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Harnessing Biostimulants to Mitigate Abiotic Stress in Soybean Production: An Overview

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Authors' contributions

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

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ABSTRACT

Abiotic stress factors, such as drought, temperature extremes, and soil salinity, significantly impact soybean (*Glycine max*) growth, yield, and quality. In recent years, biostimulants have emerged as a promising solution to improve crop resilience against these stresses. Biostimulants, derived from natural sources, enhance plant growth and tolerance by stimulating physiological and biochemical processes essential for stress adaptation. This study focuses on the application of biostimulants to

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mitigate abiotic stress in soybean, examining their effects on growth parameters, yield stability, and biochemical responses under stress conditions. Specifically, biostimulants based on seaweed extracts, amino acids, and microbial inoculants have shown considerable potential in promoting soybean resilience by enhancing water-use efficiency, modulating antioxidant systems, and improving nutrient absorption. The findings highlight the importance of biostimulants in sustainable agriculture, offering insights into optimizing their use to improve soybean production in challenging environmental conditions.

Keywords: Biostimulants; abiotic stress; soybean growth.

1. INTRODUCTION

Soybean (*Glycine max*) is a globally significant crop valued for its high protein and oil content, essential for food, animal feed, and various industrial applications. However, soybean production faces growing threats from abiotic stress factors, such as drought, elevated temperatures, and soil salinity, which can cause substantial yield losses and diminish crop quality (Miransari, 2015; Kumawat et al., 2024). These environmental stressors interfere with vital plant physiological processes, leading to reduced growth, impaired photosynthesis, and compromised nutrient uptake (Ratnaparkhe et al., 2024). As climate change escalates the frequency and severity of these stressors, developing sustainable solutions to enhance crop resilience has become a priority in agricultural research.

The term "biostimulant" has been widely adopted in scientific literature, with definitions evolving over time. Initially described as plant growth promoters by Kauffman et al. (2007), biostimulants are now defined by Du Jardin (2012) as substances or microorganisms that stimulate natural processes in plants to enhance nutrient use efficiency and/or tolerance to abiotic stress. Despite the formation of the European Biostimulants Industry Council (EBIC) to regulate these products, biostimulants are still often registered under the same legal frameworks as fertilizers and plant protection agents (Traon et al., 2014). These preparations offer numerous benefits, such as reduced fertilization costs, improved growth, and enhanced resistance to nutrient deficiency-induced diseases (Brown and Saa, 2015; Liakas et al., 2006).

Biostimulants have gained significant attention as a promising tool for bolstering crop tolerance to abiotic stresses. Unlike traditional fertilizers or pesticides, biostimulants are natural or biologically-derived products that enhance plant growth and resilience through specific mechanisms, including the stimulation of plant metabolism, improved water and nutrient absorption, and increased antioxidant activity (Chieb & Gachomo, 2023). Derived from sources such as seaweed extracts, amino acids, and beneficial microorganisms, biostimulants can help improve soybean tolerance to environmental stress by promoting root development, boosting chlorophyll content, and regulating hormone levels in stressful conditions (Sun et al., 2024).

Seaweed-based biostimulants, for example, contain phytohormones and organic compounds that enhance water retention, antioxidant defense, and photosynthetic efficiency, making plants more resilient to drought. Similarly, amino acid-based biostimulants support nitrogen metabolism and cellular osmotic balance, crucial for plant survival in drought or saline environments. Microbial inoculants, such as plant growth-promoting rhizobacteria (PGPR), improve root architecture and increase nutrient availability, which further aids plant growth under adverse conditions (Sun et al., 2024; Rouphael & Colla, 2020).

Bioinoculants and biostimulants represent innovative approaches to mitigate crop damage caused by environmental stress. Bioinoculants, particularly PGPRs, have shown promise in reducing both biotic and abiotic stress in commercial crops (Chieb & Gachomo, 2023; Ahluwalia et al., 2021; Pereira et al., 2020). Rhizobacteria induce physicochemical changes in plants, enhancing drought resilience through mechanisms like phytohormone modulation, metabolic adjustments, exopolysaccharide (EPS) production, biofilm formation, antioxidant responses, and the accumulation of beneficial organic compounds such as carbohydrates, amino acids, and polyamines (Khan et al., 2020). Similarly, biostimulants aim to improve plant stress tolerance, often containing a blend of plant growth regulators and compounds like amino acids and nutrients (Povero et al., 2016; Rouphael & Colla, 2020). This blend affects plant physiological processes, supporting nutrient uptake (Loconsole et al., 2023), enhancing both vegetative and reproductive growth (Rouphael & Colla, 2020; González-Pérez et al., 2022), and mitigating the effects of abiotic stress, as demonstrated by products derived from Ascophyllum nodosum extracts (Franzoni et al., 2022; Shukla et al., 2019; Campobenedetto et al., 2021).

