



E-ISSN: 2618-0618
P-ISSN: 2618-060X
© Agronomy
www.agronomyjournals.com
2024; SP-7(11): 351-355
Received: 14-09-2024
Accepted: 19-10-2024

Asif Waratadar
Assistant professor Department of
Agricultural Microbiology, College
of Agriculture Vijayapura,
Karnataka, India

Arun YP
Ph.D., Department of
Biotechnology, University of
Agricultural Sciences, Dharwad,
Karnataka, India

Suryawanshi Madhuri
Ph.D., Department of
Biotechnology, University of
Agricultural Sciences, Dharwad,
Karnataka, India

P Mehboobatabassum FH
M.Sc. Department of Agricultural
Microbiology, University of
Agricultural Sciences, Dharwad,
Karnataka, India

Hirudhaya Ravi
Ph.D., Scholar Department of
Agricultural Microbiology, Indian
Agricultural Research Institute,
New Delhi, India

Corresponding Author:
Asif Waratadar
Assistant professor Department of
Agricultural Microbiology, College
of Agriculture Vijayapura,
Karnataka, India

International Journal of Research in Agronomy

Microbial fertilizers-promising partner for sustainable agriculture

Asif Waratadar, Arun YP, Suryawanshi Madhuri, P Mehboobatabassum FH and Hirudhaya Ravi

DOI: <https://doi.org/10.33545/2618060X.2024.v7.i11Se.2005>

Abstract

Post green revolution era found significant increase in agricultural productivity. The high yielding varieties and chemical fertilizers share the combined credit of increased productivity. The use of chemical fertilizers gradually alarmed the negative impact of its residual effect on human health. Use of microorganisms as bio fertilizers in agriculture is most viable alternative for sustainable agriculture and human health to reduce the adverse the effect of chemical fertilizers. The rhizospheric micro biota tends to increase the plant nutrient uptake and activate the signaling mechanisms in plants under various biotic and abiotic stresses. Biofertilizers augment the plant development by various direct and indirect plant growth promoting mechanisms such as biological nitrogen fixation, production of several plant growth hormones, flavonoids, siderophores, innumerable hydrolytic enzymes and solubilization and mobilization of potassium, zinc, and phosphorus; therefore, they are the finest substitute of chemical fertilizers as they are eco-friendly for plant growth and soil fertility.

Keywords: Biofertilizer, nitrogen fixation, siderophores and phosphorus

Introduction

The term “biofertilizers” has been coined to the viable population of microbial inoculants which deliver or enhance the nutrient availability, further conserve and mobilize crop nutrients in the rhizosphere soil (Riaz *et al.*, 2020) ^[25]. The process of improving the nutrient efficiency in the soil to enhance the nutrient needed for plant growth and improve plant yield (Bargaz *et al.*, 2018) ^[3]. Beneficial soil microorganisms augment the management of the rhizosphere through different mechanisms that are multidimensional. These include the following: production of siderophore, nitrogen fixation, lytic acid production, production of hydrogen cyanide, phosphate solubilization, and production of indole acetic acid (Jacoby *et al.*, 2017) ^[10]. The mechanisms of action of these beneficial microorganisms play a crucial role in improving soil fertility, plant growth, and yield. They act as an integral part of an agro-input system in sustainable agriculture (Mohamed *et al.*, 2021; Koskey *et al.*, 2021) ^[10, 12].

Role of biofertilizers

The diverse role of microorganisms in different agro ecological systems plays a significant and protracted role in sustainability of soil health and crop production by tripartite interactions (i.e plant-soil-microbe). Besides the genetic potential, the production potential attainment depends on ecological conditions such as soil health, soil water and on adoption of suitable technologies of crop production. For sustainable agriculture, soil health is more concerned, as crops take away nutrient reserves from the soil. The practice of chemical agriculture resulting in decline of soil microbial activity and soil organic matter coupled with decreased fertilizer use efficiency becomes a serious threat to sustainability Al Abboud *et al.*, 2014; Nosheen *et al.*, 2021 ^[1, 21].

Soil is a biodynamic system as it supports a large population of diverse groups of beneficial microorganisms such as bacteria, actinomycetes, fungi, algae, protozoa etc (Shannon *et al.*, 2006) ^[28] that decompose biomass, mediate in cycling of plant nutrients and protect plants from pests and diseases. All these functions of soil microorganisms are essential for maintaining soil fertility and productivity of agriculture soils.

