Arbuscular Mycorrhizal Fungi as Plant Biostimulants for Sustainable Agriculture

Arbuscular Mycorrhizal Fungi as Plant Biostimulants for Sustainable Agriculture

Edited by

Arvind Kumar Rai, Priyanka Chandra, Nirmalendu Basak, Parul Sundha and Rajender Kumar Yadav

Cambridge Scholars Publishing

Arbuscular Mycorrhizal Fungi as Plant Biostimulants for Sustainable Agriculture

Edited by Arvind Kumar Rai, Priyanka Chandra, Nirmalendu Basak, Parul Sundha and Rajender Kumar Yadav

This book first published 2025

Cambridge Scholars Publishing

Lady Stephenson Library, Newcastle upon Tyne, NE6 2PA, UK

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

ISBN: 978-1-0364-4628-4
ISBN (Ebook): 1-0364-4628-X

TABLE OF CONTENTS

CHAPTER ONE

HARNESSING PLANT BIOSTIMULANTS: EXPLORING AGRICULTURAL APPLICATIONS AND BENEFITS

PRIYANKA CHANDRA, ARVIND KUMAR RAI, PARUL SUNDHA, NIRMALENDU BASAK, SANDEEP BEDWAL, AMAN KUMAR, POOJA DHULI, ANU SEHRAWAT, KOMALPREET KAUR AND RAJENDER KUMAR YADAV

ICAR–CENTRAL SOIL SALINITY RESEARCH INSTITUTE, KARNAL 132 001, HARYANA, INDIA

Abstract

The use of plant biostimulants represents a promising frontier in agriculture, aimed at enhancing crop productivity and resilience. Plant biostimulants are diverse substances, including natural or synthetic compounds, that positively influence plant growth, development, and stress tolerance. This abstract explores the multifaceted applications and benefits of plant biostimulants in agricultural systems. Biostimulants function through various mechanisms such as enhancing nutrient uptake, improving soil health, and promoting plant stress tolerance. They often contain substances like humic acids, seaweed extracts, amino acids, and beneficial microbes. The primary agricultural benefits of biostimulants include increased crop yield, improved quality of produce, and enhanced plant resistance to biotic and abiotic stressors. Research indicates that biostimulants can lead to significant improvements in soil structure and fertility, which supports better root development and nutrient absorption. They also play a crucial role in mitigating the impacts of environmental stresses such as drought and extreme temperatures. By fostering more efficient nutrient use and boosting plant health, biostimulants contribute to sustainable agricultural practices and reduced reliance on chemical inputs. The integration of biostimulants into crop management practices has demonstrated promising results across various crops and environmental conditions. However, ongoing research is needed to fully understand the complex interactions between biostimulants, soil microbiomes, and plant physiology. Future advancements will likely focus on optimizing biostimulant formulations, application methods, and understanding their long-term effects on agricultural ecosystems. In summary, plant biostimulants offer a valuable tool for enhancing agricultural productivity and sustainability. As the technology and understanding of these substances continue to evolve, their application is expected to become increasingly refined, offering new opportunities for improving global food security and environmental stewardship.

Keywords: Plant biostimulants, Crop productivity, Stress tolerance, Soil health, Sustainable agriculture, Nutrient uptake

Introduction

Plant biostimulants are compounds or microorganisms that are applied to the soil or plants to improve the intake of nutrients, the growth and development of the plants, and the plants' resistance to stress (du Jardin 2015; Giovannini et al 2020). In contrast to fertilisers, which give plants the necessary nutrients directly, biostimulants act indirectly by promoting organic processes in the soil microbiome or plants. They can come from a variety of natural sources, such as humic materials, seaweed extracts, helpful microbes like mycorrhizal fungi and rhizobacteria, and synthetic materials like amino acids and peptides. Utilising physiological, biochemical, and biological processes to enhance plant performance and advance sustainable farming methods is the core idea behind plant biostimulants. Because of their potential to increase crop yields, improve crop quality, and lessen reliance on traditional chemical inputs, these items are drawing attention in modern agriculture. This helps with efforts to save the environment and provide food security. Due to their many advantages and contributions to sustainable crop production, plant biostimulants are essential in agriculture. Plants are able to better use nutrients when biostimulants stimulate the root system and improve nutrient uptake efficiency. Better crop development, growth, and general health may arise from this. Biostimulants can boost crop yields and improve the quality of agricultural products by encouraging root development, flowering, and fruiting (Rouphael and Colla 2020). For farmers who want to maximise their output while upholding strict production standards, this is especially crucial. Plants can withstand a range of environmental stresses, including heat, salt, drought, and disease pressure, with the aid of biostimulants. They strengthen the plant's defence mechanisms naturally, increasing its ability to withstand adversity and survive. Reducing dependency on synthetic fertilisers and agrochemicals can be achieved by integrating biostimulants into agricultural methods. This reduces manufacturing costs while simultaneously minimising harm to the environment and encouraging environmentally responsible farming practices. By increasing nutrient cycling mechanisms, boosting beneficial microbial populations, and strengthening soil structure, biostimulants improve soil health (Zhang et al 2024). Long-term plant development and sustainable agricultural systems are supported by healthy soils. Numerous biostimulants that are permitted for use in organic agricultural systems come from natural sources. They provide organic farmers with practical methods to improve plant nutrition, soil fertility, and insect control without jeopardising their organic certification. Because biostimulants encourage resource efficiency, environmental care, and ecosystem resilience, they are consistent with the tenets of sustainable agriculture. They provide creative answers to the problems facing contemporary agriculture while reducing its environmental impact. Plant biostimulants are essential elements of contemporary farming methods because they offer a viable path towards increasing agricultural output, resilience, and sustainability (Mandal et al 2023).

Types and Classification of Plant Biostimulants

Natural Biostimulant Sources: Biostimulants, which come from a variety of natural sources, are essential to modern agriculture because they improve plant production, growth, and stress tolerance. These materials are becoming more and more popular since they are environmentally benign and work well with sustainable agricultural methods. Seaweed extracts and humic compounds are two notable examples of the wide range of natural biostimulant sources that provide special advantages to plants and the environment.