This review explores the application of biostimulants in soybean production under abiotic stress conditions, examining their mechanisms of action, benefits for crop resilience, and broader implications for sustainable agriculture. By analyzing how biostimulants enhance stress tolerance, this research aims to contribute to strategies that optimize their use in soybean cultivation, ultimately supporting improved yield stability and sustainability in the face of mounting environmental challenges.

2. MECHANISMS OF ACTION IN MITIGATING ABIOTIC STRESSES

Plants are frequently exposed to various abiotic stresses. which account for approximately 70% of the yield gap caused by changing climate conditions (Rouphael & Colla, 2020). To enhance crop productivity and maintain yield stability, the use of plant biostimulants in agricultural systems has emerged as a promising approach. Genomics, transcriptomics, and metabolomics are crucial for understanding how biostimulants enhance plant stress tolerance and growth. Genomics helps identify stress-related genes that biostimulants activate, while transcriptomics reveals how gene expression is influenced during stress. Metabolomics examines the metabolites, like osmolytes and antioxidants, produced in response to biostimulants, improving stress resistance. Together, these approaches offer insights into the genetic, transcriptional, and metabolic mechanisms that biostimulants use to boost plant resilience. This comprehensive understanding enables more targeted agricultural practices to improve plant health under stress (Fig. 1).

Plant biostimulants improve plant resilience against abiotic stresses by triggering a range of signaling pathways, increasing both enzymatic and non-enzymatic antioxidant activities, reducing lipid peroxidation and electrolyte leakage, and optimizing water and nutrient use efficiency, as well as photosynthetic performance (Francesca et al., 2021; Hashem et al., 2018). Moreover, PBs influence the expression of several crucial genes involved in antioxidant metabolism (such as CAT, SOD, POD, APX, GPX, GR, CHS, CSD1, and DHAR), abscisic acid biosynthesis and signaling (NCED), aquaporin activity (PIP1 and PIP2), osmoprotectant pathways (P5CS1), and secondary metabolite synthesis (PAL), showing distinct expression patterns under stress conditions (González-Morales et al., 2021).

The combination of genomics, transcriptomics, and metabolomics allows for a holistic understanding of how biostimulants influence plant stress tolerance and growth at the genetic, transcriptional, and metabolic levels. These powerful tools help uncover the molecular mechanisms underlying plant responses to biostimulants, enabling researchers to design more effective, targeted biostimulant treatments that improve agricultural productivity and sustainability under various environmental stresses.

3. ENHANCED NUTRIENT UPTAKE AND EFFICIENCY

By improving root architecture and activating soil microbiota, biostimulants increase the bioavailability of nutrients. Humic substances, for example, enhance root hair development, which enables soybean plants to access nutrients more efficiently. Microbial inoculants, especially Rhizobium bacteria, are critical in fixing nitrogen, directly supporting the plant’s protein synthesis needs.

The application of exogenous amino acids to plant leaves and roots has been shown to enhance nutrient uptake and improve nutrient-use efficiency for both macronutrients and micronutrients. This effect occurs through two primary mechanisms: amino acids influence nutrient uptake by modifying soil processes and by directly affecting the plant's physiology. In the soil, amino acids can enhance nutrient availability and promote microbial activity, which aids in nutrient absorption. On the plant side, they stimulate physiological processes such as root development and nutrient transporter activity, leading to more efficient nutrient uptake and utilization (Anitha, 2020).