The integration of growth enhancing factors that make a soil productive has often been referred to as 'soil quality'. The maintenance and restoration of quality is highly dependent on organic matter additions and an array of beneficial microorganisms it supports (Malusá *et al.*, 2012; Jacoby *et al.*, 2017) ^[15, 10].

Microorganisms as indicators of soil quality

Consortia of beneficial bio inoculants may act as biological indicators of soil quality that can be brought about by higher level of interactions among diverse species of soil microorganisms. The major attraction of using biofertilizers is their characteristic ability to convert the unavailable nutrient to available form, which is readily available and easily accessible by the plants. They improve soil properties and sustain soil fertility by providing aeration, biomass of organic carbon and

nutrients. Use of biofertilizers not only makes atmospheric nitrogen available but also solubilizes and mobilizes fixed phosphorus and potassium in soil and improve phosphorus and potassium uptake in plants (Nielsen and Winding 2002; Shi *et al.*, 2021; Vilkiene *et al.*, 2021; Nikitin *et al.*, 2022) ^[19, 29, 27, 20]. They enhance plant growth due to release of hormones, vitamins, auxins etc. They also help to proliferate other beneficial organisms, which, in turn, suppress soil borne plant pathogens. Besides helping to reduce deficit in fertilizer consumption, they are cheaper or without difficulty to available and eco-friendly.

The biofertilizers can be classified based on their functions and properties.

Types of biofertilizers

Nitrogen fixing microorganisms

Physiological Group	Type of association	Host (if any)	Representative Examples
Heterotrophs	a) Free-living aerobic	No Preference	<i>Azotobacter</i> , <i>Azomonas</i> , <i>Azotococcus</i> <i>Beijerinckia Derrxia</i>
	b) Facultative anaerobic	No Preference	<i>Bacillus</i> , <i>Pseudomonas</i> , <i>klebsiella</i>
	c) Strictly Anaerobic	No Preference	<i>Clostridium Desulfovibrio</i> <i>Desulfotomaculum Methanobacillus</i>
	d) Associative symbiotic	Sorghum, maize, bajra, Napier	<i>Azospirillum</i>
	e) Symbiotic aerobic	Legumes, Groundnut, Alnus, Myrica casuarina	<i>Rhizobium Bradyrhizobium</i> spp. <i>Frankia</i>
Autotrophs	a) Free-living unicellular	Not Specific	<i>Gloeocapsa</i>
	b) Filamentous: Non-heterocystous	Not Specific	<i>Trichodesmium</i>
	c) Filamentous heterocystous	Not Specific	<i>Anabaena</i> , <i>Calothrix</i> , <i>Nostoc</i>
	d) Anaerobic, Purple non-sulfur	Not Specific	<i>Rhodospirillum Rhodopseudomonas</i> , <i>Chromatium</i>
	e) Purple sulfur, Green sulfur	Not Specific	<i>Chlorobium</i>
	f) Symbiotic: non-nodulating	Lichen Liverwort Mosses Ferns-Azolla	<i>Nostoc</i> , <i>Halosiphon</i> , <i>Anabaena azollae</i>
	g) Nodulating	Gymnosperm-Cycard	<i>Nostoc</i>

Phosphatic biofertilizers

a)	Phosphate Solubilizers	<i>Bacillus megaterium</i> , <i>Pseudomonas striata</i> , <i>Serratia</i> , <i>Aspergillus</i> , <i>Penicillium</i> , <i>B. cepacia</i> ,
----	------------------------	--

Nutrient mobilizers

a)	AMF Biofertilizers	<i>Glomus</i> , <i>Gigaspora</i> , <i>Acaulospora</i>
----	--------------------	---

Plant Growth Promoting Biofertilizers

Plant Growth Promoting Rhizobacteria	<i>Pseudomonas</i> , <i>Bacillus</i> , <i>Azospirillum</i> , <i>Serratia</i> etc.
--------------------------------------	--

Composting inoculants

Organic Matter Degraders	<i>Trichoderma</i> , <i>Aspergillus</i> , <i>Trichurus</i> , <i>Phanerochaete</i> , <i>Pleurotus</i> etc.
--------------------------	--

Rhizobium

Rhizobium is a genus of Gram-negative soil bacteria that fix nitrogen. *Rhizobium* species form an endosymbiotic nitrogen-fixing association with roots of legumes. The bacteria colonize plant cells within root nodules, where they convert atmospheric nitrogen into ammonia using the enzyme nitrogenase and then provide organic nitrogenous compounds such as glutamine or ureides to the plant. The plant, in turn, provides the bacteria with organic compounds made by photosynthesis. This mutually beneficial relationship is true of all of the rhizobia, of which the genus *Rhizobium* is a typical example (Sawada *et al.*, 2003) ^[26]. *Rhizobium* is also capable to solubilize phosphorus.

