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Overview of biostimulants in horticultural products under abiotic stress: A review

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Review Article

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ABSTRACT

Global agriculture will face two major challenges in the future: population growth and climate change. One of the primary obstacles to agricultural productivity is environmental stress, with abiotic factors having a considerable negative effect on horticultural yields. As such, exploring effective strategies to mitigate plant stress is essential. Among these strategies, the use of biostimulants has emerged as an innovative and eco-friendly approach to boost growth and productivity in horticultural crops under stress conditions. Biostimulants, including seaweeds, fungi, bacteria, and amino acids, play a key role in alleviating stress effects. Their effectiveness is largely attributed to bioactive compounds such as polysaccharides, pigments, phenolics, proteins, phytohormones, and various micro- and macronutrients. Research indicates that these compounds can significantly reduce plant stress and enhance resilience. The effective use of bio-stimulants can reduce waste from fertilizers and minimize the risk of nutrient runoff that leads to environmental pollution. Economically, it enhances nutrient uptake, plant growth, and productivity under stress conditions, reduces input costs, and increases farmers' profitability. Therefore, the use of these compounds in greenhouse systems is not only environmentally significant but also economically important. This study delves into the application of biostimulants in horticulture under abiotic stress and highlights some of the key challenges associated with their broader adoption and implementation.

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1. Introduction

Plants face a wide range of stresses throughout their life cycle, from seed germination to the end of their lifespan, which can generally be categorized into two main types: biotic and abiotic stresses (Bulgari *et al*., 2019; Zuzunaga-Rosas *et al*., 2024). Biological and abiotic stresses significantly impact plant growth and yield by disrupting physiological processes and inducing various adaptive responses (Bhatla and Lal., 2023; Rahim *et al*., 2024). Biotic stresses include viruses, bacteria, fungi, insects, and pests, which cause tissue damage and reduce nutrient availability (Rahim *et al*., 2024), while abiotic stress encompasses factors like extreme temperatures, drought, salinity, light, nutrient deficiencies, and soil contamination with heavy metals, imposed on plants by the environment (ul Haq, 2019; Kulkova *et al*., 2024). Additionally, very low or very high light levels disrupt photosynthesis and stomatal function, causing harm to plants (Souf *et al*., 2024). Abiotic stresses are among the primary reasons for reduced yields of agricultural and horticultural products worldwide and cause significant economic losses (Kiranmai *et al*., 2018; Wróbel *et al*., 2023). Depending on geographical location and crop type, these stresses can reduce plant performance by 50 to 80% (Zhang *et al*., 2018; García-García *et al*., 2020). These stresses in plants can lead to a reduction in germination percentage, germination rate, decreased seed vigor, and a decline in growth indices such as hypocotyl and radicle length in *Salvia officinalis* (sage) under drought stress (Rezaei *et al*., 2024_a). Furthermore, stomatal disturbances, reduced photosynthesis, altered protein synthesis patterns, decreased enzyme activity, and reduced yield and essential oil percentage may also occur (Soroori *et al*., 2021; Khaleghi, 2024). Additionally, the loss of water from plant tissues and cells can lead to a decline in the plant's visual quality. Furthermore, a deficiency in nutrient uptake and stomatal closure, which limits access to carbon dioxide, ultimately reduces the plant's photosynthetic process (Dalvand *et al*., 2018; Sharafi, 2024).

On the other hand, while the use of chemical fertilizers has had positive initial effects, it has also led to environmental challenges and reduced effectiveness over time, harming plant health. Therefore, this method can no longer be considered a suitable approach for increasing productivity and food production under stress conditions (Wazeer *et al*., 2024). Consequently, sustainable and environmentally friendly approaches, such as the use of biostimulants, are gaining increasing importance (Kulkova *et al*., 2024). In recent years, biostimulants have attracted widespread attention due to their ability to improve productivity and quality of agricultural products. Additionally, these compounds have been able to simultaneously meet the needs for economic production and sustainable development (Del Buono *et al*., 2021). Thus, the aim of this research is to evaluate the impact of biostimulants on abiotic factors and their role in the productivity, quality, and performance of horticultural products.