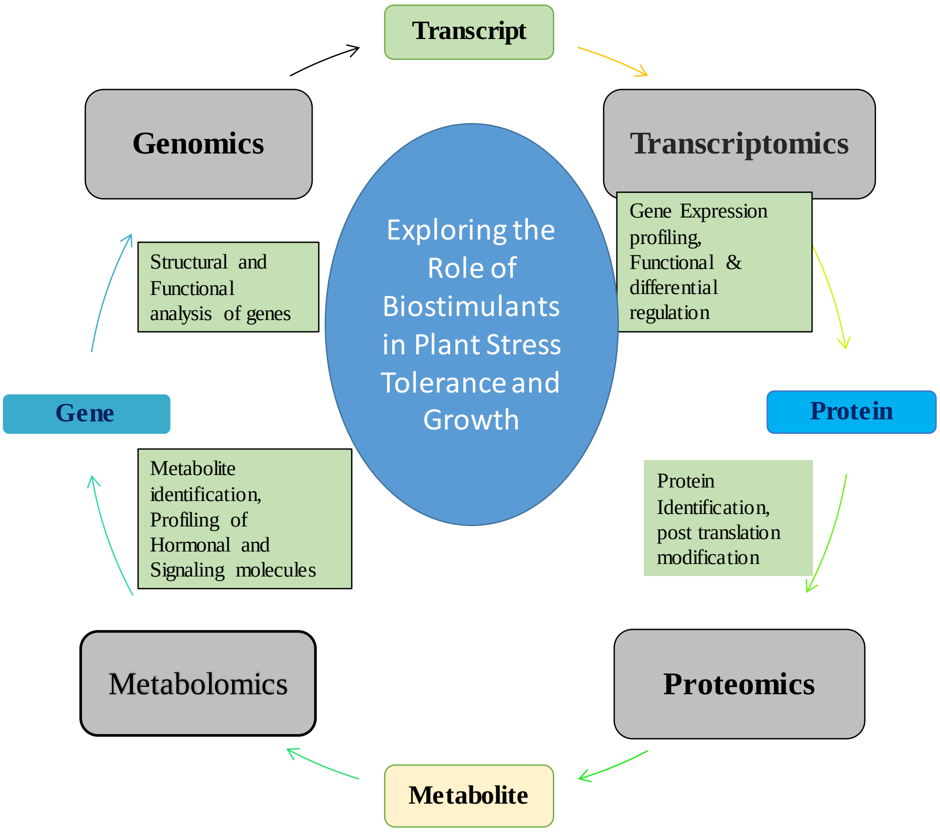

Fig. 1. Exploring the role of biostimulants in plant stress tolerance for molecular insights

4. STRESS TOLERANCE AND ANTIOXIDANT ACTIVITY

Drought and heat stress is the common abiotic challenges in soybean production, often leading to reduced growth, delayed development, and lower yields. The duration and severity of drought stress in soybean vary depending on environmental factors such as rainfall patterns, soil type, and water retention capacity (Miransari, 2015). Typically, drought stress can persist during critical growth stages such as germination, flowering, and pod filling, which are highly sensitive to water deficits. Prolonged drought during these stages can significantly impair photosynthesis, nutrient uptake, and overall plant metabolism, resulting in substantial yield losses (Rouphael & Colla, 2020).

Biostimulants offer a promising solution for mitigating the adverse effects of drought stress in soybean cultivation. These substances, derived from natural or synthetic sources, enhance the plant's physiological processes, improving stress tolerance and overall performance. Biostimulants such as humic acids, seaweed extracts, amino acids, and microbial inoculants play a crucial role in enhancing root growth, improving water-use efficiency, and promoting osmotic adjustment.

For example, biostimulants can stimulate the production of osmoprotectants like proline and glycine betaine, which help maintain cell turgor and stabilize cellular structures under water-deficit conditions. Additionally, they enhance antioxidant activity, reducing oxidative damage caused by drought-induced reactive oxygen species (ROS) (Kumawat et al., 2024). Many biostimulants contain antioxidants or stimulate the production of antioxidant enzymes, which protect soybean plants from oxidative damage under stress conditions. Seaweed extracts, which are rich in antioxidants, further boost the plant's resilience to drought and high temperatures by reducing ROS accumulation. Biostimulants also improve soil health by fostering beneficial microbial activity, which aids in nutrient availability and water retention. Furthermore, amino acids within certain biostimulants contribute to osmotic regulation, helping plants maintain cellular functions and metabolic processes during drought stress (Ratnaparkhe et al., 2024). Together, these mechanisms improve the plant's ability to withstand and recover from water-deficit conditions, ensuring better productivity and sustainability in soybean cultivation (Campobenedetto et al., 2020).

5. HORMONAL MODULATION

Biostimulants often contain or influence phytohormones like auxins, cytokinins, and gibberellins, which regulate growth and development. Seaweed extracts and PGPRs can stimulate auxin production, leading to enhanced root and shoot growth in soybeans. These hormonal effects are particularly useful during early developmental stages, promoting stronger plants capable of higher yields.