Rhizobium is the most important PGPR, which is able to develop a symbiotic association with its specific host plant and increase its growth and yield furthermore they support plant growth via synthesis of phytohormones or other growth promoting or protecting substances like siderophores and antibiotics (Harshitha and Goudar 2021) ^[9].

Azotobacter

Azotobacter is a group of Gram negative, aerobic, heterotrophic free-living, nitrogen fixing bacteria inhabiting in the soil. They are oval or spherical in shape and form thick-walled cysts (dormant cells resistant to deleterious conditions) under unfavorable environmental conditions. *Azotobacter* improves seed germination and has beneficiary response on Crop Growth Rate (CGR) (Sumbul *et al.*, 2020) ^[34]. It helps to increase nutrient availability and to restore soil fertility for better crop response. *Azotobacter* based inoculants are recommended for cereal crops like wheat, oil paddy vegetable crops like potato and tomato seed crops like mustard and sunflower and fibre crops like cotton and jute.

Azospirillum

Azospirillum is considered to be an associative symbiotic bacterium because it lives in close association with root system of plants. However, they do not produce any visible nodules or out growth on the roots (Raffi and Charyulu, 2021) ^[23]. They are microaerophilic bacteria and are known to fix atmospheric nitrogen in grasses, sugarcane, paddy, sorghum, maize, millet and wheat. Some spiral shaped bacteria are known to fix

nitrogen in maize and other grasses. They do not form nodules but fix the atmospheric nitrogen inside the roots.

Phosphate solubilizing microorganisms

Phosphate solubilizing microorganisms produce organic acids like citric acid, glutamic acid, succinic acid, lactic acid, oxalic acid, maleic acid, fumaric acid, tartaric acid and alpha - ketoglutaric acid which are responsible for solubilization of insoluble form of P in to available form of P (Kalayu, 2019) ^[11]. These organisms have a role in completing the P cycle in nature. Some promising phosphate solubilizing bacteria like *Pseudomonas striata*, *Bacillus polymyxa* and fungi *Aspergillus awamori*, *Penicillium digitatum* are being multiplied and prepared as carrier based cultures and recommended for all kinds of crops.

Plant Growth promoting Rhizobacteria

Plant growth-promoting rhizobacteria (PGPR) are the rhizosphere bacteria that can enhance plant growth by a wide variety of mechanisms like phosphate solubilization, siderophore production, biological nitrogen fixation, rhizosphere engineering, production of 1-Aminocyclopropane-1-carboxylate deaminase (ACC), quorum sensing (QS) signal interference and inhibition of biofilm formation, phytohormone production, exhibiting antifungal activity, production of volatile organic compounds (VOCs), induction of systemic resistance, promoting beneficial plant-microbe symbioses, interference with pathogen toxin production etc. The potentiality of PGPR in agriculture is steadily increased as it offers an attractive way to replace the use of chemical fertilizers, pesticides and other supplements. Growth promoting substances are likely to be produced in large quantities by these rhizosphere microorganisms that influence indirectly on the overall morphology of the plants (Bhattacharyya and Jha 2011) ^[4]. Ex: *Pseudomonas*, *Arthrobacter*, *Enterobacter*, *Flavobacterium*, *Azotobacter* and *Acetobacter*.

Composting cultures

The crop residues are mainly comprised of cellulose hemicelluloses and lignin. The cellulolytic and lignolytic microorganisms are isolated, screened and multiplied and used as composting cultures Greff *et al.*, 2022 ^[8]. The fungal cultures like *Trichoderma*, *Aspergillus*, *Phenochaete*, *Trichurus* and bacterial cultures of *Bacillus*, *Cellulomonas*, *Thiobacillus* are used as composting cultures.

