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Enhancing Crop Productivity with Biofertilizers: Exploring Multifunctional Benefits

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

ABSTRACT

The increasing demand for food production, combined with the environmental degradation caused by conventional farming practices, has prompted a shift towards sustainable agriculture. Biofertilizers, consisting of living microorganisms such as nitrogen-fixing bacteria, phosphate-

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solubilizing bacteria, and mycorrhizal fungi, offer a promising solution to enhance crop productivity while minimizing environmental impacts. This article explores the multifunctional benefits of biofertilizers, including their role in nutrient supplementation, soil structure improvement, disease suppression, and abiotic stress tolerance. Biofertilizers contribute to sustainable farming by improving nutrient availability, enhancing soil health, and promoting plant resilience to environmental stresses. The integration of biofertilizers into agricultural practices represents a crucial step towards achieving sustainable crop production, restoring soil health, and securing food systems for future generations.

Keywords: Biofertilizers; productivity; symbiosis; solubilizers.

1. INTRODUCTION

The growing global population, coupled with diminishing arable land and declining soil fertility, has placed immense pressure on agriculture to produce more food with fewer resources. Traditional farming practices, heavily reliant on chemical fertilizers, have led to a host of environmental issues, including soil degradation, water pollution, and loss of biodiversity [1]. As a result, crop productivity has stagnated or even declined in many regions, threatening food security. In this context, biofertilizers offer a promising solution to enhance crop productivity while mitigating environmental impacts. Biofertilizers, which include living microorganisms such as nitrogen-fixing bacteria, phosphate-solubilizing bacteria, and mycorrhizal fungi, promote plant growth by increasing the availability of essential nutrients in the soil [2]. The detailed classification of biofertilizers along with examples given in (Table 1). These microorganisms can improve soil health by enhancing its physical structure, increasing organic matter content, and promoting nutrient cycling. Moreover, biofertilizers contribute to sustainable agriculture by reducing the need for synthetic fertilizers [3], thereby lowering the risk of soil and water contamination [4].

Recent studies have shown that biofertilizers can significantly increase crop yields, particularly in low-input farming systems [5-7]. For example, the use of nitrogen-fixing bacteria in legume crops has been found to enhance nitrogen availability, leading to higher yields and improved soil fertility [8]. Similarly, phosphate-solubilizing bacteria can unlock phosphorus bound in soil minerals, making it accessible to plants and reducing the need for phosphate fertilizers [9]. The multifunctional benefits of biofertilizers extend beyond nutrient supply. They also improve plant resilience to environmental stresses such as drought, salinity, and disease. By enhancing the microbial diversity in the soil, biofertilizers can create a more balanced and resilient ecosystem, capable of supporting sustainable crop production [4]. As the demand for food continues to rise, the adoption of biofertilizers represents a crucial step towards achieving agricultural sustainability. By harnessing the power of beneficial microorganisms, we can enhance crop productivity, restore soil health, and protect our ecosystems for future generations. This exploration of the multifunctional benefits of biofertilizers aims to shed light on their potential to revolutionize modern agriculture and contribute to a more sustainable and secure food system.

2. ROLE OF BIOFERTILIZER IN PLANT GROWTH PROMOTION AND BIOCONTROL

Biofertilizers provides an array of beneficial role for improving the crop growth and productivity either directly through providing nutritional support or indirectly through altering the rhizosphere microclimate. The broader prospects of beneficial effect may be classified into enhancement in nutrient supplement to plant, soil structure improvement, disease pest suppression and abiotic stress tolerance (Fig. 1). These are explained as follows.

2.1 Enhanced Nutrient Supplement

Biofertilizers, derived from living organisms, offer a sustainable approach to improving soil fertility and promoting plant growth. Among their various benefits, enhancing nutrient uptake in crop plants stands out as a crucial mechanism contributing to agricultural productivity.

Table 1. Various classes of biofertilizers along with their examples

Sl. No.	Type of Biofertilizer	Examples	Crops Used	References
1.	Nitrogen-Fixers			
	Symbiosis	*Rhizobium spp*., Blue green algae	Legumes (e.g., soybeans, peas), Rice	[10-11]
	Associative symbiosis	*Azospirillum spp., Herbaspirillum spp., Clostridium spp*., Anabaena	Cereals (e.g., wheat, corn)	
	Free-living	*Azotobacter spp., Frankia spp*. (actinomycetes)	Woody plants (e.g., alders, elms)	
2.a	*Phosphorus solubilizers* and mobilizers			
	Phosphorus solubilizers	Bacteria: Bacillus megaterium, Pseudomonas striata.	Rice, wheat, Legumes, Brassicas	[12]
		Fungi: *Penicillium spp*., *Aspergillus awamori*	Cereals, legumes	
2.b	Phosphorus mobilizers	Amanita, Boletus, Vescicular arbuscular mycorrihiza (VAM)		[13]
3.	*Potassium solubilizers*			
		Bacillus mucilaginosus	Rice, wheat, fruits, vegetables	[14-15]
		Azotobacter chroococcum	Legumes, cereals	
4.	*Micronutrient solubilizers*			
		Serratia spp. *Bacillus spp. Pseudomonas spp*.		[10, 12]
5.	Plant growth promoting rhizobacteria (PGPR)			
		Trichoderma spp.	tomatoes, peppers	[16-17]
		Bacillus thuringiensis	Vegetables, fruits	
		Pseudomonas fluorescens	potatoes, tomatoes	