Seaweed Extracts: Since ancient times, seaweed extracts—which are derived from a variety of marine algae species—have been used in traditional agriculture due to their high nutrient content and ability to promote growth (Ali et al 2021). Nitrogen, phosphorus, potassium, and trace elements like iron, zinc, and manganese are among the many vital nutrients that these extracts powerfully supply. A wide range of bioactive substances are also present in them, such as vitamins, amino acids, polysaccharides, and phytohormones like gibberellins, cytokinins, and auxins. There are many benefits for plants when seaweed extracts are used as biostimulants. Growth-promoting hormones and nutrients expedite the germination of seeds, the formation of roots, and the general growth of plants (Battacharyya et al 2015).

Through enhancing their resilience and defence systems, seaweed extracts assist plants in overcoming a variety of environmental challenges, such as salinity, drought, and temperature variations (Raja and Vidya 2023). Seaweed extracts include bioactive chemicals that help plants absorb and assimilate nutrients, improving nutrient use efficiency and lowering reliance on chemical fertilisers. Frequent application of seaweed extracts enhances the flavour, colour, and nutritional value of crops by encouraging the synthesis of secondary metabolites including phenolics and antioxidants (Ali et al 2019). Because seaweed extracts are safe for the environment and biodegradable, they support ecologically friendly farming methods and reduce environmental impact (Kapur et al 2018).

Humic Substances: Organic chemicals known as humic substances are produced when plant and animal debris in soil, peat, and other organic materials breaks down. They include humin, fulvic acid, and humic acid, each of which has unique advantages for plant development and soil health. The complex molecular structure and high carbon content of humic compounds give them diverse physiological and biochemical effects on plants. Humic materials strengthen the structure, porosity, and water-retention ability of the soil, which promotes root development and aeration—two essential processes for the best possible plant development. Humic compounds prevent nutrient loss and immobilisation by chelating micronutrients and promoting their uptake by plants, guaranteeing a consistent supply of vital components for robust growth (Canellas et al 2015).

Humic materials enhance soil fertility, organic matter breakdown, and nutrient cycling in the rhizosphere by boosting microbial diversity and activity. Through the modification of stress-responsive pathways and antioxidant defences, the application of humic compounds increases plant resilience to abiotic stresses, such as salinity, drought, and heavy metal toxicity. Humic materials are a great complement to sustainable farming methods since they improve fruit quality, increase crop yields, and lengthen the shelf life of harvested produce when used on a regular basis. Humic materials and seaweed extracts are important natural sources of biostimulants that have several advantages for plant development, soil health, and environmental sustainability. By incorporating these bio-based solutions into farming operations, one may enhance yield optimisation and resource efficiency while also strengthening agroecosystems' resilience and long-term sustainability in the face of global issues like food security and climate change (Mannino 2023).

Microbial Biostimulants: Rhizobacteria and mycorrhizal fungi are examples of microbial biostimulants, a potent class of biological inputs that promote plant growth, enhance nutrient uptake, and increase total crop productivity (Fadiji et al 2022). These microbes live in symbiotic partnerships with plants, impacting a range of physiological and biochemical functions both inside and outside the rhizosphere (Castiglione et al 2021). The function of microbial biostimulants in agriculture and their possible advantages for sustainable crop production are described here:

Plant Growth-Promoting Rhizobacteria (PGPR): Beneficial bacteria known as PGPR inhabit the rhizosphere, the area of soil that surrounds plant roots (Ahkami et al 2017). By processes like nitrogen fixation, phosphate solubilization, phytohormone synthesis, and plant pathogen suppression, they promote plant development (Chandra et al 2021). There is less need for artificial nitrogen fertilisers since some rhizobacteria, like species of Rhizobium and Azospirillum, can fix atmospheric nitrogen into a form that plants can use. Pseudomonas and Bacillus are two examples of rhizobacteria that can solubilize insoluble forms of phosphorus in the soil, increasing its availability for plant absorption (Elias et al 2016; Pan and Cai 2023). Some PGPR cause plants to develop systemic resistance or manufacture antimicrobial chemicals, shielding them against diseases and infections that are carried by the soil (Hijri 2023).

Arbuscular Mycorrhizal Fungi (AMF): The majority of plant species' roots create symbiotic relationships with AMF, which facilitates nutrient exchange between the fungus and the host plant. In return for the plant's carbon, they enhance the uptake of nutrients by the plant, particularly phosphorus and micronutrients (Chandra et al 2022b). Plants with mycorrhizal fungus have greater access to soil nutrients and water by extending their effective root zone. Plant growth, vigour, and stress tolerance are all boosted by this increased nutrient intake. In order to increase soil fertility and decrease erosion, mycorrhizal hyphae build a network in the soil that enhances soil structure, aggregation, and water retention (Rouphael et al 2015).

Benefits and Challenges of Microbial Biostimulants

Microbial biostimulants increase the availability and uptake of nutrients by plants, which results in less nutrient losses to the environment and more effective fertiliser use. Microbial biostimulants give plants the ability to withstand biotic and abiotic challenges such salt, drought, and disease pressure by promoting plant growth, improving nutrient uptake, and creating systemic resistance (Kaushal et al 2023). By lowering dependency on synthetic inputs, minimising nutrient runoff and leaching, and promoting soil health and biodiversity, the use of microbial biostimulants supports sustainable agriculture. In addition to being compatible with organic farming methods, microbial biostimulants can assist organic growers in increasing crop yields, managing nutrients, and improving soil fertility without the need for chemical pesticides (Ruzzi and Aroca 2015). Microbial biostimulants need to be adapted to the local soil and climate in order to function at their best. They may also show interactions specific to individual species. For microbial biostimulants to work as effectively as possible, timing of the microbial inoculation and compatibility with other agricultural inputs (such as pesticides and fertilisers) are crucial factors. To choose the right products, apply application techniques, and comprehend the advantages of microbial biostimulants, farmers might need expert assistance and instruction. Microbial biostimulants have the potential to significantly improve agricultural output in a sustainable manner by increasing nutrient availability, fostering plant health, and having a smaller negative environmental impact. To fully profit from microbial biostimulants in agriculture and capitalise on their ability to create robust and fruitful agroecosystems, more research, education, and adoption initiatives are needed (Joshi et al 2021).