Acetobacter

Acetobacter is an obligatory aerobic, nitrogen-fixing bacteria that is known for producing acid as a result of metabolic processes. More recently, a new species of nitrogen fixing bacterium *Acetobacter diazotrophicus* has been isolated from sugarcane in different parts of the world, *A.diazotrophicus* has been isolated from the root, leaf, bud and stem samples of sugarcane cultivars (Reis *et al.*, 2015; Michavila *et al.*, 2022) ^[24, 17]. This is an acid tolerant and sucrose loving bacterium recommended for sugarcane. *Acetobacter* is a genus of acetic acid bacteria. Acetic acid bacteria are characterized by the ability to convert ethanol to acetic acid in the presence of oxygen.

Blue Green Algae (BGA)

These are free-living, photoautotrophic micro-organisms, many of which also fix atmospheric nitrogen and are found in abundance in rice fields. *Cyanobacteria* (blue green algae) like

Nostoc, *Anabaena*, *Tolypothrix* etc. Generally forming non-fibrous slimy growth on the surface of soil and water. They are photoautotrophic microbes, which utilize solar energy to reduce atmospheric dinitrogen to ammonia Lee and Ryu 2021 ^[13]. They are suitable biofertilizers for paddy.

Azolla

Azolla is a floating, fast growing, aquatic fern belonging to Pteridophyta, which lives in symbiotic association with the filamentous nitrogen fixing cyanobacterium *Anabaena* and is ubiquitous in distribution. The *Azolla-Anabaena* association has a tremendous potential for providing photosynthetic production of nitrogen fertilizer (Seleiman *et al.*, 2021; Thapa and Poundel 2021) ^[27, 35]. The six species known are *Azolla pinnata*, *A. microphylla*, *A. mexicana*, *A. caroliniana*, *A. filiculoides* and *A. rubra*.

Mycorrhizae

The symbiotic association between fungi and higher plants is known as mycorrhizal association. The term mycorrhiza was coined by a German scientist, Frank. Mycorrhiza means fungus root 'Myco' means fungus 'rhiza' means root Mycorrhizal fungi is associated with almost all the terrestrial plants. Many graminaceous plants and legumes are highly, susceptible to VAM colonization. The transfer of nutrients mainly phosphorous, Zinc and Sulphur from the soil to the cells of the root cortex is mediated by intracellular obligate fungal endosymbiont of the genera *Glomus*, *Gigaspora*, *Acaulospora*, *Sclerocystis* and *Endogone*, which possess vesicles for storage of nutrients and arbuscules for funneling these nutrients into the root system.

AM fungi are known to secrete a sticky and highly resistant substance known as glomalin a glycoprotein. This chemical has been shown to be very important in soil aggregation (Wright and Upadhyaya 1998) ^[41] which helps to maintain the soil aggregate stability and prevent the soil runoff. Mycorrhizal fungi improve the plant growth through the increased uptake of nutrients especially phosphorus, Zn, N, Cu, Mn and Soil enzyme activities like dehydrogenase, phosphates, urease activity. Due to exploration of higher soil volume by the external hyphae even beyond the root zone of nutrient absorption and better soil enzyme activity also influenced by AM fungi Waratadar *et al.*, 2022 ^[39]. Better tolerance to water stress to the extent of 7-9 days in the annual crops without affecting yield Suma *et al.*, 2019 ^[33]. Recent studies have revealed that the Mycorrhizal pre-colonization persuades resistance to plant parasitism by converting strigolactones and orobanchol biosynthetic pathway into mycorradicin, which is assembled in the root zone and thereby condensed accessibility of strigolactones and orobanchol for parasitic weed germination Madhura *et al.*, (2017) ^[14]; Manjunath *et al.*, (2018) ^[16]; Shubha *et al.* (2018) ^[30]; Chandrashekhara gowda *et al.*, (2018) ^[6]; Waratadar *et al.*, 2021a/b ^[38, 40]. They are also known to enhance the activities of beneficial microflora in the rhizosphere (free living N₂ fixers, P-solubilisers and PGPR) while reducing the disease severity caused by root pathogens (Chamkhi *et al.*, 2022) ^[5].

