into precision agriculture systems transforms plant protection into an environmentally friendly process, vital for the food security of a constantly growing global population.

This paper analyzes the fundamental contribution of soil microorganisms, bacteria and fungi, to the stabilization and productivity of agroecosystems. The main objective is to evaluate the biological mechanisms by which these microscopic entities provide essential ecosystem services, such as biological nitrogen fixation (BNF), insoluble phosphate solubilization and carbon sequestration. The roles of plant growth-promoting bacteria (PGPB) are detailed, with emphasis on hormonal modulation and stress reduction, as well as the importance of arbuscular mycorrhizal fungi (AMF) in the architecture of the soil micro-landscape. The services based on functional complementarity and cross-feeding are explored to show the complexity of microbiome interactions. The strategic integration of microbial interactions transforms soil management into a predictive system, essential for food security and resilience to climate change, a hypothesis analyzed to better understand the importance of bacteria and fungi within agroecosystems.

BACTERIAL SERVICES FOR AGRICULTURE

Beneficial bacteria are a pillar in agroecosystems due to their biofertilization and phytostimulation potential, providing a wide range of services, from the mineralization of organic matter to the bioremediation of polluted soils (Oubohssaine et al., 2025). The success of their use derives from their ability to partially or totally replace chemical inputs through complex genetic and biochemical mechanisms (Table 1).

Biological nitrogen fixation remains the most critical bacterial service, being performed by the nitrogenase enzyme complex that breaks the triple bond of atmospheric nitrogen, an extremely energetically expensive process (Pahari et al., 2021). While *Rhizobium* and *Bradyrhizobium* are well-known and widely used symbionts in legumes, endophytic species such as *Gluconacetobacter diazotrophicus* can provide have come to the attention of researchers for their high potential for N fixation (Rana et al., 2023). The efficiency of BNF is often monitored by the presence of the nifH gene, which regulates the synthesis of nitrogenase components under hypoxic conditions.

A key mechanism for balanced nutrition is the solubilization of Zn, a micronutrient frequently immobilized in high pH soils. Specialized bacteria use organic acid production and chelation to transform insoluble forms of Zn into assimilable fractions, a critical process for crop productivity (Ranadev et al., 2023; Sethi et al., 2025).

In parallel, sulfur-oxidizing bacteria, generate local acidification of the rhizosphere through the production of sulfuric acid, a mechanism that induces the indirect mobilization of phosphorus, iron and manganese.

Siderophore production represents a dual bacterial strategy for nutrition and biocontrol. These low molecular weight chelating agents, synthesized by genera such as *Pseudomonas*, sequester iron (Soares, 2022; Timofeeva et al., 2022) with high affinity, make it available to the plant while simultaneously depriving pathogenic fungi of the resources they need to thrive. Thus, competition for iron in the rhizosphere becomes an effective biological barrier in the absence of synthetic fungicides.

Table 1.

Bacterial services for agriculture

Functional category	Mechanism of action and biochemical signal	Environmental optimum and influencing factors	Temporal dynamics (strategy)	The systemic role in agriculture
Biofertilization	N2 (nitrogenase enzyme) fixation and P (organic acids) solubilization.	Soils with neutral/alkaline pH; balanced (clayey) texture.	Consolidator (K): Stabilizes long-term mineral nutrition.	Reducing dependence on external inputs; self-sustainable fertilization.
Biostimulation	Production of phytohormones (Auxins, IAA) and vitamins (B12).	Rhizoplane (root surface); depends on the root exudates.	Pioneer (r): Rapid colonization in the germination/emergence stages.	Stimulating root volume for better soil exploration.
Bioprotection (Antagonism)	Secretion of antibiotics, siderophores and lytic enzymes.	High cation exchange capacity; resistance to water stress.	Stabilizer: Establish post-colonization for persistent protection.	Suppression of soil pathogens and induction of systemic resilience.
Metabolic Cooperation	Cross-feeding and biofilm formation.	Fungal-bacterial interface; the presence of plant debris rich in C.	Synergistic: It acts throughout the vegetation cycle.	Transformation of plant residues into nutrients through trophic partnerships.