2.1.1 Nitrogen-fixing biofertilizers

Nitrogen (N) is an essential nutrient required for plant growth and development, influencing various physiological processes such as photosynthesis, protein synthesis, and enzyme activity. Nitrogen-fixing biofertilizers, such as Rhizobium spp. and Azospirillum spp., play a pivotal role in supplying plants with readily available nitrogen [10-11]. Through symbiotic associations with leguminous plants or free-living nitrogen-fixing bacteria, these biofertilizers convert atmospheric nitrogen into ammonia, which can be utilized by plants. The process of biological nitrogen fixation not only supplements soil nitrogen levels but also improves nitrogen uptake efficiency in crops. By colonizing the rhizosphere and forming nodules on plant roots, nitrogen-fixing bacteria establish a mutually beneficial relationship with plants, providing them with a direct source of nitrogen [18]. This enhanced nitrogen uptake contributes to the vigorous growth and high yield potential of nitrogen-responsive crops, including legumes, cereals, and oilseeds.

2.1.2 Phosphorus solubilizers

Phosphorus (P) is another essential nutrient critical for plant growth, particularly in processes related to energy transfer, root development, and reproductive growth. However, phosphorus availability in soil is often limited due to its tendency to form insoluble compounds, such as phosphate minerals. Phosphorus-solubilizing biofertilizers, such as Bacillus spp. and Pseudomonas spp., play a vital role in solubilizing these insoluble phosphates, making phosphorus more accessible to plants [12]. Through the secretion of organic acids, phosphatases, and chelating agents, phosphorus-solubilizing microorganisms mobilize phosphorus from soil minerals, organic matter, and fertilizer sources, thereby enhancing phosphorus uptake by crop roots. This increased phosphorus availability not only promotes early plant establishment and root proliferation but also improves nutrient use efficiency and crop productivity [10]. Phosphorus-responsive crops, including cereals, legumes, and vegetables, benefit significantly from the application of phosphorus-solubilizing biofertilizers.

2.1.3 Potassium solubilizers

Potassium (K) is essential for various physiological processes in plants, including osmoregulation, enzyme activation, and photosynthesis. Potassium deficiency can lead to reduced plant vigor, susceptibility to stress, and compromised yield potential. Potassium-producing biofertilizers, such as *Bacillus mucilaginosus* and *Azotobacter chroococcum*, contribute to soil potassium availability through mechanisms such as mineral solubilization and potassium mobilization [14]. These biofertilizers enhance potassium uptake by crop plants by promoting the release of potassium ions from soil minerals and organic matter, making them more accessible to plant roots. Additionally, potassium-producing bacteria can enhance soil structure and water retention capacity, further supporting plant growth and nutrient uptake [15]. Potassium-responsive crops, including rice, wheat, fruits, and vegetables, exhibit improved yield and quality attributes in response to potassium-supplemented biofertilizers.

2.1.4 Micronutrient solubilizers

Micronutrient solubilizing biofertilizers play a pivotal role in enhancing crop growth and productivity by facilitating the availability of essential micronutrients to plants. These biofertilizers contain beneficial microorganisms capable of solubilizing insoluble forms of micronutrients, such as iron, zinc, manganese, and copper, into soluble forms that are readily absorbed by plant roots. For instance, certain species of bacteria like *Azotobacter, Azospirillum,* and *Bacillus*, as well as fungi like *Trichoderma* and *Aspergillus*, possess the ability to produce organic acids, siderophores, and chelating agents, which aid in micronutrient solubilization from soil minerals or organic matter [10, 12]. By improving nutrient uptake efficiency, micronutrient solubilizing biofertilizers contribute to enhanced plant growth, development, and overall yield. Moreover, their application can reduce the dependency on chemical fertilizers, leading to more sustainable agricultural practices. Therefore, harnessing the potential of these biofertilizers presents a promising approach for promoting crop growth and ensuring food security in a manner that is environmentally friendly and economically viable.

2.2 Improving Soil Structure

Soil structure, the spatial arrangement of soil particles and aggregates, profoundly influences soil fertility, water retention, and root growth. However, modern agricultural practices often degrade soil structure, leading to reduced productivity and environmental degradation. Biofertilizers, derived from beneficial microorganisms, offer a sustainable approach to improve soil structure and restoring soil health in agricultural systems. Several mechanisms contribute to the soil structure-improving properties of biofertilizers:

2.2.1 Organic matter addition

Many biofertilizers, such as rhizobia, mycorrhizal fungi, and beneficial bacteria, contribute to the accumulation of organic matter in the soil through root exudation, biomass production, and residue decomposition [19]. This organic matter serves as a binding agent, promoting soil aggregation and stability.

2.2.2 Exopolysaccharide production

Certain biofertilizers, particularly nitrogen-fixing bacteria and mycorrhizal fungi, produce exopolysaccharides (EPS), which act as soil conditioners [20]. EPS enhance soil aggregation, water infiltration, and nutrient retention, thereby improving soil structure and fertility.