2. Biostimulants

One of the key components of sustainable agricultural systems is the use of biostimulants, which help mitigate the negative effects of environmental stresses and significantly reduce reliance on chemical inputs (Solgi *et al*., 2025). Biostimulants enhance growth and development processes through various mechanisms, from seed germination to plant maturation and growth. This enhancement includes increased metabolism, biomass production, yield improvement, and enhanced root growth. Quality of products and role of biostimulants enhance product quality by facilitating the absorption and transfer of nutrients, strengthening plant defenses against adverse conditions, and improving quality traits such as metabolite concentration, sugar content, and fruit color (Pérez *et al*., 2021; Liatile *et al*., 2022; Senousy *et al*., 2023; Zuzunaga-Rosas *et al*., 2024; Kaya, 2025). They are recognized as effective and promising solutions for mitigating the impacts of environmental stresses. These compounds can significantly increase plant resistance to various abiotic stresses (Bhupenchandra *et al*., 2022). Abiotic stresses, including drought (Dos Santos *et al*., 2022), salinity (Balasubramaniam *et al*., 2023), extreme temperatures (Giordano *et al*., 2021), and nutrient deficiencies (Abbas *et al*., 2021), induce detrimental alterations at morphological, physiological, biochemical, and molecular levels, significantly limiting plant growth and productivity. Biostimulants assist crop plants in countering these stress-induced damages (Figure 1), restoring plant performance, and enhancing resilience to environmental stressors (Di Sario *et al*., 2025).

