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The potential of biostimulants on soil microbial community: a review

Afeez Adesina Adedayo and Olubukola Oluranti Babalola*

Food Security and Safety Focus Area, Faculty of Natural and Agricultural Sciences, North-West University, Mmabatho, South Africa

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Vlad Stoian, University of Agricultural Sciences and Veterinary Medicine of Cluj-Napoca, Romania

*CORRESPONDENCE
Olubukola Oluranti Babalola
olubukola.babalola@nwu.ac.za

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To improve agricultural sustainability, an agriculturally productive system is required to maintain soil fertility and reduce the loss of soil biodiversity. One of the modern technologies employs microbial biostimulants that create abundant agricultural yield with high nutritional values, controlling disadvantages obtained from environmental changes. This review aimed to provide knowledge on the effects of biostimulants on microbial communities' potential to promote agricultural production. Plant biostimulants are novel materials applied in the farming sector nowadays to improve crop yield and commonly occur in plant seeds and as an alternative to chemical derivative application on crop plants. Microbial biostimulants function as biological inputs to increase crop production and reduce the decomposition of soil. In conclusion, the application of biostimulants necessitates the accomplishment of an absolute choice of beneficial microbes as well as the potential to combat problems that will be encountered later in the agricultural sector.

KEYWORDS

abiotic stress, environment, soil degradation, microbial biostimulant, PGPM, soil biodiversity, synergism

1 Introduction

According to the Food and Agriculture Organization (FAO), the soil's potential to improve plant development as a result of making available major plant nutrients and required physical, biological, and chemical features that accommodate plant growth is known as soil fertility (Xiang et al., 2022). Recently, reports claimed that the degradation of agricultural soil has caused effectual challenges in the global agricultural sector.

Up to half the percentage of the global soil for farming activities and 24% of the farmlands across the planet have been subjected to soil fertility loss, decrease in crop production, and biodiversity (Allam et al., 2022). This process results from different abiotic factors affecting the soil, including loss of organic matter, environmental pollution, salinity, water, and wind erosion (Koza et al., 2022).

Considering the high rate of development of the universe, the decrease in cultivable area, and the reduction of genetic crops, the provision of new agricultural technologies was needed. Furthermore, reduced environmental occurrence in the agricultural system, targeted at promoting plant resilience to unfavorable environmental conditions, is becoming essential in ensuring the need for food with advanced nutritional values (Wang D. et al., 2022).

An interesting part of agriculture is its sustainability, which is the Farm-to-Fork (F2F) method, as reported by the European Union (EU) in May 2020, whose intention is to neutralize climate change by 2050 (Cué Rio et al., 2022). F2F has reported how it produces environmentally friendly healthy food by improving the change into a continuous and productive process acquired by the application and usage of chemical derivatives (pesticides) and antimicrobials, and over-fertilization is decreased (Yadav et al., 2023). Furthermore, in the organic farming system, F2F assists in the improvement of farmland to maintain the richness of the agricultural soil and inhibit biodiversity loss.

The result of the study strongly concentrated on applying agroecological knowledge to reduce possible chemical derivative applications on agricultural land and handle ecological relatedness and agro-biodiversity according to Charatsari et al. (2022). Agricultural ecology (agroecology) is supported by the improvement of biodiversity, biological process fortification, and the recycling of the biogeochemical cycle (Maity et al., 2022). With the knowledge of the agroecological system, the applications of biostimulant products can carry out specific roles including plant growth promotion and inducing resistance against disease invasion on plants directly and also maintaining agricultural production through the choice and induction of advantageous soil microbes (Feldmann et al., 2022).

Nowadays, plant growth promotion and crop production have been enhanced by plant biostimulants. Biostimulants are also categorized as biofertilizers, metabolic enhancers, and plant probiotics (Hamid et al., 2021). According to the US definition, biostimulants was defined as either organic or inorganic substances made up of beneficial microorganism that, when introduced on farmlands where crop plants were grown, promote nutrient consumption and nutrient effectiveness, tolerate abiotic stress, and improve crop quality (Benito et al., 2022). In comparison to the US definition, the EU delineated them as a unique substance in fertilizer product regulation (Kisvarga et al., 2022). Biostimulants have been applied in large-scale agriculture for several years, but nowadays, their production has reduced drastically, which makes them unavailable to farmers. Mostly used biostimulants were produced from the beneficial microbes (bacteria and fungi), chitosan, extract of seaweed, protein hydrolysates or amino acids, and organic acids (Kumari et al., 2022; Meddich, 2022), and other forms used were produced from biochar, concentrated enzymes, and microbial extracts. Biostimulants can be modified based on their composition of products and are known except for concentrated enzymes. The insufficient knowledge of the production of biological materials comprises multiple constituents, and it was speculated that the good form of the materials reveals the effect of synergies on the materials as conflicted to differentiate the materials separately (Wang Y. et al., 2022). Rasse et al. (2022) showed that the synergy among components within a product made it hard to determine the perfect methods accountable for stimulating response in crop plants, and this is the best way of identifying biostimulant activity based on the efficiency in their application. Therefore, this study concentrates on how biostimulants were employed for agricultural impingements in the production of crops and how to improve soil health for agricultural sustainability. We hypothesize that the biostimulant provides the absolute choice of beneficial microbes and also tackles challenges encountered by the invasion of phytopathogens on the crops and improves soil health in the agricultural sector.

2 Biostimulant application and usefulness

Biostimulants are used in specialty crops, which sometimes produce tremendous income per acre, unlike row crops (Jolayemi et al., 2022). Specialty crops are known to be sensitive to environmental stresses (Aloisi et al., 2022). As a result, the potential is based on the commitment to an applied biostimulant that is higher for crops that are sensitive to climate-induced stress. The climatic condition has been a significant factor attributing to the cultivation of crops and poses a threat to food security globally (Koza et al., 2022). The application of biostimulants for agricultural practice has revealed their capacity to fight various stresses imposed by climate change like salinity, drought, extreme temperature, high rainfall, and pH of the agricultural soil (Mandal et al., 2023).

A typical example is obtained during planting that provides a chance to apply biostimulants to the crop planted on acres of farmland through seed treatment. After applying biostimulants, foliar application with chemical derivatives like herbicides, insecticides, and fungicides was applied on crop plants, and the chemical derivative invoked protection on the crops as revealed by Caicedo-Lopez et al. (2022). The study of Wozniak et al. (2020) on biostimulants reported the application of 380 plant biostimulant applications of 126 tests and revealed that 60% of the biostimulant usage was supplied as a foliar spray, 10% for seed treatment, and 30% in the form of soil. However, foliar applications are the most prevalent. When and how to apply and specific methods to employ biostimulant application depend on the materials used to produce the biostimulant and the technique of their application. Some problems experienced while producing the biostimulants are the potential to obtain compatible products, including chemical derivatives like fertilizers and pesticides. Despite many products in the market to produce biostimulants, there is less experience in research characterization required for the production of biostimulants (Fadiji et al., 2022a). Likewise, biostimulant reactions can be different after being applied on farmland for crop plant growth as a result of climate change (high temperature and precipitation) (Agbodjato et al., 2022). Applying biostimulants on farmlands requires adequate knowledge of the categories of the biostimulants to use.