2.2.3 Soil microbial activity stimulation

Biofertilizers stimulate soil microbial activity, including the proliferation of beneficial bacteria and fungi. These microorganisms play key roles in soil aggregation, organic matter decomposition, and nutrient cycling, contributing to improved soil structure and fertility [17, 21]. The integration of biofertilizers into agricultural practices holds significant promise for promoting soil health, biodiversity, and resilience in the face

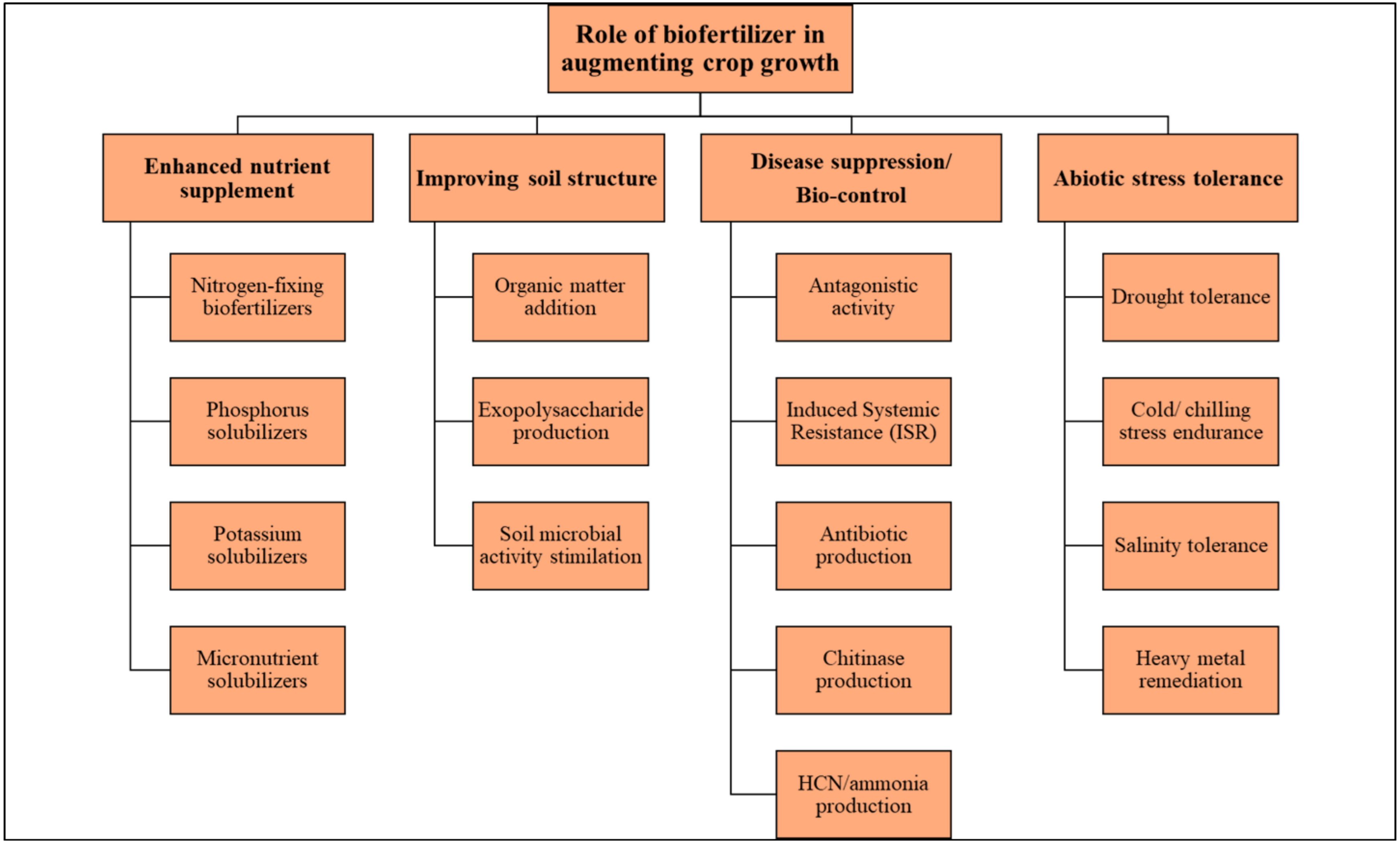

Fig. 1. Role of biofertilizers in augmenting crop growth

of climate change and environmental challenges. By fostering a symbiotic relationship between crops, microorganisms, and soil, biofertilizers contribute to the development of regenerative farming systems that prioritize soil conservation, carbon sequestration, and ecosystem stability.

2.3 Disease Suppression/ Bio-control

Plant diseases pose significant challenges to global agriculture, affecting crop yields, food security, and economic stability. Traditional disease management strategies often rely on chemical pesticides and fungicides, which have detrimental effects on human health and the environment. Biofertilizers, derived from beneficial microorganisms, offer a sustainable and eco-friendly alternative for disease suppression in crop plants (Fig 2.).

2.3.1 Antagonistic activity

Certain biofertilizers, such as *Trichoderma* spp., *Bacillus* spp., and *Pseudomonas* spp., produce antimicrobial compounds and enzymes that inhibit the growth and activity of plant pathogens [22]. These beneficial microorganisms colonize the rhizosphere and phyllosphere of plants, competing for space and resources with pathogenic organisms, thereby suppressing disease development.

2.3.2 Induced Systemic Resistance (ISR)

Biofertilizers can stimulate the plant's innate defence mechanisms, triggering induced systemic resistance (ISR) against pathogens [23]. This systemic resistance response involves the activation of plant defence pathways, leading to the production of antimicrobial compounds, phytoalexins, and pathogenesis-related (PR) proteins. ISR primes the plant's immune system for enhanced resistance against subsequent pathogen attacks, providing long-lasting protection against diseases [22].