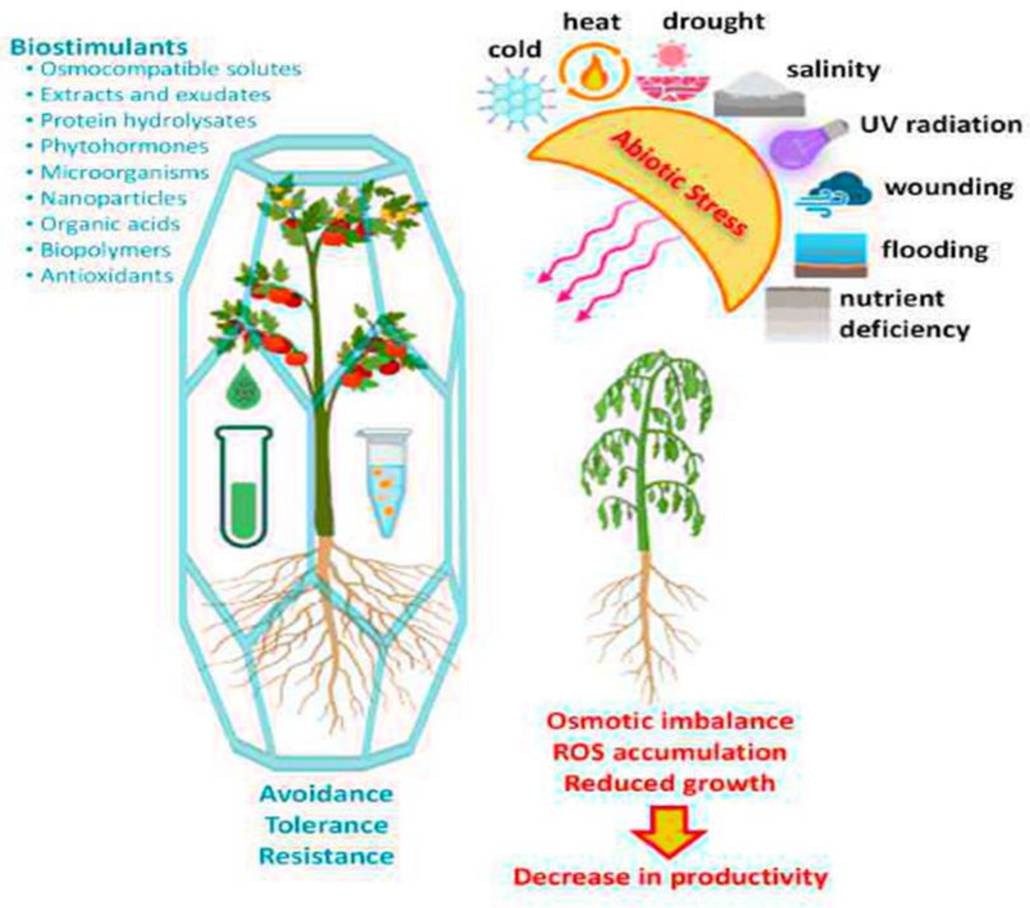

Figure 1 Enhancing Agricultural Productivity and Mitigating the Negative Impacts of Abiotic Stresses through the Application of Biostimulants (Di Sario *et al*., 2025).

Moreover, biostimulants serve as effective, sustainable, and environmentally friendly supplements for horticultural products. By reducing reliance on chemical fertilizers (Dubey and Misra, 2024; Yakob *et al*., 2024), they enhance plant metabolism and improve crop performance. These substances protect plants against stresses such as drought, salinity, and unfavorable temperatures, leading to increased nutrient absorption. Additionally, by enhancing enzymatic and microbial activity in the soil, improving root structure, and increasing micronutrient solubility, they promote soil fertility (Petropoulos *et al*., 2020; Shahrajabian *et al*., 2021; Sun *et al*., 2023). Biostimulants influence hormonal pathways, particularly abscisic acid, playing a crucial role in regulating stomatal closure and reducing water loss during drought and heat stress (Ali *et al*., 2024).

They also enhance the antioxidant system, eliminating reactive oxygen species and reducing oxidative damage caused by stress (Lau *et al*., 2025). Biostimulants are broadly classified into two categories: non-microbial and microbial. Non-microbial biostimulants include plant extracts, seaweed extracts, humic substances, and protein hydrolysates. Examples of microbial biostimulants include *Trichoderma* fungi, mycorrhizal fungi, non-mycorrhizal fungi, and plant growth-promoting rhizobacteria (PGPR) (Gedeon *et al*., 2022; Ali *et al*., 2024). A classification scheme of these biostimulants in agriculture is presented in Figure 2.

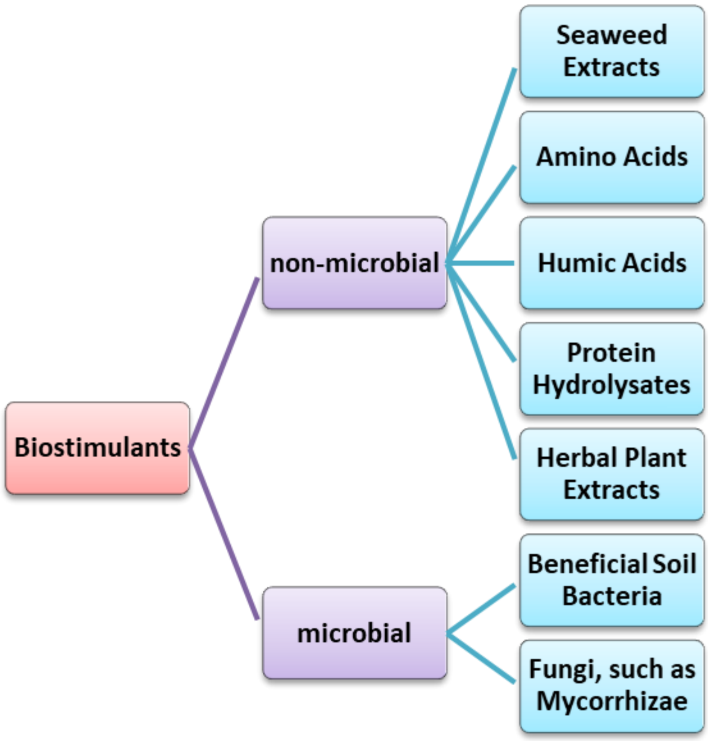

Figure 2 Types of Biostimulants. (Author's source)