2.1 Categories of biostimulant

2.1.1 Nitrogen-fixing bacteria

One of the major elements required for living microbes is nitrogen (N), a major element needed for the biosynthesis of proteins and nucleic acids. Atmospheric nitrogen (N_2) comprises 78% of air and is the most extensive storage of available N. Some microbes (diazotrophs) can convert N_2 into gaseous ammonia (NH_3) with the help of nitrogenase enzyme (Agbodjato et al., 2021). Nitrogenase enzyme has three types that are different in the cofactor of metal: vanadium–iron (V-Fe), iron–iron (Fe-Fe), or molybdenum–iron (Mo-Fe). The most common cofactor of nitrogenase is the Mo–Fe cofactor used by microorganisms, unlike another type of cofactor that reduces the fixation of nitrogen (Dong et al., 2022). The potential of nitrogenase enzyme is reduced by reaction with oxygen, which reveals how the bacteria perform the specific process to protect the enzyme under aerobic conditions. Bacteria do remove themselves from the oxygen environment through multiple mechanisms, with the prevalent methods for the production of a heterocyst or a nodule. The significant application of N-fixing bacteria in agriculture shows (Figure 1) the capacity of symbiotic relationship with the family of grasses (Poaceae) that has not been recognized to relate with biological nitrogen fixation (BNF) microbes for supplemental N (Scavo et al., 2022). One of the bacteria commonly used to produce BNF is *Azospirillum brasilense*. This bacterium has the ability to produce plant hormones and is classified as one of plant growth-promoting rhizobacteria (PGPRs). In most environments, these bacteria produce such hormones while associating with crop plants, but in an environment with high N content, N cannot be fixed (Das et al., 2022). New implements are employed to edit N-fixing microorganisms genetically to besiege the methods of modulating the N-fixation gene biological process (Figure 1). In the presence of N, BNF can be reduced, but modifying the microbe to disregard this reduction permits uninterrupted fixation of N, thereby promoting the source of N for sustainable agriculture (Yin et al., 2022). Studies have reported how endophytic symbiotes associate with crop plants intracellularly by living in the roots and/or shoots (Salhi et al., 2022; Velichko et al., 2022).

In an agricultural system, applying N-fixing microorganisms leads to an increment in the supply of N to the developing plants, which partly relieves the demand for applying N fertilizer. The important factor in improving the efficiency of the bacteria is to introduce them very close to the root of the developing plants via the in-furrow method or seed treatment (Bender et al., 2022). The relationship between bacteria and crop plants has been investigated for the Leguminosae crop plant family, including alfalfa, beans, clovers, and peas (Muresu et al., 2022). Inoculating these bacteria with soybean also revealed the prevalent function of N-fixing bacteria as biostimulants. A common example of the bacteria is *Bradyrhizobium japonicum* mostly employed as a result of its effectiveness and is the leading bacterium in the market (Krutyakov et al., 2022). Some studies have presented how *Bradyrhizobium* has been used in the USA and Argentina and showed how the production of soybeans was increased as a result of microbial inoculation (Liebrenz et al., 2022; Melissa et al., 2022; Fadel Sartori et al., 2023). Other microbes reportedly used are *Azospirillum* spp., which were introduced to crop plants through the co-inoculation method. The method does increase plant growth

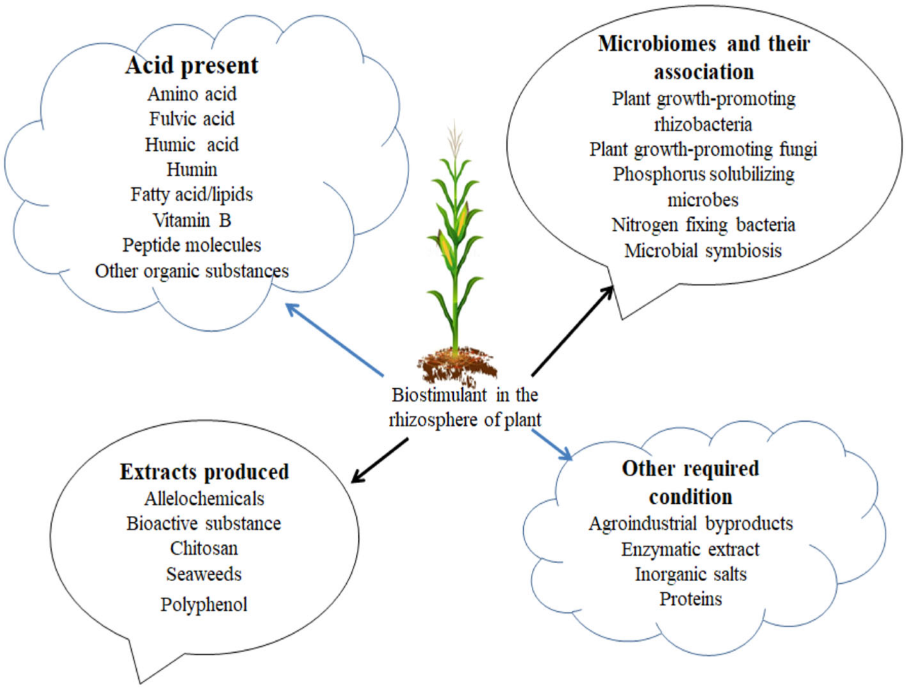

FIGURE 1
Categories of biostimulants.

(plant root and shoot), unlike the treatment with only *Bradyrhizobium*, even though combined inoculation did not improve the N content in the grain.

2.1.2 Seaweed extracts

Seaweed extracts are another biostimulant category produced from macroalgae species (seaweeds) as shown in Figure 2. These species differ in their composition and their usefulness as biostimulant effects. Macroalgae are replaceable materials that are utilized to manufacture biostimulants and closely supervised for continuous harvest to sustain the supply (Sujeeth et al., 2022). The manufactured products are produced vastly with materials used to produce them that are dependent on the species used, the state at which they were harvested, and the procedure of separation employed by the manufacturing companies. Alkaline hydrolysis is the prominent extraction process used unlike other processes, including acid hydrolysis, enzyme method, microwave method, super-critical fluid, pressurized liquid separations, ultrasound-assisted methods, and water-based methods (Samuels et al., 2022).

There are certain differences between organic products and macroalgae in their composition of carbohydrates, namely, laminarin, alginate, and fucoidan, which are greater in brown algae; ulvan is obtained from green algae and carrageen from red algae. The mentioned carbohydrate materials are sulfate compounds, and the method of extraction is a means of reducing the sulfhydryl compound production that minimizes the development of crop plants. The beneficial impacts of introducing seaweed extract to crop plants are associated with stress alleviation because they possess antioxidants that inhibit cell damage as a result of reactive oxygen species (ROS) while undergoing abiotic or biotic stress (Abideen et al., 2022; Meddich, 2022).

In the first century, the application of seaweed metabolites in the agricultural system was reported when the Roman Columella made use of organic manure and mulch treatments on agrarian fields (Armeli Minicante et al., 2022). The prevalence of the application of seaweed extracts in agricultural practice makes up foliar and has the potential to reduce abiotic stress associated with environmental factors, among which is drought tolerance (Samuels et al., 2022). Renowned concentration has been shifted to introducing biostimulants to the soil to promote the growth of plant roots and microbial functions in the rhizosphere region where plant roots are embedded (Cao et al., 2023). Certain studies have presented how seaweed extracts promote plant growth, improve abundant grain yield via phytohormones produced by the plants, control the rate of metabolism in plants, reduce stresses, and contribute to nutrient assimilation (Deolu-Ajayi et al., 2022; Rakkammal et al., 2022). No study has revealed inhibited growth and crop production, yet it does not signify that seaweed extracts constantly contribute to the wellbeing of crop plants, despite previous reports having shown dissimilarities in treated and non-treated crop plants.