2.3.3 Antibiotic production

Biofertilizers play a vital role in promoting antibiotic production, thereby aiding crop growth and protection against pathogens. Certain strains of beneficial microorganisms used as biofertilizers possess the capability to produce antibiotics as secondary metabolites. For instance, species like *Bacillus subtilis*, *Pseudomonas fluorescens*, and *Streptomyces* spp. are well-known for their ability to synthesize antibiotics such as bacitracin, pyoluteorin, and streptomycin, respectively [24]. These antibiotics exhibit antagonistic effects against various plant pathogens, including bacteria, fungi, and nematodes, thereby reducing the incidence of diseases and promoting healthier plant growth. Moreover, biofertilizers containing antibiotic-producing microorganisms contribute to the development of a conducive rhizosphere environment by suppressing the proliferation of harmful pathogens while fostering beneficial microbial communities [25]. This ultimately enhances nutrient uptake and overall plant vigour.

Incorporating biofertilizers with antibiotic-producing capabilities into agricultural practices presents a sustainable approach to crop management, reducing reliance on synthetic chemical pesticides and promoting environmentally friendly farming techniques.

2.3.4 Chitinase production

Biofertilizers serve a crucial function in fostering chitinase production, thereby facilitating crop growth and defence mechanisms against pathogenic threats. Chitinase enzymes, produced by certain microorganisms present in biofertilizers, play a pivotal role in degrading chitin– a major component of fungal cell walls into simpler compounds [26]. This enzymatic activity helps in suppressing fungal pathogens and enhancing plant health. For instance, species like *Trichoderma harzianum* and *Bacillus thuringiensis* produce chitinase enzymes that effectively degrade fungal cell walls, thus reducing the incidence of diseases such as damping-off, root rot, and wilt in various crops [13]. By promoting the activity of chitinase-producing microorganisms, biofertilizers contribute to a healthier rhizosphere environment, where plants are better equipped to resist fungal infections and absorb nutrients efficiently [27]. Integrating biofertilizers rich in chitinase-producing microbes into agricultural practices represents a sustainable approach to crop protection, reducing the reliance on synthetic fungicides and fostering environmentally friendly farming methods.

2.3.5 HCN/ammonia production

Biofertilizers play a significant role in the production of hydrogen cyanide (HCN) or ammonia, contributing to crop growth and protection against pests and pathogens. Certain