Synthetic Biostimulant Compounds: Amino acids and polyamines are examples of synthetic biostimulant compounds, a family of chemicals intended to improve plant development, growth, and stress tolerance (Popko et al 2018). These substances are chemically synthesised, but their similarity to plant biochemical processes and natural signalling molecules makes them effective biostimulants. the function and possible advantages of synthetic biostimulant substances in agriculture are describes as below:

Amino Acids: As the building blocks of proteins, amino acids are crucial for the growth, development, and metabolism of plants. Biostimulants based on synthetic amino acids are designed to give plants easy-to-access supplies of energy, carbon, and nitrogen to support a range of physiological functions(García-García et al 2020). By providing plants with the substrates they need for protein synthesis, amino acid biostimulants enable the synthesis of structural proteins, hormones, and enzymes that are vital for healthy growth and development. Nutrients in the soil can be chelated and solubilized by amino acids, increasing their accessibility for plant uptake. They also enhance the plant's ability to translocate nutrients, which increases the efficiency with which nutrients are used. As osmolytes and antioxidants, amino acids support plants' ability to withstand environmental stressors such salt, drought, and severe temperatures. Additionally, they increase plant resilience by promoting the synthesis of metabolites and proteins that react to stress. Small chemical compounds called polyamines regulate how plants grow, develop, and react to stress. Biostimulants based on synthetic polyamines are engineered to regulate many physiological processes in plants, resulting in enhanced resilience to stress. In plants, polyamines function as signalling molecules that control cell division, differentiation, and gene expression. These signalling pathways can be modulated by synthetic polyamine biostimulants to encourage development and growth. Through their promotion of root elongation, lateral root creation, and root hair production, polyamines have an impact on root growth and architecture. In situations where there are nutrient shortages or stress, they improve the effectiveness of the root system and nutrient uptake. As cell membrane stabilisers and scavengers of reactive oxygen species (ROS), polyamines are essential to plant stress responses. Plant resistance to oxidative stress, heat, salt, and drought can be increased by the use of synthetic polyamine biostimulants (Sun et al 2024).

Benefits and Challenges of Synthetic Biostimulant Compounds

With the ability to precisely manage the concentration and content of active components, synthetic biostimulant chemicals guarantee constant performance and efficacy across a variety of crop kinds and environmental situations. Plants that are exposed to synthetic biostimulants can respond physiologically quickly, which improves their growth, vigour, and ability to withstand stress. Customised application techniques and optimal performance are possible using synthetic biostimulant formulations that are tuned to target particular plant growth phases, nutritional requirements, and stress conditions. Synthetic biostimulant chemicals are useful tools for integrated crop management methods since they are typically compatible with other agricultural inputs including fertilisers, herbicides, and biologics. To maintain sustainability and reduce hazards, the environmental fate and impact of synthetic biostimulant substances, including their persistence, bioaccumulation, and potential ecological consequences, need to be carefully evaluated. Before being commercialised and used in agriculture, synthetic biostimulant substances may need to be registered with the regulatory body and approved. This means that safety, efficacy, and labelling regulations must be followed. Thorough cost-benefit studies should be used to assess the cost-effectiveness of synthetic biostimulant compounds in relation to natural alternatives and conventional inputs in order to support their uptake and investment. In agriculture, synthetic biostimulant chemicals provide useful instruments for improving plant resistance, production, and performance. Growers may maximise crop yields, enhance resource usage efficiency, and lessen the effects of environmental pressures by utilising the advantages of amino acids, polyamines, and other synthetic chemicals. This helps to create agricultural systems that are both profitable and sustainable. To properly utilise synthetic biostimulant substances and incorporate them into contemporary farming methods, more study, creativity, and cooperation are needed.

Mechanisms of Action of Plant Biostimulants

Numerous processes that affect plant physiology, metabolism, and interactions with the environment are how plant biostimulants work. Some frequent modes of action include the following, though they can vary based on the type of biostimulant and the particular plant species involved.

1. Hormonal Regulation: Biostimulants, such as auxins, cytokinins, gibberellins, and abscisic acid, are synthetic or natural substances that imitate or interact with plant hormones. These hormones control a number of processes related to plant growth and development, such as stress reactions, cell division, elongation, and differentiation.

2. Nutrient Uptake and Assimilation: Biostimulants improve the availability, absorption, and assimilation of vital nutrients by plants. Aside from improving root absorption and facilitating nutrient transport inside the plant, they may contain organic acids, amino acids, peptides, or chelating agents that solubilize nutrients in the soil.

3. Root Development and Architecture: By encouraging root elongation, lateral root proliferation, and root hair development, biostimulants support root growth and architecture. This promotes soil exploration, increases the surface area available for absorbing nutrients and water, and strengthens the anchoring and stability of plants.

4. Stress Tolerance and Resilience: Plants that are subjected to environmental stressors including salt, drought, high temperatures, insect or pathogen attacks, can be better adapted by using biostimulants. Inducing the synthesis of stress-responsive proteins, antioxidants, osmolytes, or phytohormones can improve plant resilience and reduce damage caused by stress.

5. Metabolic Activation and Enzyme Stimulation: The synthesis of enzymes necessary for important biochemical processes including photosynthesis, respiration, and nutrition metabolism is stimulated by biostimulants, which also ignite plant metabolism. This improves the synthesis of vital chemicals required for growth and development, as well as the generation of energy and carbon absorption.