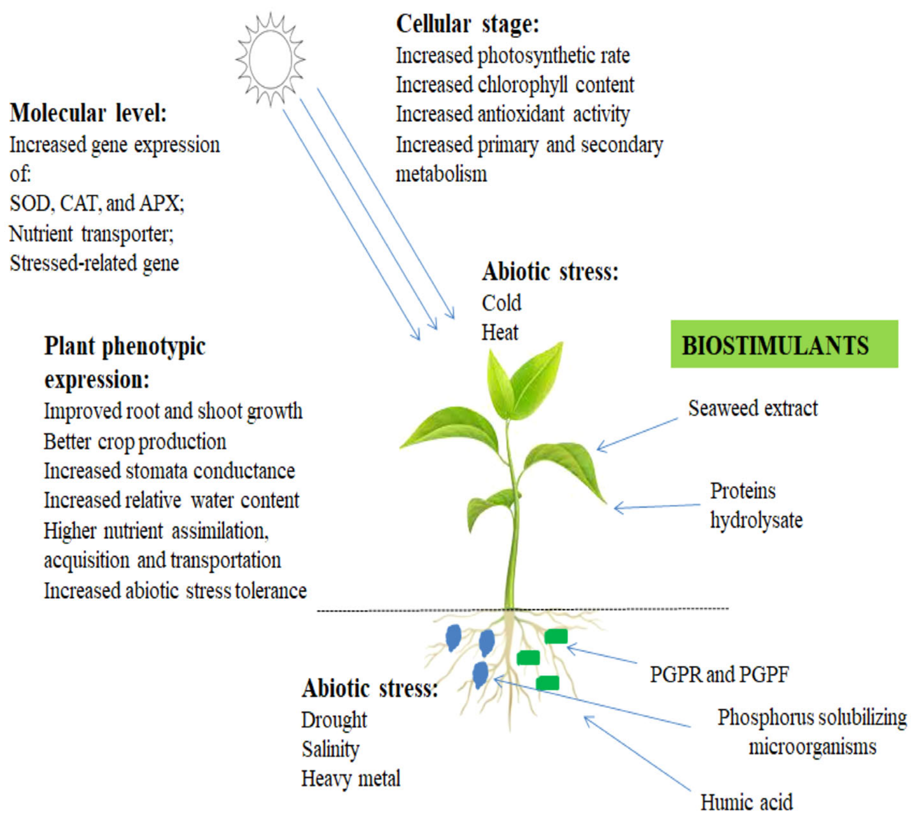

FIGURE 2
Biostimulant contributes to the healthy status and growth promotion of plants.

2.1.3 Humic and fulvic acids

The breakdown of organic matter by microorganisms is regarded as a complex procedure that manufactures byproducts through the process of degradation (Cayetano et al., 2022). Traditional perspectives of this route show that soil organic matter (SOM), which is the final product, comprises steady chemical materials known as humus (Figure 1). Humus is made up of recalcitrant materials tolerant to decomposition processes (Lv et al., 2022). These substances were grouped into different categories based on those soluble in alkali but insoluble in acid [humic acid (HA)], those soluble in alkali and acid [fulvic acid (FA)], and those insoluble in both alkali and acid (humin). They are all present and constitute approximately 60% of the organic matter inhabiting the soil (Pikuła and Ciotucha, 2022). These compounds were regarded to be resistant to degradation by traditional views; other views observed that decomposing organic matter is dynamic, so they have the ability to activate soil microbiome. Various compounds like peat soil, compost, and leonardite produce HA. The production and level of decomposition of HA or FA regulate their activities on crop plants, their composition, and their structure (Kou et al., 2022). Aside from alkali and acid feature differences, HA and FA also differ in makeup elements and their molecular size, which can supply knowledge of differences as biostimulants. HA is larger than FA in terms of molecular size, but FA constitutes various carboxylic groups and is therefore observed for possessing biological active sites in each molecule.

HA and FA have been employed for many years as farm inputs in the agricultural system for the production of crops and investigated for their activities on microbial communities, growth promotion in plants, and availability of nutrients (Yuan Y. et al., 2022). Both products have been applied on farmlands to improve soil fertility by aiding the assimilation of nutrients by plants. Both are obtained from different origins, and the sources greatly affect the potential of the products.

2.1.4 Phosphorus-solubilizing microorganisms

The phosphorus (P) content of the soil is almost 0.05% (w/w), while 0.1% of P is found in plants, and they are water-soluble (Enebe and Babalola, 2021; Peng et al., 2022). Due to their low availability, P fertilizer is required to satisfy the requirements for plant nutrients for particular crop production (Dong et al., 2023). Almost 90% of P fertilizer can attach to the soil when applied to the farmland, thereby making it inaccessible for plant assimilation, yet it can be found in the soil as stored P (Figure 2). Inaccessible P content can be accessible to crop plants via the activity of soil microbial communities through the process of degradation of organic P or dispensation of inorganic P (Emmanuel et al., 2021). The dispensation of inorganic P by microbial communities is prevalently carried out via the production of organic acids that promote accessibility of P by the following methods mentioned: chelation by cations, e.g., Fe^{2+} or Fe^{3+} and Ca^{2+}, which inhibits them from fixing available P; and reduction of soil pH, which liberates mineral P complexes, especially Ca (Sible et al., 2021). Organic acid secretion among microbial species differs, but gluconic and 2-ketogluconic acids are mostly common (Uroz et al., 2022). All living things need P as a major constituent for producing nucleotides, phospholipids, nucleic acids, and enzymes. However, microbes have methods by which they can acquire P, despite some of the microbes being more effective than others. Some microbes are P solubilizers, and recent research has revealed how fungi (*Aspergillus* and *Penicillium*) and bacteria (*Bacillus*, *Pseudomonas*, and *Rhizobium*) are the most effective P solubilizers (Sarmah and Sarma, 2022; Masowa et al., 2023). Gram-negative bacteria solubilize P more compared to gram-positive bacteria (Alori et al., 2017). Reports have revealed how tricalcium phosphate was employed as an insoluble phosphate source to obtain phosphorus-solubilizing microorganisms (PSMs), despite that some microbes can solubilize P (Fatima et al., 2022; Tariq et al., 2022). Nevertheless, the concurrent application of multiple P sources has been advocated for better means of selecting PSMs. These sources contained $FePO_4$ or $Al_2(PO_4)_3$ for acidic soils, $CaPO_4$ for alkaline soils, and phytates for those with abundant organic P. Another means of improving the soil state P is via organic phosphate hydrolysis by activating extracellular enzymes (Elhaissoufi et al., 2022). Although the process of P solubilization is clear, the rate of improving those methods via inoculation to promote the production of crops is unknown.

PSM has been investigated for several years, and many studies have been performed in the field and the laboratory. However, PSM has been employed recently as an agricultural implement, and the full activity of its exploitation has not been recognized (Fatima et al., 2022). The rate of the production of soil P varies from type to soil and agricultural system. The application of the essential organisms to improve the P solubilization for the specific process is demanding. Three strains of PSM were applied individually to reveal the degree to which they can promote the production of wheat by 19%–24%, while the co-inoculation of these strains revealed a 33% increase in production compared to the uninoculated plants (control) (Ahmad et al., 2023).

Bacillus megaterium M3 has been reported to be the most significant inoculant because it improves the characteristics of P cycling in the soil and increases the assimilation of P by crop plants, the potential of soil phosphatase, and multiplication of microbial communities biomass (Turan et al., 2012; Garbin et al., 2022). Different strains of *B. megaterium* have been investigated, contributing to the promotion of P solubilization and increased sugarcane production compared to the control (uninoculated). However, due to a 25% decrease in P fertilizer applied without lessening the production, unlike complete P application (Sundara et al., 2002; Kreutz et al., 2022), an experiment conducted in a greenhouse employing multiple strains of bacteria with and without P on maize crop plant showed how *B. megaterium* improved the development of the plant in unsterilized pots (Ibarra-Galeana et al., 2017; Lan et al., 2022), whereas other strains employed in sterilized pots cannot promote the development of the plant in unsterilized soils. The results revealed that *B. megaterium* not only displayed its potential as PSM via direct P solubilization but also promoted the potential of the soil PSM biomass.

3 Biostimulants produced by plant growth-promoting microorganisms

The physiological mechanism of crop plants is influenced by microorganisms, chiefly PGPRs and arbuscular mycorrhizal fungi (AMFs), by carrying out the biostimulant potential (Emmanuel and Babalola, 2020). The characteristics of plant growth-promoting microorganisms (PGPMs) while interacting with plants revealed various ideas. However, it is not obvious if the association is parasitic or saprophytic. These microbes influenced the crop plants to secure their survival (Gupta and Nair, 2020).