Biostimulants, including phytohormones, are gaining popularity for enhancing crop quality and mitigating environmental stress (Gu et al., 2022; Altaf et al., 2023). Their interaction during stress conditions influences gene expression, metabolic processes, and antioxidant systems, which is crucial for improving plant resilience and promoting sustainable agriculture. Melatonin (MT), a versatile biostimulant, has shown effectiveness in combating both abiotic and biotic stress, with its coordination with abscisic acid (ABA) playing a key role in regulating stomatal behavior, leaf aging, and growth (Jahan et al., 2023). Brassinosteroids (BRs), another important class of phytohormones, regulate various physiological processes such as plant growth, fruit ripening, and gene expression, highlighting their potential in enhancing crop productivity and resilience (Ahammed et al., 2013). These findings underscore the importance of biostimulants and phytohormones in advancing agricultural practices.

6. DIFFERENT BIOSTIMULANTS USED IN SOYBEAN FOR MITIGATION ABIOTIC STRESS

Soybean (*Glycine max*) is a globally important crop, valued for its protein and oil content, but it is often impacted by environmental stressors such as drought, nutrient deficiencies, and pathogens. To mitigate these challenges, biostimulants, both natural and synthetic, have gained attention for their potential to enhance plant growth, yield, and resilience under stress. Biostimulants include substances like humic acids, seaweed extracts, microbial inoculants, and amino acids, which support nutrient uptake and stress tolerance in plants (Fig. 2). As modern agriculture moves towards reducing reliance on mineral fertilizers and chemical plant protection agents, biostimulants, which alleviate environmental stress, are becoming increasingly popular (Maciejewski et al., 2007; Yakhin et al., 2017).

Abiotic stress factors such as drought, salinity, and temperature extremes induce oxidative damage, osmotic imbalance, and hinder nutrient uptake in plants. The application of biostimulants enhances plant resilience by improving osmotic regulation, reducing oxidative stress, and promoting stress-responsive gene expression, ultimately supporting plant survival and growth under adverse environmental conditions.

Fig. 2. Illustrating the impact of abiotic stress on plant growth and the mitigating effects of biostimulants

Biostimulants function by improving biochemical, morphological, and physiological processes in plants exposed to stress (Basak, 2008; Du Jardin, 2012). Natural biostimulants include amino acids, algae extracts, and humic substances, while synthetic options often contain plant growth regulators, polyphenolic compounds, and essential elements (Du Jardin, 2012). Among synthetic biostimulants, products like Atonik and Tytanit have garnered attention. Atonik, containing phenolic compounds, is used globally, although its effects on yield can vary (Kozak et al., 2008). Tytanit, which includes a titanium complex, has been developed to enhance plant productivity by stimulating enzymes, chlorophyll content, and stress tolerance (Lyu et al., 2017). However, the exact mechanisms behind these positive effects remain unclear (Ghooshchi, 2017). This paper reviews recent studies on the effectiveness of biostimulants in soybean cultivation, focusing on their roles in improving nutrient uptake, stress tolerance, and overall productivity.

7. HUMIC AND FULVIC ACIDS

Humic substances, including humic and fulvic acids, are organic compounds that improve soil health and nutrient availability. When applied to soybean crops, humic acids enhance root growth, which promotes better water and nutrient uptake. Studies have shown that humic acid treatments can increase soybean yield by improving soil structure and microbial activity around the root zone, making nutrients like phosphorus and potassium more accessible to the plant.

Humic substances are known to promote plant growth, and their beneficial effects on legumes may enhance biological nitrogen fixation in soils. This study evaluated dry matter production, nodulation, and nitrogen content in the nodules of soybean (*Glycine max* L., 'Bragg') grown in sand cultures supplemented with a fertilizer mix and varying concentrations of fulvic acid (FA) or humic acid (HA), ranging from 0 to 800 mg kg^{-1}. Results indicated that both FA and HA contributed to increased dry matter production in soybean. Root and nodule dry weights tended to increase at FA or HA concentrations between 100 and 400 mg kg^{-1}, with the most significant growth observed at 800 mg kg^{-1}. A positive correlation was observed between increasing concentrations of FA and HA and the dry weights of shoots, roots, and nodules. Although FA and HA treatments resulted in fewer nodules compared to the control, nodule mass was greater. The nitrogen content in the nodules was largely unaffected by the treatments, though a slight reduction in nitrogen was noted in soybean nodules treated with 100 mg kg^{-1} of FA (Tan & Tantiwiramanond, 1983).