6. Microbial Interactions: Certain biostimulants encourage advantageous connections, like mycorrhizal relationships, rhizobacteria that fix nitrogen, or rhizobacteria that promote plant development (PGPR). Through processes including nutrient mobilisation, hormone synthesis, and biocontrol, these microbial symbionts support plant health, disease suppression, and nutrient cycling.

7. Cell Membrane Stabilisation: Compounds included in biostimulants aid in the stabilisation of cell membranes and the preservation of membrane integrity under stressful circumstances. As a result, there is less cellular content loss, oxidative damage is reduced, and the plant is more resilient to environmental tremors.

8. Secondary Metabolite Synthesis: Secondary metabolites that are important for plant defence, signalling, and cue adaptation—such as phenolics, flavonoids, terpenoids, and antioxidants—are synthesised in response to biostimulants. These substances improve the flavour, colour, durability, and nutritional value of plants.

9. Priming and Systemic Acquired Resistance (SAR):

Plants may experience a priming effect from biostimulants, in which prior exposure to biotic or abiotic stimuli improves the plants' capacity to establish robust defences in the event of a subsequent stress exposure. Systemic acquired resistance (SAR) mechanisms may be triggered by this priming, increasing resistance to pests and infections.

Effects of Plant Biostimulants on Crop Performance

Plant biostimulants enhance many aspects of crop performance, such as development, growth, and stress tolerance. These impacts promote improvements in crop yields, quality, and resilience in agricultural systems. Biostimulants facilitate early root growth, seed germination, and seedling vigour, which can expedite crop establishment, uniform stand establishment, and speedier emergence. It is well known that biostimulants, such as seaweed extracts and plant-growth promoting rhizobacteria (PGPR), promote seed germination. It is well recognised that phytohormones, which are generally found in large quantities in seaweed extracts are crucial for seed germination. The application of *Sargassum liebmannii* extracts as plant biostimulants significantly improved the germination percentage of *Trigonella foenum-graecum* seeds. Furthermore, *Ascophylum nodosum* extract significantly raised the germination speed index and germination percentage of *Phaseolus vulgaris*. Similarly, PGPR uses secondary metabolism to produce phytohormones. While *Bacillus subtilis* enhanced the germination percentage of *Sorghum bicolour.* When wheat seeds were treated with spermidine and spermine under drought stress conditions, the quantities of zeatin, zeatin riboside, ABA, IAA and GA increased considerably. Chitosan nanoparticles sped up the production and distribution of IAA in the roots and shoots of wheat seedlings and lowered IAA oxidase activity, which is important in IAA breakdown. Cucumber, tomato, scotch marigold, and gladiolus seeds treated with smoke-water, a concoction of white willow and lemon eucalyptus, decreased the amount of abscisic acid under light conditions and improved germination. Biostimulants raise the biomass of shoots as well as roots, also expand the area of leaves by promoting cell proliferation, elongation, and differentiation. Biostimulants increase the efficiency with which nutrients are absorbed and digested by plants, hence reducing nutritional deficiencies. Microbial inoculants have occasionally been linked to enhanced plant growth and yield through better nutritional status and greater nutrient uptake. For example, after inoculating *Zea mays* with *Bacillus* and AMF, improved plant development and increased nutritional assimilation of plant total N, P, and K. Application of PGPR greatly enhanced N, P, and K uptake as well as root and shoot dry weight in *Triticum aestivum* and *Gossypium hirsutum*.

PGPR and AMF increases productivity and enhances the nutritional content in tomato. Biostimulants stimulate photosynthetic activity, chlorophyll synthesis, and carbon fixation, which increases biomass output, carbohydrate buildup, and plant yield. The role of AMF in symbiosis enhances crop quality. *Rhizoglomus irregularis* promotes *Stevia* growth. Among the bacteria that cause plant growth are *Arthrobacter, Enterobacter, Acinetobacter, Pseudomonas, Ochrobactrum, Bacillus,* and *Rhodococcus*. The majority of beneficial bacteria are Rhizobium spp. and plant growth-promoting rhizobacteria. The rhizobacteria *Streptomyces*, *Pseudomonas*, and *Bacillus* comprise the group that stimulates plant growth.

The reports in the literature indicate that *Streptomyces* spp. protect tomato plants against the putrefactive bacteria *Pectobacterium carotovorum* subsp. *brasiliensis*. Moreover, the volatiles produced by six isolates of *Streptomyces* spp. stimulate the growth of tomato roots. Biostimulants can induce flowering and improve fruit set. Endophytic bacteria from soybean root nodules were able to protect soybean roots from *Phytophthora sojae* by regulating hormone levels, and also promoting flower growth, and enhance pollen viability and pollination efficiency. Crop resilience to biotic stressors, such as pests and diseases, and abiotic stressors, such as heat, salt, drought, and cold, is enhanced by biostimulants. In addition to modifying plant-microbe interactions, they accomplish this *via* producing phytohormones, osmoprotectants, antioxidants, and stress-responsive genes.

Through promoting plant growth, stress tolerance, and nutrient uptake, biostimulants boost marketable production, improve fruit quality, lengthen shelf life, and raise crop yields. By reducing oxidative stress, enhancing cell wall integrity, and postponing senescence, biostimulants can enhance the post-harvest characteristics of crops. These characteristics include resistance to physiological diseases, shelf life, and storability. Biostimulants support sustainable agriculture practices by reducing reliance on synthetic inputs, improving resource efficiency, enhancing soil fertility and health, and minimising environmental impact.

Biostimulants can improve the advantages of fertilisers, insecticides, and other agricultural inputs by enhancing their efficacy, reducing their application rates, and limiting their negative effects on the environment and public health. Plant biostimulants are helpful in agricultural systems to maximise crop resilience, production, and sustainability. Their intricate effects on plant physiology, metabolism, and stress responses not only promote environmental stewardship and food security but also assist growers in raising yield, profitability, and quality.