The endophytic bacteria commonly found in plants and rhizosphere bacteria are found in the soil at the root region. These bacteria contribute immensely to the growth of the crop plant and are commonly referred to as PGPRs (Adedayo et al., 2022a). Aside from the potential of the bacteria to contribute to the improvement of soil productivity, they are also involved in the tolerance of abiotic stresses, thereby promoting the growth of the plants. The following are PGPR phyla in which various studies have been conducted: Acidobacter, Actinobacteria, Bacteroidetes, Chloroflexi, Firmicutes, and Proteobacteria. As a result of huge diffusion, the following PGPR genera have been investigated widely: *Bacillus*, *Aeromonas*, *Clostridium*, *Azospirillum*, *Enterobacter*, *Pseudomonas*, *Azotobacter*, *Klebsiella*, *Arthrobacter*, *Rhizobium*, *Gluconacetobacter*, and *Serratia* (Koner et al., 2022).

The fungi classified to Glomeromycota phylum are AMFs, which comprise three major classes (Archaeosporomycetes, Glomeromycetes, and Paraglomeromycetes) and five orders (Diversisporales, Glomerales, Paraglomerales, Gigasporales, and Archaeosporales). The potential of the Glomeromycota phylum is associated with the establishment of plant roots via symbiotic association of endomycorrhizae. Presently, it is revealed that 80% and above of plants can produce a beneficial relationship with AMFs (Koza et al., 2022). Despite that several AMFs have been identified, few have been utilized in the agricultural process (Khaliq et al., 2022). The obtainable inocula constitute species that belong to the genera *Funneliformis* and *Rhizophagus*, which are symbiotic and mostly inhabit soil located in a wide climate zone (Xi et al., 2022).

Even though PGPRs and AMFs have been acquiring great accomplishments in the modern agricultural system, the potential by which PGPMs beneficially influence crop plants and soil is not definite. The beneficial features count not only for microbial communities or the classification of soil but also for the stress and the form of inoculum. The potential of the microbes to contribute to plant growth are as follows: hormonal control, the promotion of nutrient utilization, equilibrium of cell oxidative nature, water use efficacy, and photosynthetic physiological response development.

3.1 Hormonal control

Some hormones play a significant role in controlling plant physiological functions, among which is abscisic acid (ABA). ABA operates as an anti-transpiration hormone that reduces the loss of water molecules from the plant via the opening and closing of stomata (Cui et al., 2022). Accordingly, the significance of ABA is evident, particularly under various stress conditions, viz., high temperature, drought, or salinity. The biosynthesis of ABA can be impacted by several agents, comprising the existence of PGPMs in the soil (Malgioglio et al., 2022). Nonetheless, the effects associated with the changes in ABA after their introduction are considered. Some studies have revealed the introduction of a high content of ABA in crop plants planted under stress conditions (Ayaz et al., 2022). On the contrary, some studies have shown improvement in ABA concentration of crop plants planted under stress conditions and propagated with PGPRs and AMFs (Cantabella et al., 2022; Paravar et al., 2023). Under stress conditions, the tomato plants inoculated with the ABA biosynthetic gene 9-*cis*-epoxy carotenoid dioxygenase (SlNCED) in AMF stress conditions showed that ABA control can be controlled by the forms of stress. Chitarra et al. (2016) revealed how SlNCED activity of receptors decreases to reduce gene expression in tomato roots inhabited by *Septoglomus constrictum* under high-temperature conditions but stayed undisturbed under heat stress conditions and showed that the biosynthesis of ABA was likewise affected by different mycorrhizae.

Auxin (IAA) is another phytohormone and specific auxin produced by the plant. This phytohormone can control various cell processes, including the production of root hairs, root growth, and cell division and elongation. The association occurring between PGPMs with phytohormones, especially auxins (IAAs), is clear. However, IAA high stimulation was detected in plant tissues planted in soil as a result of drought or high salinity. Nevertheless, as mentioned in the literature, much more IAA stimulation was documented in plants inhabited by AMFs than under stress conditions. The morphology of root variations was also observed in some crop plants, as reported by Fadiji et al. (2022b). Such a study was also described by Liu et al. (2018), which reported the auxin pathway in plants inoculated with *Funneliformis mosseae* grown under drought conditions.

The technological facts propose that AMF stimulates the secretion of IAAs and exaggerates the plants' physiological effects on abiotic stress through the production of morphological modifications of the plant root. Some PGPMs do produce IAAs, so they are regarded as the source of IAAs from the outer part of crop plants (Fadiji et al., 2022b). The potential to induce and secrete various materials that are utilizable to the crop plant is infinite to the IAA biosynthesis.

Some PGPR strains can produce an enzyme ACC deaminase that catalyzes the transformation of ACC to ammonia and α-ketobutyrate, the product of ethylene. Accordingly, the production of ACC deaminase contributes to reducing the degree of ethylene in plants and soil, with a subsequent decrease in environmental stresses on crop plants (Adedayo et al., 2022c). When PGPRs stimulate IAAs and ACC deaminase, an interference effect takes place. However, IAAs induce the development of the plant, while ACC deaminase reduces the production of plant ethylene. Certain PGPR-producing ACC deaminase regulates the growth of plants by improving the levels of stress-related hormones like jasmonic acid (JA) and salicylic acid (SA) (Gowtham et al., 2022). JA is an endogenic control hormone that performs a significant function in contrast to development procedures since it partakes in major signaling routes of biotic or abiotic responses. Studies have evaluated the biosynthesis of JA rigorously corresponding to AMF symbiosis (Diksha and Parul, 2023). Therefore, the introduction of AMF promotes the level of JA in cucumber plants, durum wheat, and maize, in both standard and stressful states (Fiorilli et al., 2022).

Meanwhile, SA stimulates stress-related gene expression to regulate membrane stability and avoid oxidative modifications. However, SA functions as a significant factor in the control of the disease signaling routes (Ayyaz et al., 2022). SA likewise partakes in the beneficial association between PGPMs and plants as reported by Tyśkiewicz et al. (2022).

3.2 Promotion of nutrient utilization

The introduction of PGPMs has been demonstrated to contribute to mineral assimilation, phosphate solubilization, siderophore production, and atmospheric nitrogen fixation, therefore impacting nutrient use efficiency (NUE) (Malgioglio et al., 2022). Major elements are essentially required in mineral uptake in plants. Such elements include Ca, Cu, Fe, Mg, Mn, K, and Zn and are better absorbed, but Na is egested because it is a deleterious element (Yuan S. et al., 2022). Several studies have associated the promotion of mineral assimilation with the increase in the morphology of plant roots upon PGPM inoculation (Ali F. et al., 2022; De Palma et al., 2022). AMF inocula produced extraradical hyphae to help plant roots increase the soil volume exploitation, hence increasing the nutrient assimilation potential (Chandra et al., 2022). This process could also be defined by the overexpression of exclusive ion channels, which results in the increment of the K^+/Na^+ ratio, leading to an effective technique that promotes plant tolerance to salt concentration environment (Karimi et al., 2022).

Another way that PGPMs can assist plantations is to assimilate nutritive substances, revealing their capability to add acid to the soil. Some PGPMs have been reported to manufacture organic compounds and release them into the soil, hence alleviating the inorganic phosphate solubilization (Pi) and K (De Palma et al., 2022). Moreover, recent research has displayed how they can produce acid phosphatases and phytases, thereby increasing the mineralization of P (Saranya et al., 2022; Zhao et al., 2022). In addition, hydrogen cyanide (HCN)-stimulating bacteria partake in accelerating the accessibility of P and the utilization of heavy metals with advantageous results for PGPRs and crop plants (Elnahal et al., 2022).

Bioinoculation also promotes the efficiency of nitrogen use with the aid of microorganisms that can fix N. A common PGPR is the genus *Rhizobium*, which fixes atmospheric nitrogen gas (N_2) to produce NH_3. However, the genera *Azotobacter* and *Azospirillum* also show their potential to fix N_2 in non-leguminous plants via a beneficial or free-living association (Patra and Mandal, 2022). Moreover, Wang H.-R. et al. (2022) reported how AMFs were introduced into tobacco plants and further revealed the association between improved N assimilation and upregulation of nitrate reductase (NR) potential. The greater the NR activity granted for a better N uptake, the greater the increase in the production of amino acid and protein biosynthesis (Bandyopadhyay et al., 2022).