Phytostimulation by hormonal modulation is dominated by the synthesis of indole-3-acetic acid (IAA). Bacteria, *Azospirillum brasilense*, produce auxins that modify root architecture, increase the density of absorbent hairs and, implicitly, the volume of soil explored for water and nutrients (Pelagio-Flores et al., 2025; Rigobelo, 2024). A remarkable advance in mitigating abiotic stress is represented by the activity of the enzyme ACC-deaminase. PGPRs possessing this enzyme, such as *Enterobacter cloacae* or *Achromobacter* species, degrade the precursor 1-aminocyclopropane-1-carboxylate, reducing the concentration of stress ethylene in plant tissues (Shahid et al., 2023). This metabolic mechanism prevents inhibition of root growth under drought, salinity or flood conditions, ensuring physiological homeostasis of crops. Inter-cellular communication through quorum sensing (QS) signals mediates the expression of beneficial traits of PGPB, including biofilm formation and production of secondary metabolites (Rigobelo, 2024). In agriculture, the stability of these bacterial biofilms on the root surface is crucial for systemic protection, providing a physical and chemical barrier against invasion by soil-borne pathogens (Alqahtani, 2025). However, interference by indigenous populations with these signals represents a major challenge for inoculum persistence.

The release of volatile organic compounds (VOCs) by bacteria such as *Bacillus subtilis* represents an opportunity for non-contact biological control (Grahovac et al., 2023). These volatile metabolites can inhibit the cellular respiration of pathogens and trigger induced systemic resistance, priming the plant's immune system for a rapid response.

Current perspectives focus on the use of cryophilic bacteria, which can ensure phosphorus solubilization and siderophore synthesis at low temperatures (Kumar et al., 2022; Rizvi et al., 2021). This adaptation is vital for winter crops or those in cold areas, ensuring the continuity of ecosystem services throughout the year and increasing the resilience of agroecosystems to climate fluctuations.

BACTERIAL SERVICES FOR AGRICULTURE

Fungi play a role in supporting soil structure and transporting water and nutrients, their network of hyphae functioning as a vital extension of the plant root system (Chaudhary et al., 2025; Goswami et al., 2025; Negi et al., 2025). These vegetative structures not only absorb water and nutrients, but also help to physically aggregate soil particles, creating a porous architecture that prevents settlement and wind or water erosion (Table 2.).

Arbuscular mycorrhizal symbiosis (AMF), established by fungi of the phylum Glomeromycota, represents one of the oldest and most efficient forms of biological cooperation on Earth (Fall et al., 2022; Lie and Chen, 2024). The process is governed by a precise molecular dialogue: the plant emits strigolactones that induce hyphal branching, and the fungus responds through Myc factors that activate the host's symbiotic program (Boyno et al., 2023; Crosino and Genre, 2022; Shah et al., 2026). The metabolic exchange takes place at the level of the arbuscules, where the fungus delivers phosphorus (P) and nitrogen (N) in exchange for the carbon fixed by photosynthesis. A fundamental ecosystem service of mycorrhizal species is the production of glomalin, a hydrophobic glycoprotein that acts as a biological adhesive for the stability of soil aggregates (Son et al., 2024). This substance converts labile carbon into stable humus, transforming agricultural soils into long-term sequestration reservoirs. Furthermore, glomalin has the ability to irreversibly immobilize heavy metals such as copper, cadmium and zinc, reducing phytotoxicity in the rhizosphere (Singh et al., 2022).

Table 2.

Fungal services for agriculture

Impact category	Mechanism and biochemical signaling	Environmentally friendly and environmentally optimal plasticity	Role in agroecosystem resilience
Mycorrhizal symbiosis	Formation of arbuscles; phosphorus transport and signaling through hyphal networks.	High tolerance to acidic pH; It requires porous texture for mycelium extension.	Expansion of absorption area (up to 100x) and critical resistance to water stress.
Biocontrol and Immunity	Mycoparasitism (degradation of pathogenic chitin) and induction of systemic resistance (SSRI).	Thermal versatility; survival by boosting resistance in the absence of the host.	Biological suppression of pathogens and "preparation" of the plant's immune system.
Edaphic restructuring	Secretion of glomalin; physical aggregation of soil particles through hyphae networks.	Optimal activity in soils with high organic matter (C) content.	Improving porosity and water holding capacity; Erosion prevention.
Recycling & Transformation	Secretion of cellulolytic and ligninolytic enzymes; solubilization of minerals.	Independence from host pH; capable of proliferation in nutrient-poor environments.	Accelerating the nutrient cycle and converting dead biomass into living resources.