2.1. Seed Priming

Seed germination is a complex and sensitive physiological process that initiates seedling growth. Successful seed germination is considered one of the effective economic and environmental strategies for protecting plants (Rezaei *et al*., 2024$_b$). However, achieving this is influenced by various ecological factors and stresses (Muhie *et al*., 2021). Seed priming is one of the simplest and most effective methods for enhancing seed germination, recognized as a cost-effective strategy for increasing resistance to abiotic stresses (Bayanati *et al*., 2023; Sorrentino *et al*., 2021). This technique involves using various chemical substances, but widespread use may lead to environmental challenges (Demir *et al*., 2018). To overcome these challenges, seed priming technology has been developed using biostimulants to improve seed quality and increase uniformity and speed of germination (Muhie *et al*., 2020; Rajput *et al*., 2021). In this method, various biostimulants such as fungi (Cardarelli *et al*., 2022), bacteria, seaweed extracts (Radwan *et al*., 2023), protein hydrolysates (Sorrentino *et al*., 2021) and herbal plant extracts (Zulfiqar *et al*., 2020) are utilized as innovative approaches to enhance germination, seedling growth, and increase plant tolerance to stresses (Wazeer *et al*., 2024). Seed priming with seaweed extract has shown very favorable results regarding seed germination and seedling characteristics under drought, salinity, and high-temperature stresses (Muhie *et al*., 2021). Seed priming with *Pseudomonas fluorescens* and *Trichoderma harzianum* has reduced the negative effects of drought stress and improved growth parameters and yield in *Cuminum cyminum* (Piri *et al*., 2019). Moringa leaf extracts (*Moringa oleifera*) enhance the germination and growth of bell pepper seeds (*Capsicum annuum*) under heavy metal and salinity stress (Desoky *et al*., 2019). Allochemicals from garlic also improve seed germination and salinity stress tolerance in tomatoes (Pérez *et al*., 2021). Seed priming with seaweed extract resulted in increased leaf flavonoid content, antioxidant activities, osmolyte accumulation, photosynthetic pigment content, and salinity tolerance in mature lettuce plants (Nezamdoost *et al*., 2023).

2.2. Seaweed Extracts

Abiotic stresses such as drought and salinity are major factors contributing to reduced agricultural productivity and soil degradation worldwide. Research indicates that biostimulants like seaweed (SWE) can be effective solutions (Deolu-Ajayi *et al*., 2022). In many countries, seaweed is used as a soil conditioner and fertilizer in agriculture. Unlike chemical fertilizers, seaweed extracts are biodegradable, non-toxic, and safe for humans and animals. This method is considered environmentally friendly and safe for soil and plants, while also increasing the economic value of seaweed (Yusuf *et al*., 2021). These extracts are important resources that contain bioactive compounds such as polysaccharides, amino acids, polyphenols, phytohormones, sterols, carbohydrates, sugars, macro- and micronutrients, vitamins, lipids, peptides, and proteins (Deolu-Ajayi *et al*., 2022). They enhance nutrient absorption, improve photosynthesis processes, increase osmoprotective production, and promote growth under stress conditions such as salinity and drought (Raja and Vidya, 2023; Sales *et al*., 2024). Additionally, compounds in seaweed extracts may act as signaling molecules, activating signaling pathways and genes/enzymes related to plant defense (Figure 3), resulting in differential expression of essential genes in crops that contribute to increased plant growth and resistance to abiotic stresses (Raja and Vidya, 2023; Mukherjee and Patel, 2020). This method offers a novel and potential strategy for protecting plants against conditions caused by abiotic stresses (Hariharan *et al*., 2024). For example, the extract of *Ascophyllum nodosum* has been shown to reduce salinity stress in tropical ornamental species like *Celosia argentea* and *Catharanthus roseus* by improving biomass production and leaf gas exchange (Sales *et al*., 2024). Seaweed extract has positively impacted the reduction of drought stress effects. Tomatoes treated with this extract under water stress conditions exhibited significantly higher values in stomatal conductance, chlorophyll content, antioxidant enzyme activity, osmolyte content, plant height, and overall yield compared to control plants (Ali *et al*., 2024). Seaweed extract improved the visual quality and flowering of *Hydrangea paniculata* under drought stress (De Clercq *et al*., 2023).