Pink pigmented facultative methylotrophs (PPFMs)

A group of bacteria that possess the ability to utilize methyl compounds as a carbon and energy source. They are known for their plant growth-promoting properties and have been studied extensively for their potential applications in agriculture. Here's how PPFMs can promote plant growth:

- **Methylotrophic Activity:** PPFMs have the ability to

metabolize methanol, methylamine, and other methyl compounds. By utilizing these compounds, PPFMs can release growth-promoting substances such as cytokinins, auxins, and gibberellins, which positively influence plant growth and development (Nysanth *et al.*, 2023) ^[22].

- **Nutrient Availability:** PPFMs can solubilize phosphate, making it more accessible to plants. They can also fix atmospheric nitrogen, converting it into a usable form for plant uptake. These activities contribute to increased nutrient availability and uptake, leading to enhanced plant growth.
- **Disease Suppression:** PPFMs have been found to possess biocontrol properties against various plant pathogens. They can produce antifungal compounds, inhibit pathogen growth, and induce systemic resistance in plants. By protecting plants from diseases, PPFMs contribute to healthier and more robust plant growth (Srivastava *et al.*, 2022) ^[32].
- **Stress Tolerance:** PPFMs can enhance plant tolerance to various abiotic stresses such as drought, salinity, and heavy metal toxicity. They do so by producing stress-related enzymes, metabolites, and antioxidants, which help plants, cope with adverse environmental conditions and improve their overall growth and survival (Bajpai *et al.*, 2022) ^[2].

Frankia

Species of the *Frankia* Genus are Gram positive bacteria. *Frankia sp.* are filamentous nitrogen-fixing bacterium that grow by branching and tip extension and thus resemble the antibiotic-producing *Streptomyces sp.* They live in the soil and have a symbiotic relationship with certain woody angiosperms, called actinorhizal plants. During growth, the *Frankia sp.* produces three cell types: sporangiospores, hyphae, and diazo-vesicles (spherical, thick walled, lipid-enveloped cellular structures).

Actinomycetes of the genus *Frankia* forms N₂ fixing nodules on several tree species and on shrubs. They are very improved N₂ fixing groups of the environments which are very poor in soil fertility. It has been estimated around 300 kg of N₂ is fixed per ha per year in these environment. *Frankia* forms nodules in at least 25 genera of plant species. These plants are woody shrubs & tree species found in temperate climate and also from the arctic to tropics and from semi- desert to rain-forest ecosystem. Their population is higher in slightly alkaline soil. The area surrounding plant rhizosphere, is richly colonized by actinomycetes. Their high synthesis of antimicrobial compounds and other metabolites gives them a competitive advantage, besides helping with the improvement of soil fertility by promoting plant growth, providing protection against phytopathogens and resisting environmental stresses (Silva *et al.*, 2022) ^[31].

Conclusion

Overreliance on the use of chemical fertilizers has encouraged industries to produce chemicals that are noxious to human health. Thus, impact on ecological imbalances. These pitfalls are combined with a high cost of production that is beyond the means of many farmers in the developing world. The application of biofertilizers is eco-friendly, relatively inexpensive, nontoxic, and possesses the significant potential to increase plant yield. Thus, the function of plant growth-promoting microorganisms and the application of biofertilizer made from viable microbial strains to the field will be promising approach for the successful management of nutrient in the rhizosphere for sustainable agriculture.