Drought resilience is ensured by the small diameter of the hyphae, which allows them to penetrate into soil micropores inaccessible to root hairs (Cheng et al., 2021; Lokhande, 2025). This geometry favors access to hygroscopic water, maintaining a constant water flow to the plant even under osmotic stress. AMF fungi additionally modulate water status by regulating the expression of aquaporins and the accumulation of compatible solutes in host tissues.

In the field of biocontrol, the genus *Trichoderma* is distinguished by its aggressive mycoparasitism and induction of systemic resistance (Kaur et al., 2021; Guzmán-Guzmán et al., 2023). The fungus detects chemical signals from pathogens (chemotropism), wraps itself around their hyphae, and secretes a set of chitinases and β-1,3-glucanases that structurally digest the cell wall of the pathogens. This activity triggers jasmonic acid and ethylene-based immune signaling pathways throughout the plant. Entomopathogenic fungi such as *Beauveria bassiana* and *Metarhizium anisopliae* provide protection against insect pests by directly penetrating the cuticle (Sharma and Sharma, 2021; Sharma et al., 2023; Zibaee et al., 2025). The spores adhere via hydrophobins and generate mechanical and enzymatic pressure (lipases, proteases) to invade the hemocoel. Once penetrated, they release toxins such as destruxins, which paralyze the insect's immune system, subsequently being able to translocate nitrogen extracted from the pest directly to the plant.

Saprophytic fungi are essential for the mineralization of recalcitrant organic matter (Ferreira Mendes et al., 2022; Selvakumar, 2025; Sulieman, 2026). They secrete organic acids (citric, oxalic) that solubilize blocked phosphorus and produce ligninolytic enzymes (laccases, manganese-peroxidases) capable of fragmenting lignin and cellulose polymers. This microbial process ensures the continuous regeneration of soil fertility by transforming hard plant residues into stable humic fractions.

The modern approach through synthetic microbial consortia utilizes N-P synergy, where nitrogen-fixing bacteria metabolically supports the fungal biomass, while the AMF mycelial network functions as a transport infrastructure for nutrients and water (Liu and Chen, 2024; Shah et al., 2026; Zeng et al., 2025). Induction of these mechanisms reduces the energetic cost of the host plant and provides superior rhizosphere competence to isolated strains (Orozco-Mosqueda et al., 2023; Mazumder et al., 2026; Santoyo et al., 2021). Integrating this type of interaction transforms agriculture into a predictive system, capable of self-regeneration under the pressure of climate change.

CONCLUSIONS

The use of microorganisms in agriculture represents the fundamental transition from an interventionist chemical management to an ecosystem-based, predictive and self-sustaining one.

The conceptual transition from inoculation with isolated strains to the assembly of synthetic microbial consortia allows overcoming ecological limitations by ensuring a superior rhizosphere through functional complementarity and cross-feeding mechanisms.

Faced with the challenges imposed by climate change, microbiological mechanisms increase plant resistance to stress, support the stabilization of soil aggregates and represent essential elements for the resilience of agroecosystems.

BIBLIOGRAPHY

ALQAHTANI, F.S., 2025 - The utilization of microorganisms for biological control of soil-borne plant pathogens: a sustainable strategy for managing plant diseases-a comprehensive review. Journal of Plant Pathology, pp.1-25.

AYAZ, M., LI, C.H., ALI, Q., ZHAO, W., CHI, Y.K., SHAFIQ, M., ALI, F., YU, X.Y., YU, Q., ZHAO, J.T., YU, J.W., 2023 - Bacterial and fungal biocontrol agents for plant disease protection: Journey from lab to field, current status, challenges, and global perspectives. Molecules, 28(18):6735.

http://doi.org/10.59463/RJAS.2026.1.35

BAKR, R., ABDELMOTELEB, A., MENDEZ-TRUJILLO, V., GONZALEZ-MENDOZA, D., HEWEDY, O., 2025 - The potential of beneficial microbes for sustainable alternative approaches to control phytopathogenic diseases. Microbiology Research, 16(5):105.