Interactions with Soil Microbiota and Rhizosphere Dynamics

Plant biostimulants are important because they shape the dynamics of the rhizosphere and soil microbiota, which in turn affects how microbes, plants, and soil conditions interact. Optimising the effectiveness of biostimulants and advancing sustainable agriculture methods require an understanding of these interactions. Through both direct and indirect means, biostimulants can affect the make-up and activity of soil microbial populations, which include bacteria, fungus, and archaea. Certain biostimulants are made of organic substances that provide soil microorganisms with carbon and energy, promoting microbial development and metabolic activity. While inhibiting dangerous pathogens, some biostimulant compounds, such as humic substances and seaweed extracts, can stimulate the growth of beneficial microbial taxa, such as plant growth-promoting rhizobacteria (PGPR) and mycorrhizal fungi (Chandra et al 2021, 2022b; Rai et al 2021). The area of soil where plant roots are most active is called the rhizosphere, and it is a hotspot for nutrient cycling and microbial activity. Through the promotion of root exudation, microbial colonisation, and nutrient mobilisation, biostimulants can improve rhizosphere activities. Root exudates, which include sugars, organic acids, and phenolic compounds, are substrates for soil microorganisms (Chandra et al 2022a) and are influenced by the application of biostimulants, which alters the composition and activities of the microbial population. Biostimulants can increase soil microbes' synthesis of extracellular enzymes, which will speed up the rhizosphere's ability to break down organic materials and mineralize nutrients. Plants can acquire nutrients and become more resilient to stress when beneficial interactions between soil microorganisms and plants, like mycorrhizal associations and nitrogen-fixing symbioses, are facilitated by biostimulants. Initiated by specific biostimulants, mycorrhizal fungi develop mutualistic associations with plant roots, augmenting their ability to absorb nutrients and enhancing plant functionality, particularly in situations where nutrients are scarce or under stress. Biostimulants-stimulated plant growth-promoting rhizobacteria (PGPR) can improve plant health and growth by producing growth-promoting hormones, fixing nitrogen, and solubilizing phosphate. Biostimulants support microbial diversity, activity, and functional redundancy in the rhizosphere, which benefits soil health and nutrient cycling. Improved nutrient cycling, organic matter breakdown, and soil aggregation are the outcomes of increased microbial activity induced by biostimulants, which improves soil fertility, structure, and resilience. By promoting nutrient uptake and utilisation by plants, decreasing the need for synthetic fertilisers, and minimising nutrient losses to the environment, biostimulants can help ameliorate nutritional imbalances and inadequacies. A priming effect, wherein the production of root exudates and microbial activity speeds up the turnover of soil organic matter and the cycling of nutrients, might result from biostimulant-induced alterations in rhizosphere dynamics. In agroecosystems, this priming effect can shape soil health and production by increasing plant nutrient availability, encouraging soil carbon sequestration, and influencing soil microbial community dynamics over time. In agricultural environments, plant biostimulants have a significant impact on the rhizosphere dynamics and soil microbiota, which in turn affects nutrient cycle, plant-microbe interactions, and soil health. Biostimulants present a viable way to boost crop output, increase soil fertility, and support sustainable agriculture practices by utilising these interactions. To fully comprehend the mechanisms behind interactions between biostimulant, soil, and microbes and to maximise their application for robust and productive agroecosystems, more study and innovation are required.

Challenges and Limitations of Plant Biostimulants

Plant biostimulants provide potential advantages for sustainable agriculture, however there are obstacles and restrictions associated with their use. Comprehending these limitations is vital for the successful incorporation of biostimulants into agricultural methodologies. The lack of precise regulatory frameworks controlling the registration, labelling, and marketing of biostimulant drugs is a major obstacle. There is considerable regional variation in the categorization of biostimulants, which causes ambiguity and irregularities in product standards and laws. There are significant gaps in our knowledge of biostimulant mechanisms of action, efficacy in various environmental contexts, and long-term consequences on soil health and ecosystem functioning, despite increased interest and funding in this field of study.

To better understand the principles underlying biostimulant activity and maximise their application in a variety of agricultural systems, more thorough scientific research is required. A number of variables, including crop species, soil composition, climate, and application techniques, can affect how successful biostimulant compounds are. Selecting the appropriate biostimulant products and application techniques that produce consistent and predictable outcomes under a range of growing circumstances might present issues for farmers. The higher cost of biostimulant products compared to traditional fertilisers and agrochemicals may discourage farmers, particularly those with tight budgets, from implementing them widely. To determine whether using biostimulants is economically viable and to support purchasing these items, cost-benefit studies are required. Getting a steady and dependable supply of high-quality biostimulant products can be difficult because of things like distribution networks, production procedures, and raw material procurement. Farmers' trust in biostimulants as a dependable input may be impacted by shortages, problems with quality control, and variations in product formulas. Biostimulants may need to be integrated into current agricultural practices and crop management systems, which may involve modifications to timing, application techniques, and compatibility with other inputs like pesticides and fertilisers (Bartucca et al 2022). In order to successfully integrate biostimulants into their agricultural practices, farmers might require direction and assistance. About the advantages and possible uses of biostimulants, farmers, agronomists, and legislators may not have a thorough grasp of the subject. Targeted education and communication initiatives are necessary to dispel misconceptions and scepticism and convey the scientific data proving the sustainability and efficacy of biostimulants. Although biostimulants are thought to be more environmentally benign than synthetic inputs, there are still worries about possible negative effects on the environment, including nutrient runoff, soil contamination, and effects on creatures that are not the intended targets. Environmental monitoring and sustainable usage methods are required to reduce any negative consequences that may arise from applying biostimulants (Bhupenchandra et al 2022). The development of evidence-based solutions, the promotion of regulatory clarity, investments in research and innovation, and the provision of support mechanisms are all necessary to address these obstacles and limitations and enable the adoption and sustainable use of plant biostimulants in agriculture. These efforts must involve researchers, policymakers, industry stakeholders, and farmers.