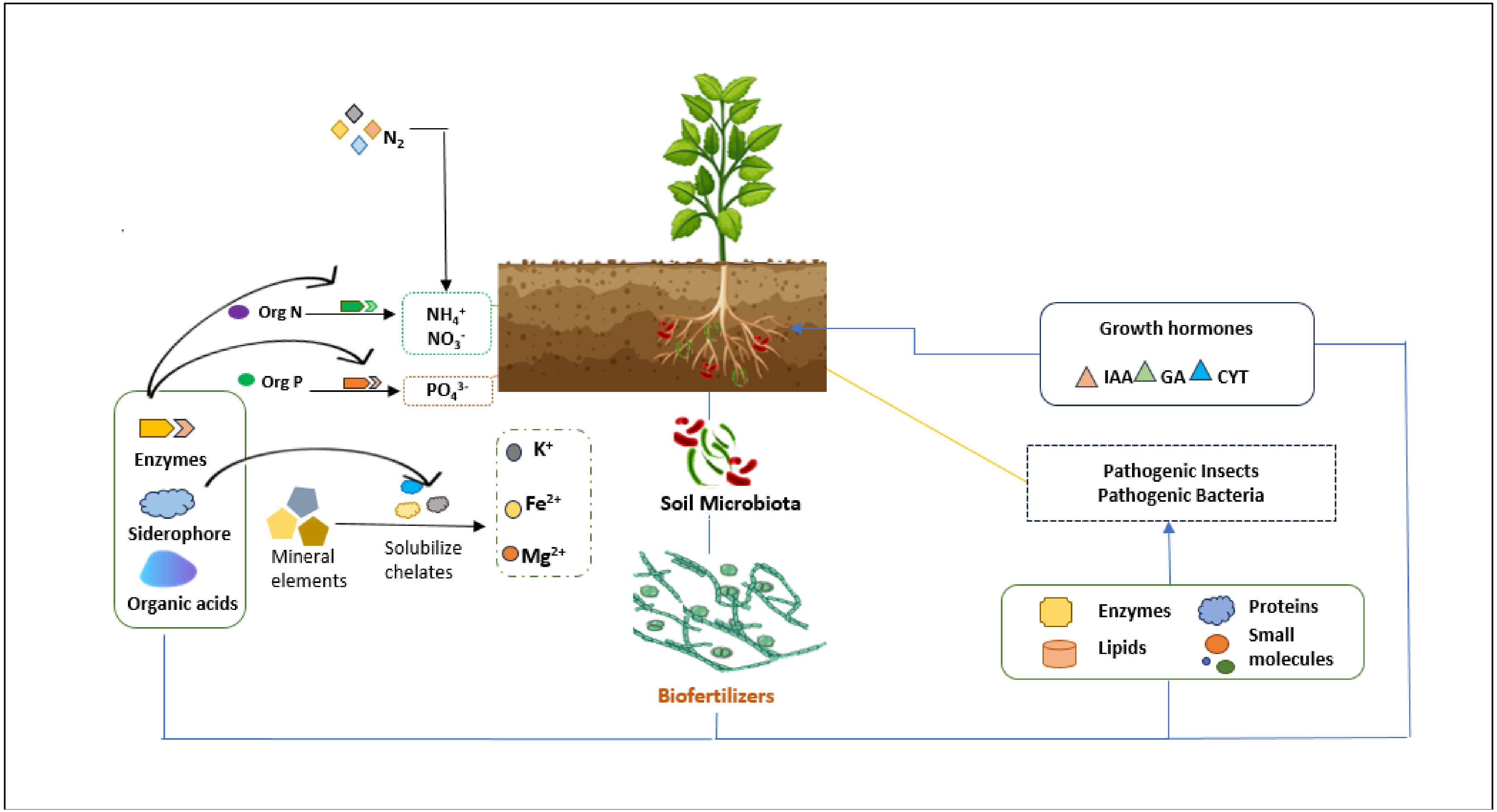

Fig. 2. Biocontrol action of biofertilizers

strains of beneficial microorganisms present in biofertilizers, such as Pseudomonas and Azotobacter species, possess the ability to produce HCN or ammonia as metabolic byproducts [28]. These compounds exhibit biocontrol properties by inhibiting the growth of various soil-borne pathogens, including fungi, bacteria, and nematodes. For example, *Pseudomonas fluorescens* produces HCN, which acts as a potent antifungal agent, suppressing the proliferation of pathogens like *Fusarium, Rhizoctonia,* and *Phytophthora* [21]. Similarly, ammonia-producing bacteria like Azotobacter spp. contribute to disease suppression and promote plant growth by altering the soil pH and competing for nutrients with pathogenic organisms [10]. By enhancing soil health and suppressing detrimental pathogens, biofertilizers rich in HCN or ammonia-producing microbes foster a conducive rhizosphere environment for crop growth, reducing the need for synthetic chemical pesticides and promoting sustainable agricultural practices.

2.3.6 Nutritional Enhancement

Biofertilizers improve plant health and vigor by enhancing nutrient uptake, root development, and physiological processes. Healthy and well-nourished plants are better equipped to withstand disease pressure and recover from pathogen attacks [13]. Biofertilizers contribute to the overall health and resilience of crop plants, reducing their susceptibility to diseases and promoting sustainable crop production.

The integration of biofertilizers into integrated pest management (IPM) strategies holds significant promise for sustainable agriculture. By harnessing the biocontrol and plant health-promoting properties of beneficial microorganisms, biofertilizers contribute to the development of resilient and eco-friendly farming systems. Adoption of biofertilizers can reduce chemical inputs, minimize environmental impacts, and promote agroecological principles, ultimately fostering a more sustainable and equitable food system.

2.4 Abiotic Stress Tolerance

Abiotic stresses, such as drought, salinity, extreme temperatures, and heavy metal contamination, adversely affect crop growth, development, and productivity worldwide. With climate change exacerbating these stresses, there is an urgent need for sustainable agricultural practices that enhance crop resilience to environmental challenges [29]. Biofertilizers, comprising beneficial microorganisms such as bacteria, fungi, and archaea, offer a promising solution to improve abiotic stress tolerance in crops while minimizing the environmental footprint associated with conventional agricultural inputs.

2.4.1 Drought tolerance

Drought is a major abiotic stress that severely affects crop productivity worldwide. Biofertilizers containing drought-tolerant microorganisms play a crucial role in mitigating the adverse effects of water scarcity on crop growth and yield. Certain rhizobacteria, such as *Azospirillum* and *Bacillus*, have been shown to enhance drought tolerance in various crops by promoting root growth, improving water use efficiency, and modulating plant hormone levels [30]. For example, *Azospirillum* inoculation increases root length and density, leading to enhanced water uptake and drought resistance in crops like maize and wheat [31]. Bacillus strains produce *osmoprotectants* and plant growth-promoting substances, which help plants maintain cell turgor and mitigate drought-induced damage. Furthermore, biofertilizers containing mycorrhizal fungi improve drought tolerance by extending the root system, increasing soil water exploration, and enhancing nutrient uptake efficiency [32]. Overall, the application of biofertilizers contributes to sustainable crop production in drought-prone regions by improving water stress resilience and ensuring better yields under adverse environmental conditions.

2.4.2 Cold/ chilling stress endurance

Cold or chilling stress poses significant challenges to crop growth and development, particularly in temperate and high-altitude regions. Biofertilizers enriched with cold-tolerant microorganisms enhance plant tolerance to low temperatures by modulating physiological processes and promoting stress adaptation mechanisms [12]. Certain rhizobacteria, such as *Pseudomonas* and *Burkholderia* spp., produce antifreeze proteins and ice nucleation inhibitors, which protect plant tissues from freezing damage and improve cold tolerance [22]. Additionally, mycorrhizal fungi enhance cold stress tolerance by increasing nutrient uptake and promoting hormone balance in plants. For example, inoculation with mycorrhizae has been shown to improve cold tolerance in crops like rice and soybean by enhancing root growth and nutrient acquisition under low-temperature conditions [33]. Overall, biofertilizers play a vital role in enhancing crop resilience to cold stress, thereby ensuring stable yields and food security in regions prone to temperature fluctuations.