References

1. Al-Abboud M A, Ghany TA, Alawlaqi MM. Role of biofertilizers in agriculture: a brief review. *Mycopath.* 2014;11(2):95-101.
2. Bajpai A, Mahawar H, Dubey G, Atoliya N, Parmar R, Devi MH, *et al.* Prospect of pink pigmented facultative methylotrophs in mitigating abiotic stress and climate change. *Journal of Basic Microbiology.* 2022;62(8):889-899.
3. Bargaz A, Lyamlouli K, Chtouki M, Zeroual Y, Dhiba D. Soil microbial resources for improving fertilizers efficiency in an integrated plant nutrient management system. *Frontiers in Microbiology.* 2018;9:1606.
4. Bhattacharyya PN, Jha DK. Plant growth-promoting rhizobacteria (PGPR): emergence in agriculture. *World Journal of Microbiology and Biotechnology.* 2011;28(4):1327-1350.
5. Chamkhi I, El Omari N, Balahbib A, El Menyiy N, Benali T, Ghoulam C. Is the rhizosphere a source of applicable multi-beneficial microorganisms for plant enhancement? *Saudi Journal of Biological Sciences.* 2022;29(2):1246-1259.
6. Chandrashekhargowda B, Jones PN, Shiney A, Matiade PS, Jagadeesh KS. Suppression of *Orobanche* spp. in tobacco by native arbuscular mycorrhizal fungi. *International Journal of Current Microbiology and Applied Sciences.* 2018;7(4):1890-1896.
7. Fasusi OA, Cruz C, Babalola OO. Agricultural sustainability: microbial biofertilizers in rhizosphere management. *Agriculture.* 2021;11:163.
8. Greff B, Szigeti J, Nagy Á, Lakatos E, Varga L. Influence of microbial inoculants on co-composting of lignocellulosic crop residues with farm animal manure: a review. *Journal of Environmental Management.* 2022;302:114088.
9. Harshitha HA, Goudar G. Influence of plant growth promoting *Rhizobium* on growth of pigeon pea (*Cajanus cajan* (L.) Millsp.). *Legume Research.* 2021;LR-4573:1-6.
10. Jacoby R, Peukert M, Succurro A, Koprivova A, Kopriva S. The role of soil microorganisms in plant mineral nutrition—current knowledge and future directions. *Frontiers in Plant Science.* 2017;8:1617.
11. Kalayu G. Phosphate solubilizing microorganisms: promising approach as biofertilizers. *International Journal of Agronomy.* 2019;2019:1-7.
12. Koskey G, Mburu SW, Awino R, Njeru EM, Maingi JM. Potential use of beneficial microorganisms for soil amelioration, phytopathogen biocontrol, and sustainable crop production in smallholder agroecosystems. *Frontiers in Sustainable Food Systems.* 2021;5:130.
13. Lee SM, Ryu CM. Algae as new kids in the beneficial plant microbiome. *Frontiers in Plant Science.* 2021;12:599742.
14. Madhura AS, Jones NP, Netravati M. *Striga* (*Striga asiatica*), a parasitic weed inhibition by arbuscular mycorrhizal fungi in sugarcane (*Saccharum officinarum*). *International Journal of Applied and Pure Science and Agriculture.* 2017;3(3):394-402.
15. Malusá E, Sas-Paszt L, Ciesielska J. Technologies for beneficial microorganisms inocula used as biofertilizers. *The Scientific World Journal.* 2012;2012:1-12.
16. Manjunath HP, Jones PN, Chandranath HT, Shiney A, Jagadeesh K S. Field evaluation of native arbuscular mycorrhizal fungi in the management of *Striga* in sugarcane (*Saccharum officinarum* L.). *Journal of Pharmacognosy and Phytochemistry.* 2018;7(2):2496-2500.