One of the significant features of PGPMs is their capacity to make ion-chelating substances, called siderophores. Although Fe is one of the elements existing in the abundant form in the soil, it exists as an impure state Fe^{3+}, which is insoluble and not readily bioavailable. Accordingly, some microorganisms produce siderophores to clean the iron from the mineral phases and ingest the Fe. Therefore, plants can gain from the siderophore that the bacteria produce to assimilate Fe required for several mechanisms like photosynthesis (Dhankhar et al., 2022).

3.3 Cell oxidative condition

Under stress conditions, ROS and reactive nitrogen species (RNS) are formed to control the diversity of physiological methods to ensure the survival of plants (Adedeji et al., 2020). Several biomolecules, including nucleic acids and lipids, are sensitive to their strong oxidative potential because ROS and RNS are highly reactive molecules. Therefore, unmaintainable harm can be introduced to cell membranes, DNA, enzymes, and RNA, causing cell death. Some researchers have reported how plants inoculated with PGPMs had huge cleansing potential against ROS and RNS (Singh et al., 2021). In comparing the tissue of inoculated plants to non-inoculated plants, lesser quantities of H_2O_2 and malondialdehyde were confirmed.

The decrease in the level of ROS stages under various stress conditions could be demonstrated by the rise in the potential of antioxidant enzymes in crop plants already inoculated with PGPM (Castiglione et al., 2021). Under abiotic stress conditions, ascorbate peroxidase (APX), peroxidase (POD), catalase (CAT), superoxide dismutase (SOD), glutathione reductase (GR), and glutathione peroxidase (GPX) activities are considerably promoted in colonized plants. The inhibited potential of GR, SOD, and POD in the mycorrhizal roots of the drought-sensitive wheat plant and digit grass was confirmed (Faria et al., 2022). However, some reports revealed that PGPR treatments reduced CAT, SOD, GR, and GPX potentials when introduced to crop plants in comparison to uninoculated ones (Castiglione et al., 2021). Camaille et al. (2021) proposed that IAA-producing bacteria promoted the aggregation of osmolytes and decreased enzymatic antioxidant potential by speeding up the transition of the biochemical reactions occurring in wheat plants.

In contrast, non-enzymatic antioxidants, including carotenoids, glutathione, organic acids, polyphenols, and vitamins, take part in the activity of PGPMs' relationship with crop plants, causing their effects on oxidative stress. A case study revealed the collection of glycine betaine and proline used for preventing cellular oxidative impairment in crop plants already inoculated with AMFs and PGPRs. An exclusion was proclaimed by Zhao et al. (2023), who provided inconsistent data concerning rhizobacteria that produce proline in plant tissues in comparison with inoculated crop plants grown in the drought-stress region. Ali and Khan (2021) explained how inoculation could credibly activate early proline collection in plantations by decreasing the choice of late collection and encouraging the adaptation of the crop plant under drought-stress conditions. Moreover, the plant growth stage was also revealed to perform a significant function in proline accumulation.

3.4 Water use and photosynthetic physiological effect

Many studies on PGPM have described that its application can influence the relationship of plant and water features by improving the activity of plant leaf water, water content, stomatal conductance, transpiration process, or other features that can specify affirmative results on the utilization of water.

AMF-inoculated tomato and maize plants under irrigation and drought-stress conditions revealed an essential promotion of the specific apoplastic flow of water, unlike as described in control plants by Castiglione et al. (2021). AMFs possess the potential to control the shift between cell-to-cell and apoplastic water transport, resulting in higher flexibility in the process of plant effects under stress conditions. The condition can be the result of positive control of aquaporin genes that significantly promote the water activity in the leaf, thereby proposing that AMF plants control water content in cells. From another point of view, the sustenance of a high stomatal conductance permits the assimilation of CO_2 during the process of photosynthesis in plants. A huge amount of CO_2 that occurs intracellularly piled up under the nature of stress negatively impacts the absorption of sunlight in *Ricinus communis*. However, it has been explained that the existence of AMFs decreases the concentration of intracellular CO_2, relieving the decrease in the process of photosynthesis as a result of stress conditions (Koza et al., 2022). The symbiotic activity of PGPM on plant photosynthesis was confirmed by the promotion of photosynthetic processes under drought salt stress and other optimal conditions (Maitra et al., 2022). The accumulation of increased photosynthetic pigment content was found in various plant species. Most importantly, the green pigment of the leaves (chlorophyll) appeared to be modified. It has been considered that the symbiosis association of PGPM with plants negates the impact of stress, antagonizing the breaking down of chlorophyll and improving the quantum product of open photosystem II.

4 Selection of PGPMs as plant biostimulant producers

Some studies have used native or allochthonous PGPMs, and their ability as biostimulants was compared (Kashyap et al., 2023). In most cases, plants are influenced positively by inoculants, which promote the ability to assimilate nutrients and reduce oxidative stress (Emmanuel and Babalola, 2020). To obtain the best inoculation methods for planting and growing vegetation in degraded ecosystems, autochthonous and allochthonous microbial communities were assessed (Ojuederie and Babalola, 2017). Some studies have explained the activity of autochthonous microbes that are adapted to the stress conditions and physiologically and genetically of the referenced region, unlike allochthonous ones (Ojuederie and Babalola, 2017; Enebe and Babalola, 2018). Mainly, since autochthonous microbes can quickly and efficiently infect the root of a plant, they, therefore, show suitability to antagonize the negative factors obtained from stressed environments to promote the assimilation and transportation of P and to improve plant growth compared to those obtained from the collections. Nevertheless, other reports likewise revealed how PGPMs are required not as biostimulants when compared to non-native microbes.

Pseudomonas putida allochthonous strain is a typical bacterium that is effective as a phosphate-solubilizing bacterium (Khajeeyan et al., 2022). This is equivalent to significant characteristics since the speedy attraction of P in a fixed state is unavailable for assimilation by plants. However, from the soil samples obtained in the agricultural soil, *Bacillus* spp. were isolated and used to improve the development of maize, tomato, and *Arabidopsis* plants in a greenhouse (Olowe et al., 2022).

Some microbes isolated from desert and salinity soils were evaluated. Studies have revealed how PGPMs isolated from decomposed matter applied with high salt concentration and drought could promote tolerance of plants to high temperatures and salinity (Munir et al., 2022). The investigations propose that the effectiveness of biostimulants does not inevitably correspond to the origin of the inoculant but primarily to its internal features by which their relationship with the host is satisfactory and advantageous. Orozco-Mosqueda et al. (2022) agreed with the proposition that revealed the introduction of some bacteria, chiefly *Herbaspirillum* sp. and *Rhizobium* sp., on two major plants' hosts and the different results they produced. Most especially, they discovered the growth of the plant in ryegrass inoculated with *Rhizobium* sp. and the highest growth improvement in red clover inoculated with *Herbaspirillum* sp. under a P-deficient soil stress environment. Furthermore, two different methods of promoting the availability of P were suggested and explained based on the inoculum and plant relationship. The same knowledge was used to explain the factors obtained from the introduction of three different PGPR halotolerant variants, namely, *Exiguobacterium aurantiacum*, *Bacillus pumilus*, and *Pseudomonas fluorescens*, in salinity-tolerant and wheat cultivars sensitive to salinity (Sayahi et al., 2022). It was reported that *B. pumilus* and *E. aurantiacum* showed more results on the salt-resistant genotype, in contrast to the development of promotion of the genotype sensitive to salinity conducted by *P. fluorescens*. As a result, the outcome revealed the assortment of potential variants to be introduced in the soil and the greatest significant influence to improve the accomplishment of bioinoculation under stressful environment. The accomplishment of abundant yield and presentable attribute may pose unusual choices, particularly the type of microorganism introduced when considering the purpose of making salt environment and high-temperature soils fertile, as compared to the restoration (replanting) of a forest that had been reduced by fire or cutting and restoration of plants in dissolved soil. Therefore, the idea of applying microbial biostimulants is more efficient than others.