2.3. Amino Acids

The application of amino acids under stress conditions in plants increases stress tolerance and improves growth and physiological performance. When applied externally, amino acids can mitigate the adverse effects of various abiotic stresses such as temperature fluctuations, salinity, and drought. They achieve this by enhancing antioxidant defense systems, improving osmolyte accumulation, and regulating stress response gene expression (Trovato *et al*., 2021).

Amino acids play roles in stress reduction, enhancing photosynthesis, nutrient absorption, pollination, fruit formation, and hormone and growth factor production. As building blocks of proteins, they stimulate cell growth and are crucial for the growth, development, and synthesis of plant metabolites (Shahrajabian *et al*., 2022). The use of amino acids and Ascophyllum nodosum increased drought tolerance in broccoli with specific responses (Kałużewicz *et al*., 2017). In spinach, amino acids improved salt tolerance by increasing antioxidant activity, osmolyte accumulation, and nutrient balance, leading to enhanced plant performance (Saddique *et al*., 2022).

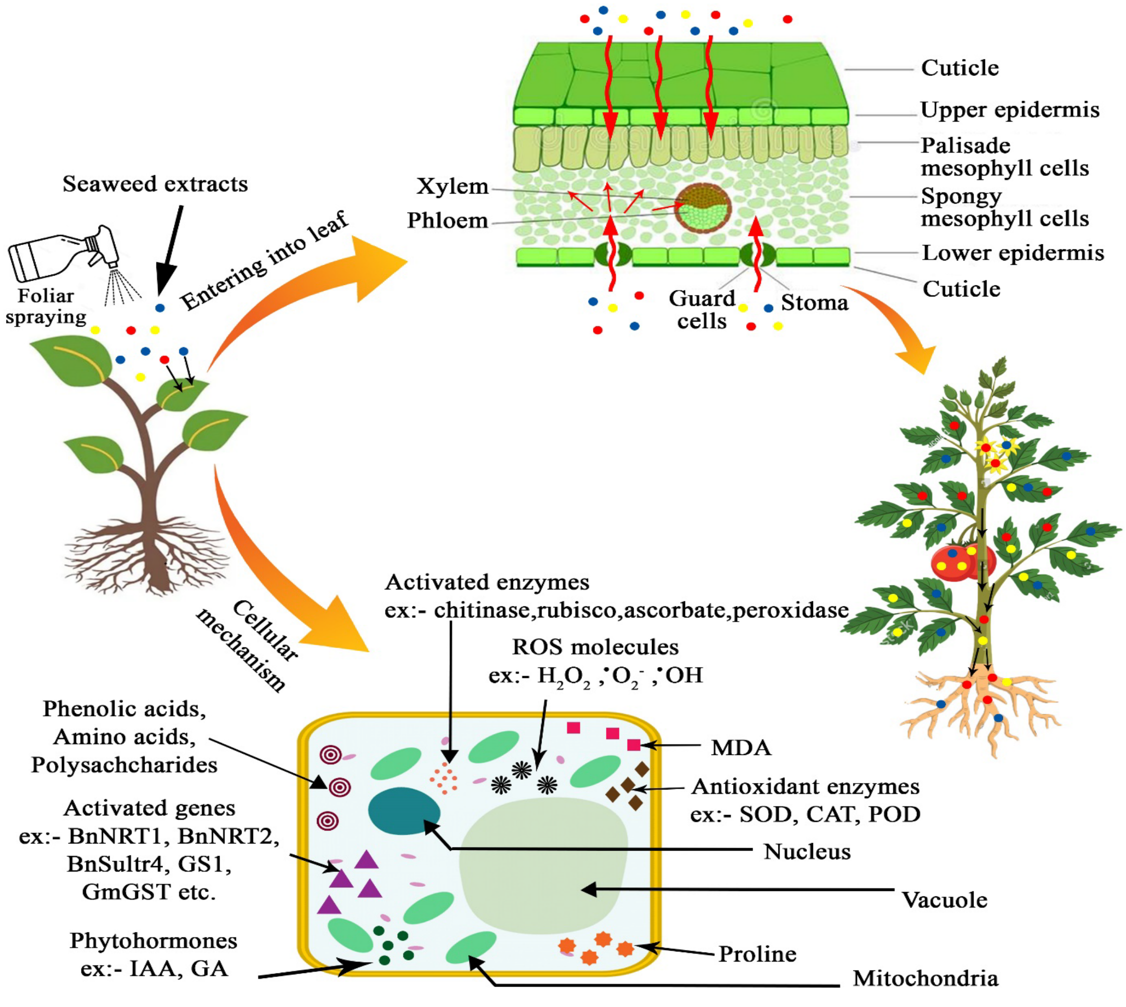

Figure 3 Importance of Seaweed Extracts in Reducing Abiotic Stresses at the Cellular Level in Plants. (IAA; Indole-3-Acetic Acid, GA; Gibberellic Acid, ROS; Reactive Oxygen Species, MDA; Malondialdehyde, SOD; Superoxide Dismutase, CAT; Catalase, POD; Peroxidase) (Hariharan *et al*., 2024).

When amino acids are used through foliar spraying, they enhance photosynthetic activity and essential oil production, increasing the resilience of medicinal plants to salinity and drought. Specific amino acids like L-phenylalanine and arginine have been shown to improve morphological traits and performance in plants like Salvia officinalis (Ismail *et al*., 2024). The study of the effects of exogenous amino acids on metabolic processes indicates their potential role in increasing lettuce plants' tolerance to salinity stress (Abdelkader *et al*., 2023).

2.4. Humic Acids