Plant Biostimulant Integration with Sustainable Agriculture

The incorporation of plant biostimulants into sustainable agriculture signifies a paradigm shift in favour of more ecologically friendly and holistic farming methods. Farmers may promote long-term sustainability and resilience in agricultural systems while increasing crop output, improving soil health, and mitigating environmental effects by utilising the special qualities of biostimulants. By encouraging microbial diversity, boosting nutrient cycling, and strengthening soil structure and fertility, biostimulants are essential for improving soil health. Biostimulants help to sustainably produce crops by fostering the growth of robust, biodiverse soil ecosystems through the addition of organic matter and helpful microbes to the soil. One of the main advantages of biostimulants is their capacity to lessen dependency on agrochemicals and synthetic fertilisers. Biostimulants help farmers obtain greater yields with less chemical input, minimising pollution, cutting greenhouse gas emissions, and preserving the health of ecosystems by boosting nutrient intake, improving stress tolerance, and encouraging plant development. The resilience of agricultural systems becomes increasingly important as climate variability grows and extreme weather events become more common. By providing plants with natural defences against environmental stresses like heat, salinity, and drought, biostimulants increase agricultural resilience and make it easier for farmers to adjust to shifting climatic circumstances. By increasing soil water retention, decreasing nutrient runoff and leaching, and optimising nutrient usage efficiency, the application of biostimulants aids sustainable resource management techniques. Biostimulants help reduce environmental impact and increase resource efficiency by increasing plant nutrient availability and minimising environmental loss. By encouraging the development of a greater variety of crop varieties and bolstering the resilience of traditional and indigenous farming systems, biostimulants can also help to promote agrobiodiversity. Farmers may maintain genetic variety and traditional knowledge while simultaneously strengthening their resistance to pests, diseases, and environmental challenges through cropping system diversification and encouraging the use of locally adapted plant biostimulants. Plant biostimulants must be integrated into sustainable agriculture through cooperation, capacity building, and knowledge exchange amongst a variety of stakeholders, including farmers, researchers, legislators, and agricultural extension agents. The adoption and application of biostimulant technologies and practices can be hasten by promoting knowledge sharing, training initiatives, and research collaborations, especially in smallholder farming communities where resources and experience may be scarce.

Strategies for Promoting Biostimulant Adoption among Farmers

A multimodal strategy that addresses adoption barriers, offers information and training, illustrates the advantages of biostimulants, and cultivates alliances and supporting policies is needed to encourage farmers to adopt biostimulants (Mannino 2023). To inform farmers about the uses and advantages of biostimulants, conduct workshops, field trips, and training sessions. Create instructional resources to spread knowledge about biostimulant agents, modes of action, and best practices, such as fact sheets, manuals, and web sites. Work together with universities, research centres, and agricultural extension agencies to integrate biostimulant knowledge into current farmer training initiatives and extension programmes. To demonstrate the effectiveness of biostimulants in enhancing crop yield, quality, and resilience in real-world circumstances, conduct on-farm demonstration trials. Involve farmers as co-investors in demonstration trials so they can witness directly the advantages of biostimulants and develop trust in their efficacy. Encourage farmers to take part in research programmes that allow them to actively assess various biostimulant products and techniques of application on their own farms through participatory research. Provide individualised advice on the usage of biostimulants based on evaluations of the soil's health, crop needs, and regional agroecological circumstances. Provide farmers with online resources or consulting services to assist them in choosing the right biostimulant products and rates of application for their particular farming techniques and objectives. Provide farmers with financial subsidies or incentives to help defray the upfront expenses of implementing biostimulants, especially smallholder farmers or those switching to organic or sustainable farming methods. Develop financial initiatives or grant possibilities that are especially geared towards the adoption and study of biostimulants in collaboration with governmental bodies, agricultural associations, and business partners. Encourage the adoption of laws that acknowledge and reward the use of biostimulants in agriculture on a local, national, and worldwide scale. Work together with legislators, regulatory bodies, and industry players to create standards and rules for biostimulant labelling, marketing, and registration that are grounded on research. Encourage farmers to participate in online forums, discussion groups, and farmer networks so they may exchange knowledge, learn from one other's triumphs and failures with biostimulant adoption, and share their experiences. Organise farm visits, study tours, and information exchange activities centred around the use of biostimulants and sustainable agriculture techniques to foster peer-to-peer learning and knowledge sharing among farmers. Encourage the advancement of biostimulant science through research and development projects that examine the mechanisms of action, cropping system suitability, and long-term effects on soil health and ecosystem resilience. Encourage cooperation between scientists, business associates, and farmers to jointly develop and assess novel biostimulant compositions, delivery systems, and application technologies catered to farmers' requirements and preferences. Encouragement of farmers can be done to widely use biostimulants by putting these methods into practice in a coordinated and cooperative manner. This will result in more robust and sustainable agricultural systems that will benefit farmers and the environment (Bahuguna et al 2022).

Conclusions

Plant biostimulants have a wide range of applications in agriculture and can be very helpful in addressing the changing issues that affect sustainability and global food production. Using biostimulants offers a chance to transform agricultural methods and increase crop output while reducing environmental impact as we navigate a fast changing climate, depleting natural resources, and mounting need to feed a growing population. The capacity of plant biostimulants to encourage plant growth and resilience via natural processes is among its most alluring features. In contrast to synthetic fertilisers and agrochemicals, which frequently have negative long-term effects on the environment, biostimulants function in unison with the natural world by utilising plants' innate capacity to flourish under a variety of circumstances.

Through the utilisation of bioactive chemicals found in natural sources such humic substances, seaweed extracts, and microbial inoculants, biostimulants are able to stimulate physiological processes in plants, resulting in better nutrient uptake, increased stress tolerance, and higher yields. Furthermore, the application of plant biostimulants is consistent with sustainable agriculture's tenets, which prioritise soil health, biodiversity, and ecosystem resilience. Biostimulants help prevent environmental deterioration and preserve natural resources by increasing soil fertility, fostering microbial diversity, and lowering dependency on synthetic inputs. By lowering input costs and increasing soil production over the long term, this holistic farming method not only helps farmers but also protects the wellbeing of nearby people and ecosystems.