17. Michavila G, Alibrandi P, Cinà P, Welin B, Castagnaro AP, Chalfoun NR, *et al.* Plant growth-promoting bacteria isolated from sugarcane improve the survival of micropropagated plants during acclimatisation. *Italian Journal of Agronomy*. 2022;17(2):1-10.
18. Mohamed HI, El-Beltagi S, Abd-Elsalam KA. Plant growth-promoting microbes for sustainable biotic and abiotic stress management. Springer. 2021;94-106.
19. Nielsen MN, Winding A. Microorganisms as indicators of soil health. National Environmental Research Institute, Denmark. Technical Report No. 388. 2002.
20. Nikitin DA, Semenov MV, Chernov TI, Ksenofontova NA, Zhelezova AD, Ivanova EA, *et al.* Microbiological indicators of soil ecological functions: a review. *Eurasian Soil Science*. 2022;55(2):221-234.
21. Nosheen S, Ajmal I, Song Y. Microbes as biofertilizers, a potential approach for sustainable crop production. *Sustainability*. 2021;13(4):1868.
22. Nysanth NS, Anu RS, Sivapriya SL, Anith KN. Pink pigmented facultative methylotrophs (PPFMs): potential bioinoculants for sustainable crop production. *Journal of Pure & Applied Microbiology*. 2023;17(2):1-10.
23. Raffi MM, Charyulu PBBN. Azospirillum-biofertilizer for sustainable cereal crop production: current status. In: *Recent Developments in Applied Microbiology and Biochemistry*. Academic Press; 2021. p. 193-209.
24. Reis VM, Teixeira KR. Nitrogen fixing bacteria in the family Acetobacteraceae and their role in agriculture. *Journal of Basic Microbiology*. 2015;55(8):931-949.
25. Riaz U, Mehdi SM, Iqbal S, Khalid HI, Qadir AA, Anum W. Bio-fertilizers: eco-friendly approach for plant and soil environment. In: *Bioremediation and Biotechnology: Sustainable Approaches to Pollution Degradation*. Springer; 2020. p. 188-214.
26. Sawada H, Kuykendall LD, Young JM. Changing concepts in the systematics of bacterial nitrogen-fixing legume symbionts. *The Journal of General and Applied Microbiology*. 2003;49(3):155-179.
27. Seleiman MF, Elshayb OM, Nada AM, El-Leithy SA, Baz L, Alhammad BA, *et al.* Azolla compost as an approach for enhancing growth, productivity, and nutrient uptake of *Oryza sativa* L. *Agronomy*. 2022;12(2):416.
28. Shannon D, Sen AM, Johnson DB. A comparative study of the microbiology of soils managed under organic and conventional regimes. *Soil Use and Management*. 2006;18:274-283.
29. Shi G, Sun H, Calderón-Urrea A, Li M, Yang H, Wang W, *et al.* Bacterial communities as indicators of soil health under a continuous cropping system. *Land Degradation & Development*. 2021;32(7):2393-2402.
30. Shubha C, Jones PN, Madhura AS, Jagadeesh KS, Ramesh B. Isolation, screening and selection of efficient native arbuscular mycorrhizal fungi for suppression of *Striga* in sugarcane. *Indian Journal of Weed Science*. 2018;50(1):51-55.
31. Silva GDC, Kitano IT, Ribeiro IADF, Lacava PT. The potential use of actinomycetes as microbial inoculants and biopesticides in agriculture. *Frontiers in Soil Science*. 2022;2:1-7.
32. Srivastava A, Dixit R, Chand N, Kumar P. Overview of methylotrophic microorganisms in agriculture. *Bio Science Research Bulletin*. 2022;38(1):65-71.
33. Suma RK, Jones NP, Jagadeesh KS. Role of AM fungi in mitigating moisture stress in soybean (*Glycine max* L. Merrill). *International Journal of Current Microbiology and Applied Sciences*. 2019;8(7):1451-1462.
34. Sumbul A, Ali Ansari R, Rizvi R, Mahmood I. *Azotobacter*: A potential bio-fertilizer for soil and plant health management. *Saudi Journal of Biological Sciences*. 2020;27(12):3634-3640.
35. Thapa P, Poundel K. *Azolla*: Potential biofertilizer for increasing rice productivity and government policy for implementation. *Journal of Wastes and Biomass Management*. 2021;3:62-68.
36. Van Dommelen A, Vanderleyden J. Associative nitrogen fixation. In: *Biology of the Nitrogen Cycle*. Elsevier; 2007. p.179-192.
37. Vilkiene M, Mockeviciene I, Karcauskiene D, Suproniene S, Doyeni MO, Ambrazaitiene D. Biological indicators of soil quality under different tillage systems in Retisol. *Sustainability*. 2021;13(17):9624.
38. Waratadar A, Nirmalnath PJ, Matiwade PS, Navi V. Field evaluation of arbuscular mycorrhizal fungi in the management of *Orobanche*: A parasitic weed in tobacco (*Nicotiana tabacum* L.). *International Journal of Environment and Climate Change*. 2021a;11(8):82-93.
39. Waratadar A, Nirmalnath PJ, Matiwade PS, Navi V. Soil enzyme activity and nutrient uptake as influenced by arbuscular mycorrhizal fungi in tobacco rhizosphere under parasitic weed stress condition. *International Journal of Plant & Soil Science*. 2022;34(22):984-995.
40. Waratadar A, Nirmalnath PJ, Matiwade PS, Navi V. Effectiveness of mycorrhizal biofertilizer in the management of *Orobanche* in tomato (*Lycopersicon esculentum* L.). *Biological Forum - An International Journal*. 2021b;13(3):295-302.
41. Wright S F, Upadhyaya A. A survey of soils for aggregate stability and glomalin, a glycoprotein produced by hyphae of arbuscular mycorrhizal fungi. *Plant and Soil*. 1998;198:97-107.