2.4.3 Salinity tolerance

Salinity stress, resulting from high levels of soluble salts in soil and irrigation water, negatively impacts crop growth and productivity in many parts of the world. Biofertilizers containing salt-tolerant microorganisms offer an eco-friendly approach to alleviate salinity stress and improve crop performance under saline conditions. Certain halotolerant rhizobacteria, such as *Halomonas* and *Marinobacter* species, enhance salinity tolerance in crops by facilitating ion homeostasis, osmotic adjustment, and antioxidant defense mechanisms [34]. These bacteria also produce exopolysaccharides and siderophores, which bind toxic ions and enhance nutrient uptake in saline soils [35]. Additionally, mycorrhizal fungi form symbiotic associations with plants, increasing salt tolerance by improving water and nutrient uptake efficiency. For instance, inoculation with arbuscular mycorrhizal fungi has been shown to enhance salinity tolerance in crops like tomato and wheat by increasing root biomass and reducing sodium uptake under saline conditions [10]. By promoting plant growth and mitigating salt-induced damage, biofertilizers contribute to sustainable agriculture in saline-affected regions, where conventional practices are often ineffective or environmentally damaging.

2.4.4 Heavy metal remediation

Heavy metal contamination of soil, resulting from industrial activities, mining, and improper waste disposal, poses serious threats to agricultural productivity and environmental health. Biofertilizers containing metal-tolerant microorganisms offer a promising solution to mitigate heavy metal stress and detoxify contaminated soils [10, 36]. Certain metal-resistant bacteria, such as *Pseudomonas* and *Bacillus* strains, possess the ability to sequester, immobilize, or detoxify heavy metals through mechanisms such as biosorption, complexation, and enzymatic reduction [37-38]. These bacteria also promote plant growth and enhance nutrient availability, thereby facilitating plant uptake of essential nutrients while reducing the uptake of toxic metals. Additionally, mycorrhizal fungi enhance heavy metal tolerance in plants by forming a physical barrier around root cells, preventing metal uptake, and facilitating metal sequestration in fungal hyphae [39]. For example, inoculation with mycorrhizae has been shown to improve heavy metal tolerance in crops like maize and sunflower by reducing metal translocation to shoot tissues and enhancing plant growth under metal stress conditions [40]. Overall, biofertilizers play a crucial role in phytoremediation and sustainable land management by reducing heavy metal toxicity in soils and ensuring safe food production in contaminated environments.

Hence, the biofertilizers offer effective strategies to enhance abiotic stress tolerance in crops, contributing to sustainable agriculture and food security worldwide. By harnessing the beneficial effects of microorganisms, biofertilizers improve plant resilience to drought, cold, salinity, and heavy metal stress, thereby ensuring stable yields and environmental sustainability in diverse agroecosystems. Continued research and innovation in biofertilizer development and application are essential to maximize their potential benefits and address the challenges posed by abiotic stresses in agricultural production.

3. CONCLUSION

Biofertilizers offer a transformative approach to modern agriculture by addressing the dual challenges of enhancing crop productivity and promoting environmental sustainability. The multiple benefits of biofertilizers demonstrate their pivotal role in nutrient supplementation, soil structure improvement, disease suppression, and the enhancement of abiotic stress tolerance. By harnessing the power of beneficial microorganisms such as nitrogen-fixing bacteria, phosphate-solubilizing bacteria, and mycorrhizal fungi, biofertilizers improve nutrient availability and uptake, thereby increasing crop yields and reducing dependence on chemical fertilizers. Furthermore, biofertilizers contribute to healthier and more resilient soils through the addition of organic matter, stimulation of microbial activity, and improvement of soil physical properties. These enhancements not only foster robust plant growth but also create a more sustainable soil ecosystem capable of withstanding environmental stresses. The ability of biofertilizers to suppress plant diseases through antagonistic activities and induced systemic resistance reduces the need for chemical pesticides, promoting safer and more eco-friendly farming practices. In addition to the direct benefits, biofertilizers play a crucial role in mitigating the adverse effects of abiotic stresses such as drought, salinity, and heavy metal contamination. By enhancing plant resilience, biofertilizers ensure more consistent agricultural output in the face of increasingly unpredictable climatic conditions, thereby contributing to food security and sustainable agricultural development.