BOYNO, G., REZAEE DANESH, Y., DEMIR, S., TENIZ, N., MULET, J.M., PORCEL, R., 2023 - The complex interplay between arbuscular mycorrhizal fungi and strigolactone: mechanisms, sinergies, applications and future directions. International Journal of Molecular Sciences, 24(23):16774.

CHAUDHARY, A., POUDYAL, S., KAUNDAL, A., 2025 - Role of arbuscular mycorrhizal fungi in maintaining sustainable agroecosystems. Applied Microbiology, 5(1):6.

CHENG, S., ZOU, Y.N., KUČA, K., HASHEM, A., ABD_ALLAH, E.F., WU, Q.S., 2021 - Elucidating the mechanisms underlying enhanced drought tolerance in plants mediated by arbuscular mycorrhizal fungi. Frontiers in Microbiology, 12:809473.

CROSINO, A., GENRE, A., 2022 -. Peace talks: symbiotic signaling molecules in arbuscular mycorrhizas and their potential application. Journal of Plant Interactions, 17(1):824-839.

DESAI, A., ARCHANA, G., 2011 - Role of siderophores in crop improvement. In Bacteria in agrobiology: plant nutrient management (pp. 109-139). Berlin, Heidelberg: Springer Berlin Heidelberg.

FALL, A.F., NAKABONGE, G., SSEKANDI, J., FOUNOUNE-MBOUP, H., APORI, S.O., NDIAYE, A., BADJI, A., Ngom, K., 2022 - Roles of arbuscular mycorrhizal fungi on soil fertility: contribution in the improvement of physical, chemical, and biological properties of the soil. Frontiers in Fungal Biology, 3:723892.

FERNANDO, W.G.D., NAWALAGE, V., 2011 – Bacterial, Fungal, and Plant Volatile Compounds in Reducing Plant Pathogen Inoculums. Bacteria in Agrobiology: Plant Nutrient Management, Springer, 13: 301-319, Germania.

FERREIRA MENDES, K., NOGUEIRA DE SOUSA, R.,, CABRAL MIELKE, K., (eds)., 2022 - Biodegradation Technology of Organic and Inorganic Pollutants. IntechOpen. Available at: http://dx.doi.org/10.5772/intechopen.94650.

GOSWAMI, R., SINGH, V., CHAUHAN, A., VAMIL, R., BHADAURIA, S., 2025 - The Hidden World Beneath: An Exploration of Soil Fungi. Notion Press.

GRAHOVAC, J., PAJČIN, I., VLAJKOV, V., 2023 - Bacillus VOCs in the context of biological control. Antibiotics, 12(3):581.

GUZMÁN-GUZMÁN, P., KUMAR, A., DE LOS SANTOS-VILLALOBOS, S., PARRA-COTA, F.I., OROZCO-MOSQUEDA, M.D.C., FADIJI, A.E., HYDER, S., BABALOLA, O.O., SANTOYO, G., 2023 - Trichoderma species: Our best fungal allies in the biocontrol of plant diseases—A review. Plants, 12(3):432.

KAUR, R., KALIA, A., LORE, J.S., KAUR, A., YADAV, I., SHARMA, P., SANDHU, J.S., 2021 - Trichoderma sp. endochitinase and β-1, 3-glucanase impede *Rhizoctonia solani* growth independently, and their combined use does not enhance impediment. Plant Pathology, 70(6):1388-1396.

KAZEMI, H., KLUG, H., KAMKAR, B., 2018 - New services and roles of biodiversity in modern agroecosystems: A review. Ecological indicators, 93:1126-1135.

KUMAR, S., SRAVANI, B., KORRA, T., BEHERA, L., DATTA, D., DHAKAD, P.K., YADAV, M.K., 2022 - Psychrophilic microbes: biodiversity, beneficial role and improvement of cold stress in crop plants. In New and future developments in microbial biotechnology and bioengineering (pp. 177-198). Elsevier.

LIU, R., CHEN, Y., 2024 - Mycorrhizal symbiosis: evolution, opportunities, challenges, and prospects. Arbuscular mycorrhizal fungi in sustainable agriculture: inoculum production and application, pp.1-35.