8. AMINO ACIDS AND PROTEIN HYDROLYSATES

Amino acids and protein hydrolysates serve as organic nitrogen sources and can be absorbed through leaves and roots. In soybeans, amino acid applications promote better nitrogen assimilation, leading to increased leaf area, plant biomass, and yield. Additionally, amino acids stimulate stress-response pathways, helping soybean plants better withstand adverse conditions such as salinity and drought.

Amino acids play a vital role in plants, acting as both building blocks for proteins and a source of organic nitrogen, which helps mitigate drought and salt stress while promoting cell growth. They are essential for metabolite synthesis, plant growth, and development (Abdelkader et al., 2021; Alcazar et al., 2010). Foliar application of amino acids and amino acid-based biostimulants has been shown to improve the quality and quantity of various plants, including Foeniculum vulgare, Coriandrum sativum, and Satureja hortensis (Shahrajabian et al., 2023; Noroozlo et al., 2019; Ayyat et al., 2021). These amino acids are derived from plant proteins (e.g., algae, soybean, corn) and animal proteins through chemical and enzymatic hydrolysis, with enzymatic hydrolysis being the most common method (Islam et al., 2022; Peslerbes et al., 2022). Protein hydrolysates, which consist of peptides, free amino acids, and partially degraded proteins, are the primary source for these biostimulants (Cosovanu et al., 2022; Aluko et al., 2015). Such biostimulants are cost-effective and widely available, often sourced from agro-industrial waste (Makhaye et al., 2021; Brown et al., 2015).

9. SEAWEED EXTRACTS

Derived primarily from brown algae, seaweed extracts contain phytohormones, amino acids, and minerals that promote plant growth. Seaweed extracts have been shown to enhance photosynthesis, root elongation, and resistance to abiotic stress in soybeans. For instance, soybean plants treated with seaweed extracts demonstrate improved drought tolerance and higher yield, likely due to increased chlorophyll production and enhanced antioxidant activity.

Ascophyllum nodosum, native to the North Atlantic's harsh, tidal environments (Pereira et al., 2020), has developed survival strategies by accumulating a wide range of organic compounds such as amino acids, phytohormones, polyphenols, betaines, polysaccharides, fatty acids, steroids, polyamines, and essential nutrients (Craigie, 2011). When absorbed by plants, these compounds enhance stomatal control, increase CO_2 conductance, stimulate antioxidant enzyme production, and protect photosystems (Elansary et al., 2016; Goñi et al., 2016), ultimately improving water use efficiency and reducing water stress (Carvalho et al., 2018; Do Rosário Rosa et al., 2021; Frioni et al., 2021).

Sun et al. (2024) evaluated the hypothesis that a commercial biostimulant derived from Ascophyllum nodosum can enhance the physiological resilience and water efficiency of soybean (*Glycine max*) plants under water-deficit stress. Conducted in a controlled greenhouse environment, the experiment included five treatments: a control group, biostimulant application, water deficit (WD), WD combined with biostimulant, and WD with split biostimulant application. The experiment used a completely randomized block design with four replications per treatment, employing polyethylene pots containing 10 L of soil, each with three plants. Watering occurred daily, while water deficit conditions reduced soil moisture to 50% of field capacity from the beginning of flowering (R1 stage) for a duration of ten days. The biostimulant was applied at the onset of the water deficit. Results supported the hypothesis, indicating that a foliar application of 1.0 L ha^{-1} of the biostimulant mitigated the effects of water deficit on soybean plants. The biostimulant application significantly reduced oxidative stress (as shown by a 31.2% decrease in malondialdehyde synthesis in WD plants), preserved water potential and cellular stability (10.2% higher relative water content compared to WD plants), and maintained chlorophyll levels. Furthermore, the treatment enhanced photosynthetic activity, leading to a 68% increase in net photosynthesis and a 49.3% improvement in carboxylation efficiency relative to WD plants. However, when applied in a split dosage, the biostimulant did not show efficacy in reducing water stress effects.

In conclusion, A. nodosum-based biostimulants show potential to reduce water deficit damage in soybean crops, suggesting promising applications for this extract in large-scale agriculture.