DECLARATION

Authors hereby declare that NO generative AI technologies and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Hossain ME, Shahrukh S, Hossain SA. Chemical fertilizers and pesticides: Impacts on soil degradation, groundwater, and human health in Bangladesh. In environmental degradation: challenges and strategies for mitigation. Cham: Springer International Publishing. 2022;63-92.
2. Kumar R, Kumawat N, Sahu YK. Role of biofertilizers in agriculture. Popular kheti. 2017;5(4):63-6.
3. Kumar MS, Reddy GC, Phogat M, Korav S. Role of bio-fertilizers towards sustainable agricultural development: A review. Journal of Pharmacognosy and Phytochemistry. 2018;7(6):1915-21.
4. Mahanty T, Bhattacharjee S, Goswami M, Bhattacharyya P, Das B, Ghosh A, Tribedi P. Biofertilizers: A potential approach for sustainable agriculture development. Environmental Science and Pollution Research. 2017;24:3315-35.
5. Malusà E, Pinzari F, Canfora L. Efficacy of biofertilizers: Challenges to improve crop production. Microbial Inoculants in Sustainable Agricultural Productivity: Vol. 2: Functional Applications. 2016;17-40.
6. Mohammadi K, Sohrabi Y. Bacterial biofertilizers for sustainable crop production: A review. ARPN J Agric Biol Sci. 2012;7(5):307-16.
7. Soleimanzadeh H, Ghooshchi F. Response of growth and yield of maize to biofertilizers in organic and conventional cropping systems. International Journal of Agriculture and Crop Sciences. 2013;5(7):797.
8. Kebede E. Contribution, utilization, and improvement of legumes-driven biological nitrogen fixation in agricultural systems. Frontiers in Sustainable Food Systems. 2021;5:767998.
9. Billah M, Khan M, Bano A, Hassan TU, Munir A, Gurmani AR. Phosphorus and phosphate solubilizing bacteria: Keys for sustainable agriculture. Geomicrobiology Journal. 2019;36(10):904-16.
10. Mahmud AA, Upadhyay SK, Srivastava AK, Bhojiya AA. Biofertilizers: A Nexus between soil fertility and crop productivity under abiotic stress. Current Research in Environmental Sustainability. 2021;3(100063).
11. Mpongwana S, Manyevere A, Mupangwa J, Conference Thando M, Mashamaite CV. Improving soil fertility through dual inoculation with arbuscular mycorrhizal fungi and Rhizobium on a eutric cambisol cultivated with forage legumes in a semi-arid region. Heliyon. 2024;10(2):e24817. Available:https://doi.org/10.1016/j.heliyon.2024.e24817
12. Sharma B, Yadav L, Pandey M, Shrestha J. Application of biofertilizers in crop production: A review. Peruvian Journal of Agronomy, 2022;6(1):13–31. Available:https://doi.org/10.21704/pja.v6i1.1864
13. Shahwar D, Mushtaq Z, Mushtaq H, Alqarawi AA, Park Y, Alshahrani TS, Faizan S. Role of microbial inoculants as bio fertilizers for improving crop productivity: A review. Heliyon, 2023;9(6):e16134. Available:https://doi.org/10.1016/j.heliyon.2023.e16134
14. Etesami H, Maheshwari DK. Use of plant growth promoting rhizobacteria (PGPRs) with multiple plant growth promoting traits in stress agriculture: Action mechanisms and future prospects. Ecotoxicology and Environmental Safety. 2018;156:225–246. Available:https://doi.org/10.1016/j.ecoenv.2018.03.013
15. Ding B, Cao H, Bai Y, Guo S, Zhang J, He Z, Wang B, Jia Z, Liu H. Effect of biofertilizer addition on soil physicochemical properties, biological properties, and cotton yield under water

irrigation with different salinity levels in Xinjiang, China. Field Crops Research. 2024;308(109300).
Available:https://doi.org/10.1016/j.fcr.2024.109300

16. Vejan P, Abdullah R, Khadiran T, Ismail S, Nasrulhaq Boyce A. Role of plant growth promoting rhizobacteria in agricultural sustainability—A review. Molecules (Basel, Switzerland). 2016;21(5):573.
Available:https://doi.org/10.3390/molecules21050573
17. Khoso MA, Wagan S, Alam I, Hussain A, Ali Q, Saha S, Poudel TR, Manghwar H, Liu F. Impact of plant growth-promoting rhizobacteria (PGPR) on plant nutrition and root characteristics: Current perspective. Plant Stress. 2024;11:100341.
Available:https://doi.org/10.1016/j.stress.2023.100341
18. Wu SC, Cao ZH, Li ZG, Cheung KC, Wong MH. Effects of biofertilizer containing N-fixer, P and K solubilizers and AM fungi on maize growth: A greenhouse trial. Geoderma, 2005;125:(1–2):155–166.
Available:https://doi.org/10.1016/j.geoderma.2004.07.003
19. Ali AM, Awad MYM, Hegab SA, Gawad AMAE, Eissa MA. Effect of potassium solubilizing bacteria (*Bacillus cereus*) on growth and yield of potato. Journal of Plant Nutrition, 2021;44(3):411–420.
Available:https://doi.org/10.1080/01904167.2020.1822399
20. Khan N, Bano A. Exopolysaccharide producing rhizobacteria and their impact on growth and drought tolerance of wheat grown under rainfed conditions. PloS One, 2019;14(9):e0222302.
Available:https://doi.org/10.1371/journal.pone.0222302
21. Kumar S, Diksha Sindhu SS, Kumar R. Biofertilizers: An ecofriendly technology for nutrient recycling and environmental sustainability. Current Research in Microbial Sciences. 2022;3:100094.
Available:https://doi.org/10.1016/j.crmicr.2021.100094
22. Glick BR. Plant growth-promoting bacteria: Mechanisms and applications. Scientifica. 2012:1–15.
Available:https://doi.org/10.6064/2012/963401
23. Zehra A, Raytekar NA, Meena M, Swapnil P. Efficiency of microbial bio-agents as elicitors in plant defense mechanism under biotic stress: A review. Current Research in Microbial Sciences. 2021;2:100054.
Available:https://doi.org/10.1016/j.crmicr.2021.100054
24. Zhao G, Zhu X, Zheng G, Meng G, Dong Z, Baek JH, Jeon CO, Yao Y, Xuan YH, Zhang J, Jia B. Development of biofertilizers for sustainable agriculture over four decades (1980–2022). Geography and Sustainability. 2024;5(1):19–28.
Available:https://doi.org/10.1016/j.geosus.2023.09.006
25. Tariq M, Jameel F, Ijaz U, Abdullah M, Rashid K. Biofertilizer microorganisms accompanying pathogenic attributes: A potential threat. Physiology and Molecular Biology of Plants: An International Journal of Functional Plant Biology. 2022;28(1):77–90.
Available:https://doi.org/10.1007/s12298-022-01138-y
26. Sharp R. A review of the applications of chitin and its derivatives in agriculture to modify plant-microbial interactions and improve crop yields. Agronomy (Basel, Switzerland). 2013;3(4):757–793.
Available:https://doi.org/10.3390/agronomy3040757
27. Chaudhary P, Singh S, Chaudhary A, Sharma A, Kumar G. Overview of biofertilizers in crop production and stress management for sustainable agriculture. Frontiers in Plant Science. 2022;13.
Available:https://doi.org/10.3389/fpls.2022.930340
28. Daniel AI, Fadaka AO, Gokul A, Bakare OO, Aina O, Fisher S, Burt AF, Mavumengwana V, Keyster M, Klein A. Biofertilizer: The future of food security and food safety. Microorganisms. 2022;10(6):1220.
29. Mishra P, Padhan SR, Sahoo JP, Sahoo JP, Mohanty AA, Barik S, Pradhan P, Samal KC. Molecular understanding of signaling compounds for optimizing cell signal transduction mechanism under abiotic stresses in crop plants. In N. K. Gupta, Y. Shavrukov, R. K. Singhal, & N. Borisjuk (Eds.), Multiple Abiotic Stress Tolerances in Higher Plants, 2023;163–181. CRC Press.
Available:https://doi.org/10.1201/9781003300564-11
30. Abdelaal K, AlKahtani M, Attia K, Hafez Y, Király L, Künstler A. The role of plant growth-promoting bacteria in alleviating the