LIU, R., CHEN, Y., 2024 - Mycorrhizal symbiosis: evolution, opportunities, challenges, and prospects. Arbuscular mycorrhizal fungi in sustainable agriculture: inoculum production and application, pp.1-35.

LOKHANDE, M.S., 2025 - Mycorrhiza in Plant Growth and Soil Health. AG Publishing House (AGPH Books).

MAZUMDER, M., TIKARIHA, H., MAYALAGU, S., MAJEDI, S.M., HAMID, N.A.B.A., MUKHOPADHYAY, S., PAVAGADHI, S., SELVARAJ, P., NAQVI, N.I., SWARUP, S., 2026 - An ecology-driven microbial consortium enhances plant growth and immunity while sustaining rhizospheric microbial balance. Plant Communications, 7(3).

NEGI, M., SHARMA, S., SINGH, M., 2025 - Plant-driven soil dynamics: Exploring the role of roots, fungi and soil traffic in shaping the soil structure. Communications in Soil Science and Plant Analysis, 56(18):2727-2746.

OROZCO-MOSQUEDA, M.D.C., KUMAR, A., BABALOLA, O.O., SANTOYO, G., 2023 - Rhizobiome transplantation: a novel strategy beyond single-strain/consortium inoculation for crop improvement. Plants, 12(18):3226.

OSORIO, N.W., 2011 – Effectiveness of Phosphate Solubilizing Microorganism in Increasing Plant Phosphate Uptake and Growth in Tropical Soils. Bacteria in Agrobiology: Plant Nutrient Management, Springer, 4: 65-80, Germania.

OUBOHSSAINE, M., SBABOU, L., AURAG, J., 2025 - Enhancing ecosystem restoration and soil productivity through PGPR: a sustainable approach to bioremediation and biofertilization. Discover Applied Sciences, 7(12):1379.

PAHARI, A., NAYAK, S.K., BANIK, A., LAKRA, P.B., MISHRA, B.B., 2021 - Biological nitrogen fixation mechanism and applications. In Agriculturally Important Microorganisms (pp. 137-151). CRC Press.

PATHMA, J., KENNEDY, R.K., BHUSHAN, L.S., SHANKAR, B.K., THAKUR, K., 2020 - Microbial biofertilizers and biopesticides: nature's assets fostering sustainable agriculture. In Recent developments in microbial technologies (pp. 39-69). Singapore: Springer Nature Singapore.

PELAGIO-FLORES, R., RAVELO-ORTEGA, G., GARCÍA-PINEDA, E., LÓPEZ-BUCIO, J., 2025 - A century of Azospirillum: plant growth promotion and agricultural promise. Plant Signaling & Behavior, 20(1):2551609.

PHILIPPOT, L., CHENU, C., KAPPLER, A., RILLIG, M.C. AND FIERER, N., 2024 -The interplay between microbial communities and soil properties. Nature Reviews Microbiology, 22(4):226-239.

RANA, K.L., KOUR, D., KAUR, T., NEGI, R., DEVI, R., YADAV, N., RAI, P.K., SINGH, S., RAI, A.K., YADAV, A., SAYYED, R.Z., 2023 -. Endophytic nitrogen-fixing bacteria: untapped treasurer for agricultural sustainability. J. Appl. Biol. Biotechnol, 11(2):75-93.

RANADEV, P., REVANNA, A., BAGYARAJ, D.J., SHINDE, A.H., 2023 - Sulfur oxidizing bacteria in agro ecosystem and its role in plant productivity—a review. Journal of Applied Microbiology, 134(8):lxad161.

RIAZ, M., YASMEEN, E., SALEEM, B., HAMEED, M.K., SAEED ALMHEIRI, M.T., SAEED AL MIR, R.O., ALAMERI, G., KHAMIS ALGHAFRI, J.S., GURURANI, M.A., 2025 - Evolution of agricultural biotechnology is the paradigm shift in crop resilience and development: a review. Frontiers in Plant Science, 16:1585826.

RIGOBELO, E.C., 2024 Microbial Services for Cereal Crops: Reducing Costs and Environmental Impact (pp. 19-38). Cham: Springer Nature Switzerland.