Humic acid, derived from organic materials, enhances plants' access to essential elements by increasing cation exchange capacity and facilitating the active uptake of nutrients. This compound not only improves soil fertility but also promotes root growth and development (Roosta *et al*., 2017; Kazemi *et al*., 2024). The use of humic acid (HA) under stress conditions enhances plant growth and resilience by reducing abiotic stresses. As a biostimulant, it improves plant tolerance to drought, alkalinity, and salinity by modulating physiological and biochemical processes through increased antioxidant enzyme activity, osmotic regulation, and nutrient balance (Mordai *et al*., 2024). Various methods are employed to improve plant performance and soil quality, one of which is the use of humic substances. These organic materials enhance the chemical and biological properties of soil and the root environment (Aytaç *et al*., 2022). These compounds increase root growth, chlorophyll content, and stimulate stress-related enzyme production. They have been shown to improve visual quality and growth of ornamental plants under drought and salinity stress (Franzoni *et al*., 2022; Ma *et al*., 2022). The combined application of humic acid and Bacillus bacteria significantly enhances biomass and chlorophyll fluorescence in tomato plants under heat stress. This combination also increases the activity of antioxidant enzymes: Ascorbate Peroxidase (APX), Superoxide Dismutase (SOD), and Reduced Glutathione (GSH) (Khan *et al*., 2020). For rose plants under alkaline stress, the use of humic acid increased total protein activity, proline, catalase, and guaiacol peroxidase, enhancing antioxidant capacity. This treatment led to a reduction in malondialdehyde and electrolyte leakage, indicating decreased cellular damage and improved stress tolerance (Mordai *et al*., 2024). In tomato plants, the application of humic acid under drought stress improved branch and root biomass, chlorophyll content, and relative water content. It also increased catalase (CAT) activity and reduced glutathione reductase (GR) activity, which are vital for stress resistance (Aytaç *et al*., 2024).