Plant biostimulants have the potential to solve urgent global concerns like food security, climate change adaption, and agricultural resilience in addition to their agronomic advantages. The demand for resilient crop types and sustainable agricultural methods rises in tandem with climate variability and the frequency of extreme weather events. In order to assist plants, endure environmental challenges including heat, salinity, drought, and pest pressure, biostimulants provide a toolbox of natural solutions. This increases agricultural resilience and ensures food security in the face of hardship. Moreover, the implementation of plant biostimulants has promise for promoting creativity and cooperation among several fields, such as environmental science, biotechnology, and agriculture. Plant biostimulants present a viable route to more robust, efficient, and ecologically friendly farming systems when included into sustainable agriculture. Through the utilisation of natural resources and creative thinking, sustainable food system can be created that feeds more people, safeguards the environment, and fosters wealth for all.

References

Ahkami AH, Allen White R, Handakumbura PP, Jansson C (2017) Rhizosphere engineering: Enhancing sustainable plant ecosystem productivity. Rhizosphere 3:233–243. https://doi.org/https://doi.org/10.1016/j.rhisph.2017.04.012

Ali O, Ramsubhag A, Jayaraman J (2021) Biostimulant Properties of Seaweed Extracts in Plants: Implications towards Sustainable Crop Production. Plants (Basel, Switzerland) 10: https://doi.org/10.3390/plants10030531

Ali O, Ramsubhag A, Jayaraman J (2019) Biostimulatory activities of Ascophyllum nodosum extract in tomato and sweet pepper crops in a tropical environment. PLoS One 14:e0216710. https://doi.org/10.1371/journal.pone.0216710

Bahuguna A, Sharma S, Rai A, et al (2022) Advance technology for biostimulants in agriculture. In: Singh HB, Vaishnav ABT-N and FD in MB and B (eds). Elsevier, pp 393–412

Bartucca ML, Cerri M, Del Buono D, Forni C (2022) Use of Biostimulants as a New Approach for the Improvement of Phytoremediation Performance-A Review. Plants (Basel, Switzerland) 11: https://doi.org/10.3390/plants11151946

Battacharyya D, Babgohari MZ, Rathor P, Prithiviraj B (2015) Seaweed extracts as biostimulants in horticulture. Sci Hortic (Amsterdam) 196:39–48. https://doi.org/https://doi.org/10.1016/j.scienta.2015.09.012

Bhupenchandra I, Chongtham SK, Devi EL, et al (2022) Role of biostimulants in mitigating the effects of climate change on crop performance. Front Plant Sci 13.

Canellas LP, Olivares FL, Aguiar NO, et al (2015) Humic and fulvic acids as biostimulants in horticulture. Sci Hortic (Amsterdam) 196:15–27. https://doi.org/https://doi.org/10.1016/j.scienta.2015.09.013

Castiglione AM, Mannino G, Contartese V, et al (2021) Microbial Biostimulants as Response to Modern Agriculture Needs: Composition, Role and Application of These Innovative Products. Plants (Basel,

Switzerland) 10 https://doi.org/10.3390/plants10081533
Chandra P, Rai AK, Sundha P, et al (2022a) Rhizospheric Soil–Plant-Microbial Interactions for Abiotic Stress Mitigation and Enhancing Crop Performance BT - Soil Health and Environmental Sustainability: Application of Geospatial Technology. In: Shit PK, Adhikary PP, Bhunia GS, Sengupta D (eds). Springer International Publishing, Cham, pp 593–614
Chandra P, Singh A, Prajapat K, et al (2022b) Native arbuscular mycorrhizal fungi improve growth, biomass yield, and phosphorus nutrition of sorghum in saline and sodic soils of the semi–arid region. Environ Exp Bot 201:104982. https://doi.org/https://doi.org/10.1016/j.envexpbot.2022.104982
Chandra P, Wunnava A, Verma P, et al (2021) Strategies to mitigate the adverse effect of drought stress on crop plants—influences of soil bacteria: A review. Pedosphere 31:496–509. https://doi.org/https://doi.org/10.1016/S1002-0160(20)60092-3
du Jardin P (2015) Plant biostimulants: Definition, concept, main categories and regulation. Sci Hortic (Amsterdam) 196:3–14. https://doi.org/https://doi.org/10.1016/j.scienta.2015.09.021
Elias F, Woyessa D, Muleta D (2016) Phosphate Solubilization Potential of Rhizosphere Fungi Isolated from Plants in Jimma Zone, Southwest Ethiopia. Int J Microbiol 2016:5472601. https://doi.org/10.1155/2016/5472601
Fadiji AE, Babalola OO, Santoyo G, Perazzolli M (2022) The Potential Role of Microbial Biostimulants in the Amelioration of Climate Change-Associated Abiotic Stresses on Crops. Front Microbiol 12:
García-García AL, García-Machado FJ, Borges AA, et al (2020) Pure Organic Active Compounds Against Abiotic Stress: A Biostimulant Overview. Front Plant Sci 11:
Giovannini L, Palla M, Agnolucci M, et al (2020) Arbuscular Mycorrhizal Fungi and associated microbiota as plant biostimulants: research strategies for the selection of the best performing inocula. Agronomy 10
Hijri M (2023) Microbial-Based Plant Biostimulants. Microorganisms 11
Joshi N, Parewa HP, Joshi S, et al (2021) Chapter 5 - Use of microbial biostimulants in organic farming. In: Meena VS, Meena SK, Rakshit A, et al (eds). Woodhead Publishing, pp 59–73
Kapur B, Sarıdaş MA, Çeliktopuz E, et al (2018) Health and taste related compounds in strawberries under various irrigation regimes and bio-stimulant application. Food Chem 263:67–73. https://doi.org/https://doi.org/10.1016/j.foodchem.2018.04.108