The application of biostimulants to soybean seed treatment can have positive effects on crop performance, owing to the synergistic action of the organic compounds found in natural products. Given the limited research on biostimulants for soybean seed treatment, this study aimed to assess the impact of different biostimulant doses on agronomic traits, productivity components, and the profitability of soybean cultivation. Two field experiments were conducted during the 2016/17 and 2017/18 growing seasons, using a randomized block design with six replications and four treatment levels: 0.00, 0.05, 0.10, and 0.15 L per 100 kg of seeds. The study evaluated agronomic characteristics, grain yield, and the profitability of biostimulant use. Results showed that a dose of 0.15 L per 100 kg of seeds resulted in the highest profitability in both seasons. Additionally, doses above 0.12 L per 100 kg of seeds increased grain yield, grain mass, and other productivity components.

Drought negatively affects the growth, physiology, and yield of many plants, including soybean. Seaweed extracts, rich in bioactive compounds such as antioxidants, have the potential to act as biostimulants to enhance yield and mitigate the detrimental effects of drought stress. This study aimed to assess the impact of different concentrations (0.0%, 5.0%, and 10.0% v/v) of water extracts from the red seaweed Gracilaria tenuistipitata var. liui on soybean growth and yield under both well-watered (80% of field capacity (FC)) and drought (40% of FC) conditions. Drought stress reduced soybean grain yield by 45.58% compared to well-watered conditions, while increasing the water saturation deficit by 37.87%. Additionally, drought led to decreased leaf water content, chlorophyll levels, plant height, and the fresh weight of leaves, stems, and petioles. Foliar application of seaweed extracts significantly enhanced soybean growth and yield under both drought and well-watered conditions. A 10.0% seaweed extract treatment increased grain yield by 54.87% under drought conditions and by 23.97% under well-watered conditions compared to untreated plants. The results indicate that Gracilaria tenuistipitata var. liui seaweed extracts may serve as effective biostimulants to improve soybean yield and drought resilience. However, the specific mechanisms behind these benefits require further investigation under field conditions.

10. MICROBIAL INOCULANTS

Microbial inoculants, including beneficial bacteria and fungi, form symbiotic relationships with soybean roots to promote growth and nutrient uptake. Rhizobium and mycorrhizal fungi are among the most commonly used inoculants in soybean cultivation; Rhizobium bacteria fix atmospheric nitrogen essential for soybean growth, while mycorrhizal fungi enhance phosphorus uptake. These microbial treatments not only improve soybean growth but also reduce reliance on chemical fertilizers.

Rhizobia, a type of nitrogen-fixing bacteria, form nodules on legume roots, a process known as biological nitrogen fixation (BNF), which can supply between 50 to 300 kg of nitrogen per hectare to enrich soil nitrogen levels (Bokhtiar and Sakurai, 2005). BNF is considered more energy-efficient than conventional mineral nitrogen fixation (Dubey, 2012), making rhizobial inoculation an essential practice for increasing nitrogen availability to legumes like soybean and reducing the need for synthetic nitrogen fertilizers. In contrast, non-leguminous crops, such as cereals, rely more heavily on external nitrogen sources.

In addition to rhizobia, free-living nitrogen-fixing bacteria, such as Azotobacter and Azospirillum, along with phosphate-solubilizing bacteria like Bacillus and Pseudomonas, play essential roles in maintaining soil fertility and enhancing crop yields. Azospirillum inoculation in cereal crops has gained attention due to its beneficial relationship with grass roots (Dubey, 2012). Other beneficial bacteria, including Azotobacter, Herbaspirillum, and Acetobacter, are commonly found in crops like maize, wheat, rice, and sugarcane and offer significant agronomic benefits (Reinhold and Hurek, 1993; Sundaram et al., 1988). Bacillus species further support plant growth by enhancing nutrient uptake, while Trichoderma promotes root development, nutrient utilization, and stress tolerance. Certain Fusarium strains also contribute to plant health by suppressing soil-borne diseases, thereby improving soil health (Katan, 1971; Gordon et al., 1989; Larkin et al., 1993). Despite the proven benefits of rhizobial and mycorrhizal inoculants in boosting crop yields (Giller, 2001), there remains limited scientific evidence on the effectiveness of many biological and chemical products currently available to farmers for enhancing crop productivity (Laditi et al., 2012).