2.5. Protein Hydrolysates

Protein hydrolysates, derived from plant or animal sources, are rich in amino acids and peptides and are recognized as one of the most effective types of biostimulants that stimulate plant metabolism (Kałużewicz *et al*., 2017; Liatile *et al*., 2022; Shahrajabian *et al*., 2022; Zuluaga *et al*., 2023). These compounds act as signaling molecules and have a remarkable ability to enhance crop performance, especially under environmental stress conditions. They also improve nutrient absorption and increase antioxidant production, mitigating stress effects. Studies have shown that protein hydrolysates can increase flower number and biomass in ornamental plants under saline conditions by improving ion homeostasis, reducing sodium uptake, and increasing osmoprotectants like proline (Van Oosten *et al*., 2017; Abdou *et al*., 2021). A biostimulant containing protein hydrolysates and seaweed extract improved the drought tolerance of spinach by increasing chlorophyll content and antioxidant enzyme activity (Liatile *et al*., 2022). Extreme temperatures, whether high or low, can harm ornamental plants by disrupting cellular processes and membrane stability. Protein hydrolysates improve temperature stress tolerance by enhancing membrane stability, increasing antioxidant production, and modulating hormonal balance. For example, protein hydrolysates have been shown to enhance growth and flowering in ornamental plants under heat stress (Van Oosten *et al*., 2017; Ma *et al*., 2022). Protein hydrolysates improved the salt-stressed lettuce more than tomatoes, highlighting species-specific efficiency (Zuluaga *et al*., 2023). Biostimulants containing hydrolyzed protein in nutrient solutions showed improvements in volatile content, primary metabolism, and basil performance under salinity stress (Zamljen *et al*., 2023).

2.6. Plant Extracts

Natural biostimulants derived from plants play a significant role in sustainable horticultural production systems and have attracted global attention. These substances not only enhance the growth, yield, and quality of horticultural products but also improve the ability of plants to cope with abiotic stresses (Zulfiqar *et al*., 2020). Plant antioxidants, especially extracts, contain a diverse range of bioactive compounds, including cytokinins, flavonoids, carotenoids, and phenolics. These compounds significantly influence various physiological and metabolic processes by regulating endogenous plant hormones and increasing carbohydrate accumulation. As a result, they enhance plant growth and productivity even under stress conditions.

Additionally, by directly affecting the biosynthesis pathways of terpenoids, they contribute to increased production of essential oils (Elsayed *et al*., 2023; Solgi *et al*., 2025). Foliar application of moringa oil has been shown to increase plant height, fruit number, improve biochemical characteristics of fruit, and enhance overall performance in eggplants grown under stress conditions (Haggag *et al*., 2024). Simultaneous use of moringa and licorice extracts has improved the fruit yield of bell peppers and reduced contamination in saline soils containing heavy metals (Desoky *et al*., 2019). The combined use of heavy metal-resistant bacteria and moringa extracts improves spinach yield while reducing pollutant levels in heavy metal-contaminated soils (Eltahawy *et al*., 2022).

2.7. Bacteria

Microbial biostimulants enhance nutrient availability through solubilization and promote better plant nutrition under stress (Ali *et al*., 2024). Microbial biostimulants enhance drought tolerance by improving water use efficiency, increasing root depth, and stimulating antioxidant production. For example, microbial biostimulants have been shown to improve growth and flowering of Petunia × hybrida under water stress (Sangiorgio *et al*., 2020; Nordstedt and Jones, 2020). Plant growth-promoting rhizobacteria (PGPR) colonize the rhizosphere and enhance plant growth by producing plant hormones, solubilizing minerals, and suppressing pathogens. For instance, PGPR strains like Pseudomonas spp. have been shown to increase flower number and biomass in ornamental plants under drought and nutrient-deficient conditions (Lin and Jones, 2022; Nordstedt *et al*., 2020). Seaweed extract and microbial biostimulants improved tomato performance under salinity stress (Ntanasi *et al*., 2024).

2.8. Fungi

Arbuscular mycorrhizal fungi are among the most important biostimulants that play a key role in enhancing product quality and performance in sustainable agriculture. These beneficial soil microorganisms form symbiotic relationships with the roots of many plants and significantly improve plant performance. They enhance plant growth by optimizing nutrient and water absorption, producing plant growth regulators, increasing resistance to pathogens, and reducing the negative effects of environmental stresses (Ali *et al*., 2018; Sun *et al*., 2023). The application of mycorrhizal fungi has reduced drought effects in strawberries (Moradtalab *et al*., 2019), increased lettuce tolerance under high temperatures (Yan *et al*., 2021), and prevented salinity damage in carrots (Yadav *et al*., 2021).