RIZVI, A., AHMED, B., KHAN, M.S., UMAR, S., LEE, J., 2021 - Psychrophilic bacterial phosphate-biofertilizers: a novel extremophile for sustainable crop production under cold environment. Microorganisms, 9(12):2451.

SANTOYO, G., GUZMÁN-GUZMÁN, P., PARRA-COTA, F.I., SANTOS-VILLALOBOS, S.D.L., OROZCO-MOSQUEDA, M.D.C., GLICK, B.R., 2021 - Plant growth stimulation by microbial consortia. Agronomy, 11(2):219.

SARAVANAN, V.S., KUMAR, M.R., SA, T.M., 2011 – Microbial zinc solubilization and their role on plants. Bacteria in Agrobiology: Plant Nutrient Management, Springer, 3: 47-63, Germania.

http://doi.org/10.59463/RJAS.2026.1.35

SELVAKUMAR, P., 2025 - Fungal Biodegradation: Breaking Down Agricultural Wastes. In Mycological Inventions for Sustainable Agriculture and Food Production (pp. 261-282). IGI Global Scientific Publishing.

SETHI, G., BEHERA, K.K., SAYYED, R., ADARSH, V., SIPRA, B.S., SINGH, L., ALAMRO, A.A., BEHERA, M., 2025 - Enhancing soil health and crop productivity: the role of zinc-solubilizing bacteria in sustainable agriculture. Plant Growth Regulation, 105(3):601-617.

SHAH, S., KHAN, Y., WANG, M., ZHANG, T., 2026 - Arbuscular mycorrhizal fungi as mediators of nitrogen, phosphorus, and carbon: implications for plant growth and development. Journal of Plant Nutrition, 49(4):687-707.

SHAH, S., KHAN, Y., WANG, M., ZHANG, T., 2026. Arbuscular mycorrhizal fungi as mediators of nitrogen, phosphorus, and carbon: implications for plant growth and development. Journal of Plant Nutrition, 49(4):687-707.

SHAHID, M., SINGH, U.B., KHAN, M.S., SINGH, P., KUMAR, R., SINGH, R.N., KUMAR, A., SINGH, H.V., 2023 - Bacterial ACC deaminase: Insights into enzymology, biochemistry, genetics, and potential role in amelioration of environmental stress in crop plants. Frontiers in microbiology, 14:1132770.

SHARMA, A., SHARMA, S., YADAV, P.K., 2023 - Entomopathogenic fungi and their relevance in sustainable agriculture: A review. Cogent Food & Agriculture, 9(1):2180857.

SHARMA, R., SHARMA, P., 2021 - Fungal entomopathogens: a systematic review. Egyptian Journal of Biological Pest Control, 31(1):57.

SINGH, A.K., ZHU, X., CHEN, C., WU, J., YANG, B., ZAKARI, S., JIANG, X.J., SINGH, N., LIU, W., 2022 - The role of glomalin in mitigation of multiple soil degradation problems. Critical Reviews in Environmental Science and Technology, 52(9):1604-1638.

SOARES, E.V., 2022 - Perspective on the biotechnological production of bacterial siderophores and their use. Applied Microbiology and Biotechnology, 106(11):3985-4004.

SON, Y., MARTÍNEZ, C.E., KAO-KNIFFIN, J., 2024 - Three important roles and chemical properties of glomalin-related soil protein. Frontiers in Soil Science, 4, p.1418072.

SULIEMAN, A.M.E., 2026 - Extracellular enzyme activity and its implications for organic matter cycling. Microbial Enzymes, pp.323-332.

TIMOFEEVA, A.M., GALYAMOVA, M.R., SEDYKH, S.E., 2022 - Bacterial siderophores: classification, biosynthesis, perspectives of use in agriculture. Plants, 11(22):3065.

ZENG, Y., WANG, Y., WANG, X., JING, X., SHU, X., REN, P., LIU, W., YE, Q., FU, W., HAO, Z., ZHANG, X., 2025 - Arbuscular mycorrhizal fungi as core engineers in synthetic microbial communities: Boosting plant growth and soil health for sustainable agriculture. Journal of Fungi, 11(11):769.

ZIBAEE, A., MALAGOLI, D., DUBOVSKIY, I., 2025 - Entomopathogenic Fungi in Insects: From Physiological Effects to Applications. Academic Press.