11. PLANT GROWTH-PROMOTING RHIZOBACTERIA (PGPR)

PGPRs, such as Bacillus and Pseudomonas species, are known for their ability to produce growth hormones like auxins and gibberellins, solubilize phosphate, and produce siderophores that help plants absorb iron. Research indicates that PGPR-treated soybean plants exhibit enhanced root growth, leading to improved nutrient uptake and greater yield under both normal and stressful conditions.

PGPB (Plant Growth-Promoting Bacteria) are found in the bulk soil or rhizosphere and can promote plant growth under certain conditions (Bashan and de Bashan, 2005). These bacteria belong to various genera and promote plant growth through different mechanisms. PGPB have been shown to positively affect plant growth in several ways, including controlling pathogens (Bashan and de Bashan, 2005).

12. OTHERS BIOSTIMULANTS

Biostimulants encompass a wide range of natural compounds and metabolites that significantly enhance plant growth and resilience. These include organic acids, amino acids, polyamines, and vitamins, which support cell division, root development, and nutrient uptake. Additionally, compounds such as humic and fulvic acids improve soil structure and water retention, further aiding plant growth. Secondary metabolites like phenolic compounds and flavonoids provide antioxidant protection, helping plants manage environmental stresses. Together, these biostimulants offer a sustainable approach to boosting crop yield and health by optimizing physiological and biochemical processes in plants.

Several studies have demonstrated the effectiveness of different biostimulants in improving crop growth and quality. For instance, Kocira (2019) explored the application of the Terra Sorb Complex biostimulant on soybean, observing significant improvements in yield and antioxidant properties under stress conditions. The study revealed that biostimulant applications led to a 25% increase in yield and enhanced phenolic and flavonoid content, with varying results depending on the application strategy and concentration. This highlights the versatility of biostimulants in enhancing both yield and quality, tailored to specific needs and conditions. Similarly, de Lima et al. (2024) investigated the potential of nicotinamide, a form of vitamin B3, as a biostimulant for soybean growth and yield. Their research demonstrated that foliar application of nicotinamide significantly improved vegetative growth and yield, with optimal concentrations leading to increases in pod count, grain number, and overall yield. This further supports the use of biostimulants as an effective tool for maximizing crop productivity across diverse environments.

In addition to these, Chalfoun, N.R. (2018) examined PSP1, a biostimulant based on the fungal protease AsES, which enhances disease protection in soybean crops. The field trials showed that PSP1, when combined with other agricultural inputs, successfully reduced disease development caused by fungi and significantly increased yields. This suggests that biostimulants like PSP1 can not only improve growth but also provide protection against pathogens, offering a more sustainable approach to crop management.

Together, these studies demonstrate the broad range of biostimulants available, each offering unique benefits to crop growth, yield, and resilience. Whether enhancing nutrient uptake, improving disease resistance, or boosting antioxidant levels, biostimulants provide valuable solutions for improving agricultural productivity in the face of environmental challenges.

13. CONCLUSION

Climate change has intensified environmental stress on crops, contributing to a rise in plant diseases and creating an urgent need to find sustainable, eco-friendly alternatives for improving crop yield and food quality. One promising solution lies in the use of biostimulants, which have been shown to enhance soybean yield, resilience, and soil health. Their ability to improve nutrient efficiency, stress tolerance, and crop productivity makes them valuable tools for sustainable agriculture. While challenges related to standardization and regulatory approval remain, the growing body of research points to the significant potential of biostimulants in modern soybean farming. Future advancements in biostimulant formulation and application will be critical for achieving consistent, scalable benefits in soybean production.

At the same time, there is an increasing focus on reducing dependency on chemical fertilizers and pesticides. A key strategy involves harnessing beneficial plant–microbe interactions to restore plant ecosystems, improve crop productivity, and boost stress tolerance. The positive effects of microbial consortia and plant biostimulants (PBs) in mitigating the adverse impacts of environmental stresses on crop growth and yield are well-documented. Studies indicate that a healthy crop microbiome, combined with the strategic application of PBs, can restore soil health and productivity, particularly in low-nutrient conditions, thereby supporting more sustainable food production systems. This integrated approach highlights the role of biostimulants in addressing the challenges posed by climate change and advancing the sustainability of agriculture.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that generative AI such as ChatGPT-4 (developed by OpenAI) have been used for text correction and refinement. The tool was utilized to improve the clarity, grammar, and coherence of this manuscript.

COMPETING INTERESTS

The authors of this manuscript declare that they have no financial or non-financial conflicts of interest that could influence their research or the interpretation of their results.

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