Considering the major facts, it is relevant to choose available PGPMs and symbiotic associations under the most deviated environmental conditions. Nevertheless, as a result of the increased genetic attributes of PGPMs, further studies need to identify the features of the bioinoculants and the potential of using various PGPM genera as plant biostimulants to acquire the essential multispecies variants or single strains based on the selected purpose.

4.1 Other required conditions of biostimulant potential

4.1.1 Soil enzymes

Biostimulants improve the rate of assimilation of nutrients in crop plants. However, the major mechanisms resulting from the improved nutrient assimilation and availability are not primarily known. The major potential of biostimulants on available nutrients is via modifications in enzyme action due to the catalysis of hydrolytic and oxidative breakdown of organic materials by soil enzymes (Sible et al., 2021). These changes take place in multi-step methods with particular enzymes changing the stages, making it hard to observe specifically where the action of the biostimulant takes place. However, these mechanisms include multiple steps that change one after the other by the action of a specific protein. The alignment of enzyme-mediated degradation stages is made up of the initial (first) and terminal (last) steps (Lopez-Cantu et al., 2022).

Terminal-step enzymes are effective in treatments as a result of their involvement in the catalytic modification of food material to bioavailable products. Therefore, the last stage in the nutrient product is an indirect means of making available the nutrient and renders perceptivity, as a biostimulant can produce nutrients. Agricultural soil is made up of soil organic matter that consists richly of nutrients, C, N, P, and S (Vermeiren et al., 2022) and, likewise, enzymes associated with the nutrients mineralization, which is a major signal for clarifying biostimulant mechanisms associated with nutrient availability. They function in the recurrences of SOM that subject soil enzyme potentials as signs of healthy soil, thereby producing a major usage of biostimulants as soil health materials (Asghar et al., 2022). The following are primary terminal-step enzymes.

4.1.1.1 β-Glucosidase

It is involved in the catalytic hydrolysis of complex sugar glycosidic bonds to produce glucose (Samanta, 2022). The glycosidic bonds are a crucial factor in the cell wall, and this bond decomposition is interceded by bacteria and fungi (Pourjafar et al., 2022). The variable activity of β-glucosidase shows the distinguishing factor in breaking down residue and soil C accumulation and has been employed by the U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) Soil Health Division as a soil biological health indicator.

4.1.1.2 Proteases

These enzymes act on proteins. They are specific components of organic N embedded in the soil and are, therefore, expected to be the rate-restrictive state in the process of mineralization of N from SOM (Tang et al., 2022). In the hydrolysis of proteins, the protease cleaves the peptide bonds in amino acid molecules, producing peptide materials that are worked upon by aminopeptidases to liberate available N and amino acids. Variability in protease activity showed microbial biomass or breakdown of residue as a result of activity in the crop plant root and nutrient cycling (Hakimi et al., 2022).

4.1.1.3 Leucine aminopeptidase

Amino acid residues produced from this enzyme are the N-terminus of proteins and peptide chains. Many enzymes take part in the decomposition of proteins, majorly in the peptide bonds. Nevertheless, leucine aminopeptidase is common in soils and is otherwise referred to as a good indicator of protein degradation (Gong et al., 2022). Together with other aminopeptidases, leucine aminopeptidase carries out an important function in the release of organic N as the terminal stage of protein decomposition into amino acids (Ghifari et al., 2022). Higher stages of leucine aminopeptidase potential show improved mineralization of organic N, and therefore, N is released from SOM upon the organic process of deaminase.

4.1.1.4 Phosphatases

These enzymes, composed of phosphomonoesterases and phosphodiesterases, are included in the production of orthophosphate from organic P (Richardson et al., 2022). Organic phosphates do occur as a single-ester or double-ester bond that is joined by unique organic catalysts, phosphomonoesterases or phosphodiesterases. Microbes multiply to occupy their ecosystems and are involved in the phosphomonoesterase tract, while others are involved in the phosphodiesterase tract (Bauters et al., 2022). The measurement of the activity of both P-producing enzymes provided a broad range classification of P activities. Similar to the mineralization of N obtained via SOM, the two P enzymes worked hand in hand to make crop-available P from its organic form.

4.1.1.5 Arylsulfatase

This enzyme helps in the production of inorganic S (SO_4^{2-}) by linking the S ester linkage to the OM (Silva et al., 2022). Approximately 98% of soil S can be found in the SOM, and 35%–74% of this S content is attributed to the S esters (Kumar et al., 2022). For proper assimilation of S by crop plants, the potential level of arylsulfatase can be derived from the organic S. Therefore, the estimation of soil enzyme potentials as characterized by biostimulants can suggest how the biostimulant affects nutrient transportation in the rhizosphere soil of crop plants. However, as a result of β-glucosidase, it acts coincidentally as an effect produced on soil health.

4.1.2 Microbial community diversity

Any initiation of enzymatic procedures due to biostimulant introduction will be triggered by plant–microbe activities except if the biostimulant is an enzyme. Abundant enzyme activities do take place via higher production of enzymes in plant–microbe interaction (Ayangbenro et al., 2022) or by improving microbial biomass or crop growth, thereby producing abundant enzymes. The biomass of microorganisms and the diversity of the microbes can be traced to the potential methods and activity of biostimulants applied to agricultural soil (Table 1). Moreover, the evaluation of microbial communities inhabiting tomato plant soil is conducted to confirm the quality of the soil and its potential for agricultural management practices, generating information on the attributes and health status of the soil (Adedayo et al., 2022b). Several procedures were employed to evaluate microbial communities, total microbial biomass, and microbial respiration due to their utilization of C substrates to increase their biomass in the soil. These procedures include Sanger sequencing [16S rRNA and internal transcribed spacer (ITS)] analysis, whole genome sequencing, phospholipid fatty acid (PLFA) analysis, and metagenomic sequencing analysis and are mostly adopted nowadays to reveal the diversity of the microbes inhabiting various soils (Adedayo et al., 2022c). These procedures are likewise employed to confirm the persistence of applied microbial communities and microbial functional diversities in the rhizosphere soil when analyzed with the control soil samples. Despite the analysis of microbial communities' diversity to derive biostimulants and their environmental challenges as a result of their introduction being expensive to investigate, the potential of microbial diversity analysis makes available functional features for assessing biostimulants.

TABLE 1 The effect of plant growth-promoting microbes as biostimulants on crop plants.