Kaushal P, Ali N, Saini S, et al (2023) Physiological and molecular insight of microbial biostimulants for sustainable agriculture. Front Plant Sci 14:

Mandal S, Anand U, López-Bucio J et al (2023) Biostimulants and environmental stress mitigation in crops: A novel and emerging approach for agricultural sustainability under climate change. Environ Res 233:116357. https://doi.org/https://doi.org/10.1016/j.envres.2023.116357

Mannino G (2023) A New Era of Sustainability: Plant Biostimulants. Int. J. Mol. Sci. 24

Pan L, Cai B (2023) Phosphate-Solubilizing Bacteria: Advances in Their Physiology, Molecular Mechanisms and Microbial Community Effects. Microorganisms 11:. https://doi.org/10.3390/microorganisms11122904

Popko M, Michalak I, Wilk R, et al (2018) Effect of the New Plant Growth Biostimulants Based on Amino Acids on Yield and Grain Quality of Winter Wheat. Molecules 23:. https://doi.org/10.3390/molecules23020470

Rai AK, Dinkar A, Basak N, et al (2021) Phosphorus nutrition of oats genotypes in acidic soils: Exploiting responsive plant-microbe partnership. Appl Soil Ecol 167:104094. https://doi.org/https://doi.org/10.1016/j.apsoil.2021.104094

Raja B, Vidya R (2023) Application of seaweed extracts to mitigate biotic and abiotic stresses in plants. Physiol Mol Biol plants an Int J Funct plant Biol 29:641–661. https://doi.org/10.1007/s12298-023-01313-9

Rouphael Y, Colla G (2020) Biostimulants in Agriculture. Front Plant Sci 11:. https://doi.org/10.3389/fpls.2020.00040

Rouphael Y, Franken P, Schneider C, et al (2015) Arbuscular mycorrhizal fungi act as biostimulants in horticultural crops. Sci Hortic (Amsterdam) 196:91–108. https://doi.org/https://doi.org/10.1016/j.scienta.2015.09.002

Ruzzi M, Aroca R (2015) Plant growth-promoting rhizobacteria act as biostimulants in horticulture. Sci Hortic (Amsterdam) 196:124–134. https://doi.org/https://doi.org/10.1016/j.scienta.2015.08.042

Sun W, Shahrajabian MH, Kuang Y, Wang N (2024) Amino Acids Biostimulants and Protein Hydrolysates in Agricultural Sciences. Plants 13

Zhang X, Yin J, Ma Y, et al (2024) Unlocking the potential of biostimulants derived from organic waste and by-product sources: Improving plant growth and tolerance to abiotic stresses in agriculture. Environ Technol Innov 34:103571. https://doi.org/https://doi.org/10.1016/j.eti.2024.103571

CHAPTER TWO

PLANT-AMF INTERACTIONS: LINKING PLANT NUTRITIONAL AND BIOCHEMICAL STATUS FOR SUSTAINABLE AGRICULTURE

PRASHANTKUMAR S HANJAGI[1], SUSHMA M. AWAJI[1], GUND SURAJ NIVARUTTI[1,2], K.S.VIDHYA BHARATHI[1,2] AND R G VYSHNAVI[1]

[1]ICAR-NATIONAL INSTITUTE OF ABIOTIC STRESS MANAGEMENT, BARAMATI

[2]MAHATMA PHULE KRISHI VIDYAPEETH, RAHURI

Abstract

The use of chemical fertilizers significantly enhances agricultural productivity, but it also poses considerable risk to both human well-being and the ecosystem. Arbuscular Mycorrhizal Fungi (AMF), have the ability to replace chemical fertilizers in maintaining agricultural productivity as they establish a mutualistic partnership with more than 80% of plants on earth. The hyphal network they possess effectively dissolve soil nutrients (phosphorus, zinc, copper etc.) which in turn improves plant absorption and decrease the need for synthetic fertilizers. Plant-fungal interactions can potentially increase the availability of nutrients by changing the structure and function of plant roots. These interactions can also assist in improving the micronutrient levels in plants through different processes, including acidification, solubilization, chelation, oxidation/reduction, and the release of substances that can either stimulate or hinder plant growth. There is extensive evidence that a lack of micronutrients in the soil leads to decreased crop production and a decline in the nutritional value of the harvest. The symbiotic relationship between AMF and plants also contributes to improve the overall health of nutrient-depleted soil by enhancing its physical, chemical, and biological characteristics, ultimately increasing the plants' ability to withstand stress and protects them from the detrimental effects caused by stress. Additionally, this association can also help to decrease the levels of phytates in food grains and enhance the activation of metal transporters. Embracing AMF's potential signifies a shift towards a future where healthy soils nourish thriving crops, ensuring food security for generations to come. This compilation provides an overview of the published literature and identifies future research requirements for incorporating fungal alternatives in integrated agricultural management strategies.

Keywords: Arbuscular Mycorrhizal Fungi, agricultural productivity, ecosystem, symbiotic relationship, food security, biofertilization

Introduction

With Agriculture's ability to provide food and resources to a growing population is crucial for human survival. However, it faces numerous threats, including climate change, biodiversity loss, soil degradation, water depletion, pollution, rising costs, and declining rural populations. Modern agricultural practices have contributed significantly to these issues (Beus and Dunlap 1990).

Sustainable agriculture is defined by the 1990 U.S. Farm Bill as an integrated system of plant and animal production practices that, over the long term, aim to: Satisfy human food and fiber needs, enhance environmental quality, utilize non-renewable and on-farm resources efficiently, sustain farm economic viability and improve the quality of life for farmers and society (Koohafkan et al., 2012). Sustainable farms must produce high-quality food, protect resources, and be environmentally safe and profitable, relying on natural processes and renewable resources. Sustainable agriculture should conserve resources, minimize waste, and promote resilience and self-regulation in agroecosystems.

Practically, sustainable agriculture avoids synthetic fertilizers, pesticides, growth regulators, and feed additives due to their environmental and health impacts. Instead, it uses crop rotations, residues, manures, legumes,