adverse effects of drought on plants. Biology. 2021;10(6):520. Available:https://doi.org/10.3390/biology10060520

31. Boleta EHM, Shintate Galindo F, Jalal A, Santini JMK, Rodrigues WL, Lima BH, Arf O, Silva MR, da Buzetti S, Teixeira Filho MCM. Inoculation with growth-promoting bacteria Azospirillum brasilense and its effects on productivity and nutritional accumulation of wheat cultivars. Frontiers in Sustainable Food Systems. 2020;4. Available:https://doi.org/10.3389/fsufs.2020.607262
32. Gu Z, Hu C, Gan Y, Zhou J, Tian G, Gao L. Role of microbes in alleviating crop drought stress: A review. Plants, 2024;13(3):384. Available:https://doi.org/10.3390/plants13030384
33. Begum N, Qin C, Ahanger MA, Raza S, Khan MI, Ashraf M, Ahmed N, Zhang L. Role of arbuscular mycorrhizal fungi in plant growth regulation: Implications in abiotic stress tolerance. Frontiers in Plant Science, 2019;10. Available:https://doi.org/10.3389/fpls.2019.01068
34. Kumar Arora N, Fatima T, Mishra J, Mishra I, Verma S, Verma R, Verma M, Bhattacharya A, Verma P, Mishra P, Bharti C. Halo-tolerant plant growth promoting rhizobacteria for improving productivity and remediation of saline soils. Journal of Advanced Research, 2020;26:69–82. Available:https://doi.org/10.1016/j.jare.2020.07.003
35. Sagar A, Rai S, Ilyas N, Sayyed RZ, Al-Turki AI, El Enshasy HA, Simarmata T. Halotolerant rhizobacteria for salinity-stress mitigation: Diversity, mechanisms and molecular approaches. Sustainability. 2022;14(1):490. Available:https://doi.org/10.3390/su14010490
36. Nungula EZ, Raza MA, Nasar J, Maitra S, Seleiman MF, Ranjan S, Padhan SR, Sow S, Gaikwad DJ, Gitari HH. Cadmium in soil and plants: A review. In: Jha, A.K., Kumar, N. (eds) Cadmium Toxicity in Water. Springer Water 2024;21–43. Springer, Cham. https://doi.org/10.1007/978-3-031-54005-9_2
37. Alotaibi BS, Khan M, Shamim S. Unravelling the underlying heavy metal detoxification mechanisms of Bacillus species. Microorganisms. 2021;9(8): 1628. Available:https://doi.org/10.3390/microorganisms9081628
38. Dawar R, Meena DK, Padhan SR. Bioremediation: A tool for reducing environmental pollution. In A. Mangaraj, A. Sarma, K. Pandey, S. Hazarika, & G. Tamuly (Eds.), Frontiers in Agriculture Sustainability 2023;51–68. Integrated Publications. ISBN: 978-93-5834-031-0
39. Priya AK, Gnanasekaran L, Dutta K, Rajendran S, Balakrishnan D, Soto-Moscoso M. Biosorption of heavy metals by microorganisms: Evaluation of different underlying mechanisms. Chemosphere, 2022;307(135957):135957.
40. Wang FY, Lin XG, Yin R. Inoculation with arbuscular mycorrhizal fungus *Acaulospora mellea* decreases Cu phytoextraction by maize from Cu-contaminated soil. Pedobiologia. 2007;51(2):99–109. Available:https://doi.org/10.1016/j.pedobi.2007.02.003

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