PGPMs	Microbial plant biostimulants	Effect of biostimulants on plants	References
Bacteria	*Arthrobacter*, *Azotobacter*, *Azospirillum*, *Bacillus*, and *Pseudomonas*	The microbes are cost-effective and environmentally friendly; they stimulate plant immune systems, uptake nutrients, and assist crops in enduring abiotic stresses	(Ali S. et al., 2022)
	Pseudomonas sp.	Improve the length of seedling roots and shoots in Kentucky bluegrass, carrot, and wheat	(Zhang Q. et al., 2022)
	Arbuscular mycorrhizal fungi, *Trichoderma* spp., and rhizobia	The microbes form an association with plants, producing biostimulant effects like plant-growth promotion, improved nutrient assimilation, and mitigation of abiotic stress	(Cardarelli et al., 2022)
	Pseudomonas pergaminensis sp. nov. strain 1008^T	In *in vitro* analysis, phosphate-solubilizing potential, and the production of IAA, the strain was formulated to inoculate the wheat plant	(Díaz et al., 2022)
	Pseudomonas, *Klebsiella*, *Enterobacter*, and *Acinetobacter*	These microorganisms are biofertilizers that make provision of nutrients, improve plant growth, and protect crop plants from harsh environmental conditions like drought and salinity	(Kumari et al., 2022)
	Bacillus spp.	Promote plant growth, stimulate lytic enzymes, versatile antibiotics, and inhibition effect, and induce systemic resistance	(Prabhukarthikeyan et al., 2022)
	Pseudomonas sp. and *Pantoea agglomerans*	Tolerate drought-stress conditions and promote plant growth from the root and rhizosheath of *Stipagrostis pennata*	(Naderi et al., 2022)
Fungi	*Rhizobium* spp. and mycorrhizal fungi	They contribute to plant growth and production of phytohormones, e.g. IAA, GA, cytokinin, abscisic acid, and siderophore	(Ali S. et al., 2022)
	Arbuscular mycorrhizal (AM) fungi	They are growth-stimulating and nutrient-enriching and are involved in the phytoremediation process that incurs protection for plants from diseases and resistance to drought, salinity stress, and heavy metal toxicity	(Sakthieaswari et al., 2022)
	Metarhizium brunneum	The microorganism produces volatile organic compounds are activities that take part in plant growth promotion	(Wood et al., 2022)
	Sargassum vulgare, *Acanthophora spicifera*, and *Ascophyllum nodosum*	The microorganisms' extract from the rhizosphere, endosphere, and phyllosphere contribute to the abundant production of plant growth parameters like chlorophyll content, root and shoot dry weight, plant height, number of flowers, root length, fruit number, and overall fruit production in pepper and a tomato plant	(Ali O. et al., 2022)
	Trichoderma spp. and AMFs	Promote plant growth induction, promote nutrient assimilation, inhibit phytopathogens, and induce plant defense mechanism	(Savarese et al., 2022)
	Trichoderma viride, *Penicillium chrysogenum*, *Cladosporium cladosporioides*, *Aspergillus fumigatus*, arbuscular mycorrhizae, etc.	Contribute to the growth promotion of crop plant	(Adedayo and Babalola, 2023)

PGPMs, plant growth-promoting microorganisms; IAA, auxin; GA, gibberellin; AMFs, arbuscular mycorrhizal fungi.

4.2 The biostimulant and activity of improving soil health

The idea of the health status of soil has been in existence for a long time in the field of agricultural systems, and it was regarded as soil quality and tilth (Liptzin et al., 2022). Attention to environmental challenges of improper, unsuitable management leads to higher soil management resulting in erosion of nutrients into surrounding bodies of water, causing pollution to the waterways and a rise in the idea of soil health. Multiple features are characterized by soil health, which is biologically mediated and promoted by the introduction of biostimulants. The USDA NRCS is conducting thorough research with scientists in the USA to set up consistent methods for testing and observing the health indicators of soil and to choose some enzymes produced by microbes inhabiting the soil, detect soil respiration levels, and confirm the total soil organic C (Gutknecht et al., 2022). These features can likewise be signals of biostimulant potential in crops, thereby providing knowledge for their introduction to control the development of the crop and the health status of the soil as observed in Table 1.

Farmers employed biostimulants for adequate production of yield in the growing season with little concentration for long-period impacts on the soils they have inoculated over time. Although biostimulants do not produce immediate effect upon its application on plants, yet, improvement of soil health and production of abundant yield will be achieved overtime. Nevertheless, measuring biostimulants in soils by employing long-term methods is unsatisfactory. The direct effect on soil bioactivities promotes soil health as the potential of soil microbes to utilize C substrate. Biochar, a typical example of a biostimulant, when added as a C substrate to the agricultural field, is resistant to decomposition (Xin et al., 2022). It has been proposed that the reiterated introduction of biostimulants can improve the rates of soil C and agricultural yield, resulting in abundant production of seasonal crops and biological C utilization (Zanli et al., 2022). The continuous increase of C can transform the ratio of C:N in the soils, which can control more N and reduce plant activities. These require the employment of an extended study of a biostimulant's attribute on the cycling of nutrients in the soil, soil C, and improving soil health (van der Sloot et al., 2022).

5 Synergistic response of microbial biostimulant components

Green Deal intentions, in addition to the rules of the European Regulation 2019/1009, proposed to decrease the application of chemical fertilizer through various methods. The methods, including the promotion of biostimulant efficacy, were brought to attention. To obtain the necessary tools that can be employed to exert the efficient biostimulant potential in plants, various reports concentrated on the association of plants and microorganisms, including PGPRs and AMFs (Bartucca et al., 2022).

The advantageous factor of the accumulation of various forms of microbes employed as plant biofertilizers may hinge upon their potentiality under unfavorable conditions of the environments. Studies have revealed the activity of biostimulants when different materials were added together, describing synergistic interactions (Montoneri et al., 2022; Navarro-León et al., 2022; Canellas et al., 2023). This review portrays how biostimulants (microbial-based) can be produced employing the following methods: AMF/PGPR multispecies consortia, a single PGPM strain, and aggregation of PGPMs with inorganic and organic chemicals.

5.1 The action of biostimulant upon co-inoculation of AMFs and PGPRs

PGPRs may behave not only as a biostimulant in the presence of AMFs but also act as a mycorrhizal supporter, mostly when rigorously related to their mycelium and spores (Pandit et al., 2022). In other words, AMFs can improve the potential of solubilizing phosphorus and fixing nitrogen. Mycorrhizal supporter potential can be demonstrated under concurrent introduction with PGPRs and AMFs. The inhabitation of plant roots by PGPRs may improve their potential to stimulate cell wall-destructing enzymes that alleviate AMF formation. Furthermore, PGPRs do produce enormous secondary metabolites that can improve root exudation, producing higher cell porosity and hyphal growth (Koza et al., 2022).

The application of co-inoculation of AMFs and PGPRs not only improves plant growth but also has an advantageous status for AMFs and PGPRs. Accordingly, the application of combined PGPRs and AMFs as biostimulants has been inquired about in various reports. The efficacy of a biostimulant made up of both bacteria assisting plants and AMFs was observed in various plants, contributing to their growth characteristics. Improvement is obtained in the plant *via* microbial multiplication, and the production of abundant crops follows as a result of PGPR and AMF introduction, unlike uninoculated plants or plants introduced with only a PGPR or AMF strain alone (Cantabella et al., 2022). Moreover, the research investigating wheat plants by Zhang L.-L. et al. (2022) showed an absolute improvement of particular gluten protein fractions included in dough intensity and its elastic nature.

5.2 Biostimulant factors obtained from the PGPM introduction with bioactive materials

To improve the effectiveness of microbial biostimulants, various preparations constituting PGPMs and bioactive materials, like composts, protein hydrolysates, humic acids, plant exudates, agronomic or industrial materials produced, sewage, algae, and/or their extracts, were estimated.

5.2.1 Compost and PGPM combination

Compost and compost products (vermicompost) are regarded as significant unprocessed materials for the production of biostimulants. Though they are considered biostimulants, the biologically active materials can be acquired from amino acids, phytohormones, humic substances, etc., which reveal fascinating features (Figure 1). Microbial communities inhabiting the soil are employed for producing biostimulants, and such examples of microbes include PGPRs and plant growth-promoting fungi (PGPFs), which may be either living or dead microbes, and the metabolites produced (Adedayo and Babalola, 2023). They can also be manufactured from extracts obtained from food wastes, aquaculture waste, composts, vermicompost, manure, animal wastes, etc. (Tolisano and Del Buono, 2023). Some ideas have been described that when PGPMs and compost were combined, they showed the potential to ensure a positive synergistic effect on the development of the plant (Table 2). A typical example of an advantageous factor was observed in plant growth in which upon introducing a halotolerant bacterial strain (*Dietzia natronolimnaea*) and AMFs, *Glomus intraradices* improved with compost product (Hossain et al., 2022). This effect has also been employed upon inoculation of AMF to green waste compost; after observation, a salinity tolerance on palm tree was observed, as verified by the improved K^+/Na^+ and Ca^{2+}/Na^+ proportion (Bello et al., 2021). The advantageous factors for plant growth were proposed and could be connected to the more effective acquisition of nutrients relinquished by compost as a result of AMF presence. Therefore, the development of nutrient uptake (K, Na, Ca, Mg, Al, and N) was observed when AMFs were introduced with compost but were less apparent once the plants were inoculated with compost or AMFs.

TABLE 2 Microorganisms, the byproducts produced, and their activities as biostimulants.

Microbes	Byproducts or exudate produced	Roles	References
PGPRs, PGPFs	Microbial exudates	Contribute to plant growth, plant defense, and biotic and abiotic stress control	(Ansari et al., 2023)
Photosynthetic microbe	Secondary metabolites like indole alkaloids and exopolysaccharides	Support the development of the plant and stress control	(Renaud et al., 2023)
Bacteria and fungi	Nanomaterials	Enhance food quality, safety, and security, and ability to promote plant growth and nutrition	(Magnabosco et al., 2023)
PGPRs, PGPFs	Microbial, non-microbial, and waste-derived source	Elicit metabolite accumulation and trans-generational plasticity	(Johnson et al., 2023)
Bacteria and arbuscular mycorrhiza	Primary metabolites, phenolics, and anthocyanin	They are used in the vegetative growth of strawberries	(Schmitzer et al., 2023)
AMFs (*Rhizoglomus irregulare* and *Funneliformis mosseae*) and *Trichoderma* spp.	Carotenoid compound	The compound improves the ripening development of tomato fruits	(Ganugi et al., 2023)
Fungi	Solid-state fermentation byproducts	The byproducts are used in the production of biopesticides	(Mattedi et al., 2023)
Sewage sludge	Alkaloids and jasmonic acid	Reduce the content of heavy metals in the agricultural soil	(Hao et al., 2023)
–	Folcare and ZnO nanoparticles	They possess advantageous effects on morphological and physiological indicators of plant health of pea (*Pisum sativum*) plant	(Missaoui et al., 2023)
Bacteria	Polyhydroxyl-alkanoate (PHA) protein hydroxylated-rich byproducts	They aid the growth and development of tomato plants, thereby contributing to plant health and tomato fruit production	(Bastianelli et al., 2023)
Bacteria (*Bacillus* spp.)	Metabolites	They help control various abiotic stresses including inorganic and organic pollutant toxicity, salinity, nutritional imbalance, waterlogging, low temperature, and drought	(Etesami et al., 2023)
Bacteria and fungi	Humic acid, fulvic acid, protein hydroxylate, and seaweed extracts	The biostimulants promote the cultivation of forage grass quality, tolerate environmental stresses, and facilitate assimilation of nutrients	(Mackiewicz-Walec and Olszewska, 2023)
Yeast (*Saccharomyces cerevisiae*)	2,3-Butanediol	The metabolite 2,3-butanediol produced by the yeast can stimulate tolerance of drought in *Arabidopsis* plants	(Lee et al., 2023)
Bacteria (*Pseudomonas*, *Burkholderia*, and *Rhodanobacter*) and fungi (*Fusarium*, *Mortierella*, *Penicillium*, and *Trichoderma*)	Gelatin	The microbes produce microbial consortia and enzymes and produce gelatin to improve the potential of biostimulants in the soil	(Costa et al., 2023)

PGPRs, plant growth-promoting rhizobacteria; PGPFs, plant growth-promoting fungi; AMFs, arbuscular mycorrhizal fungi.

5.2.2 Addition of PGPMs with amino acids

The formulation of biostimulants situated on amino acids is considered for their advantageous potential on the development of plants and crop yield levels, most importantly when stress occurs in the environment (Franzoni et al., 2022). Among the several features of amino acids are metal ion chelators, promoters of photosynthesis activity, anti-stress components, and metabolism of the hormone. Through the process of chemical or enzymatic hydrolysis, amino acids can be acquired from proteins of plants and/or animals.

Gowtham et al. (2022) explained that the application of PGPR strains (*Bacillus cereus*, *B. pumilus*, and *Pseudomonas* sp.) obtained from non-moisturized regions produces IAA, gibberellin (GA), and ABA content and reduced relative water content (RWC) (Malik et al., 2022). This process, promoted by the introduction of L-tryptophan, permits the preservation of a phytohormone proportion in dried environments, reducing the harmful activities of abiotic stress (Adeleke et al., 2022). Moreover, conservation of water was detected in the treatments in which PGPRs obtained from moisturized environments were introduced concerning tryptophan. Consequently, the dry weight of the root and shoot of the inoculated plants was greater, thereby proposing the development of these organs.

5.2.3 PGPMs in combination with silicon

Biostimulant improvement activities on plants stimulated via synergistic association were likewise confirmed with AMFs and inorganic minor elements. An example is observed in rice plants; a greater yield was observed after the introduction of *Rhizophagus clarus* and silicon (Si) under normal and high-temperature environments (Etesami et al., 2022). The Si improved the colonization of AMF and the production of fungal structures; likewise, AMF improved the assimilation of Si by the plants. However, the high rate of Zn and Fe assimilation improved the formulation of the gene sequencing for enzymes included in the antioxidative defense system. Also, the assimilation of water and water use efficiency (WUE) may be associated with the activity of AMF and Si (Akensous et al., 2022). Most importantly, the assimilation of Fe and Zn can be affected by Si inoculation and can stimulate the upregulation of genes coding for IRT1 and IRT2, regarded as the Fe transporters classified to the Zrt/IRT-like protein (ZIP) family (Israel et al., 2022), which comprises Zn transporters. In contrast, the cellular oxidative condition can likewise be changed. This advantageous potential could result from the potential of Si to improve the stimulation of secondary metabolites or from the potential of the enzymes or gene expression of antioxidant enzymes, such as catalase, glutathione peroxidase, and superoxide dismutase.

6 Conclusions

The major problem encountered in the biostimulant market is unlimited usage. Despite agronomic inputs comprising a method of choosing, the proposed reason for biostimulant usage is sometimes direct. Chemical derivatives have been employed in the inhibition and total eradication of phytopathogens. The fertilizer market has a large number of alternatives to fertilizer accessible to farmers. Irrespective of the chemical fertilizer production site and selected means of usage, biostimulants are intensively employed to provide needed nutrients to encourage the developing plants to an ambitious stage of crop growth. Biostimulants are known to be different from other agronomic inputs and are in individual products irrespective of the desired response. Biostimulant application, for example, seaweed extract, to crop plants can introduce the microbial communities at the point of inoculation. In contrast, foliar application to vegetative growth stages is aimed at stimulating signal tracts to reduce abiotic stresses. Using biostimulants to promote the chosen product is another potential factor that farmers take. Chemical-derived fertilizers and pesticide markets are likewise gaining product options, and the major difference between the chemical derivatives and biostimulants is in its undefined lane. There are three features of product skillfulness, and they include little knowledge of the composition of the product and associated potential mechanisms and acquirable alternatives that left the biostimulant sale disorganized and modified for row crops. Moreover, the actual variability in season products enables farmers' hesitance, and the successful application of biostimulants to farmland currently allows an instruction method that enables multiple seasons of fine-tuning for the successful employment of novel patterns.

The variability of information and demand for agricultural land observation is feasible. Biostimulants can promote crop and soil systems to adequately improve crop productivity. Attention has shifted to the potential of the fertilizer, which is presently the primary research method for biostimulants employed in crop systems, with the ability to increase the planting process and crop productivity, which is a result of effective nutrient utilization. Although some biostimulants are aimed at the application to the plantation of crops to improve their production, some products obtain these effects through their interaction with soils and their association with the plant root. Comparative observation of biostimulant impacts on the quality of soil and biological signals may show previously unidentified advantages of their introduction. The public authorities' efforts are on orienting the public on agricultural systems and their potential to characterize the quality of water and manage nutrients, the application of biostimulants act as an alternative to greater sustainability of agriculture systems, and the promotion of soil quality that allows a feasible choice despite the lack of increased crop production.

Author contributions

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