Mycorrhizal fungi showed greater effects on the physiological and biochemical traits of tarragon under drought stress. These fungi helped increase tarragon's tolerance to drought and played a positive role in more effective scavenging of free radicals produced under stress conditions (Mansori *et al*., 2024). The application of Glomus mosseae fungi and the growth-promoting bacteria Azospirillum brasilense mitigated the negative effects of drought stress on lemon balm plants (Eshaghi Gorji *et al*., 2023). The use of mycorrhizal fungi is an effective strategy for reducing cold stress in eggplants. AMF effectively reduced cold stress in this plant by improving photochemical responses, activating antioxidant defense systems, accumulating protective molecules, and reducing membrane damage (Pasbani *et al*., 2020). A study found that the symbiosis of mycorrhizal fungi could play an important role in enhancing cold resistance in watermelon seedlings by restoring photosynthetic efficiency and reducing cold-induced oxidative stress (Shirani *et al*., 2020).

3. Practical Applications

Soil application and foliar spraying of biostimulants, including seaweed extracts, amino acids, humic acids, protein hydrolysates, plant extracts, fungi, and bacteria, can enhance the performance of horticultural crops and mitigate the negative impacts of environmental stresses (Table 1). By influencing plant physiological processes, these biostimulants improve:

- **Nutrient Uptake Enhancement:** Biostimulants improve nutrient uptake, thereby increasing plant growth and development.
- **Photosynthetic Performance Improvement:** By facilitating photosynthetic processes, biostimulants increase crop production.
- **Root Development and Germination Enhancement:** These compounds strengthen the root system, facilitating access to water and nutrients.
- **Antioxidant Defense:** They enhance antioxidant enzyme activity, protecting plants from oxidative damage caused by stress conditions.
- **Abiotic Stress Reduction:** These compounds can increase plant resistance to pests and diseases.
- **Product Quality Improvement:** Enhanced appearance, aroma, and flavor of agricultural products are additional benefits of biostimulant application.

Given these advantages, the use of biostimulants can represent a sustainable and environmentally friendly supplement in horticultural production, serving as an effective strategy for reducing reliance on chemical fertilizers, improving productivity, and alleviating damage from environmental stresses.

Table 1 Comparison of biostimulants and their effects on horticultural products

Type of Biostimulant	Plant	Stress	Effects	Reference
Moringa and Licorice Extract	*Capsicum annuum*	heavy metals-contaminated saline soil	Increased plant growth and yield, elevated leaf photosynthetic pigments, free proline, total soluble sugars, N, P, and K^+, and the upregulation of CAT, POX, APX, SOD, and GR activities, Decreased Na^+, Cd, Cu, Pb and Ni content in plant leaves and fruits	Desoky *et al*., 2019
Seed Priming with Fungi	*Cuminum cyminum*	Drought	Increased soluble protein content and antioxidant enzyme activities of CAT and APX, Improve germination speed	Piri *et al*., 2019
Seaweed Extract	*Hydrangea paniculata*	Drought	Improved flowering	De Clercq *et al*., 2023
Humic Acid	*Solanum lycopersicum*	Heat	Increased antioxidant enzyme activity, Increase chlorophyll fluorescence	Khan *et al*., 2020
***Pseudomonas spp* Bacteria**	Ornamental Plants	Drought	Increased flower number	Lin and Jones, 2022; Nordstedt *et al*., 2020
Amino Acids	*Lactuca sativa*	Salinity	Increased leaf number, leaf and root dry biomass and total leaf area of the plant	Hancı and Tuncer 2020
Protein Hydrolysates	*Ocimum basilicum*	Salinity	Improved primary metabolism	Zamljen *et al*., 2023
Mycorrhizal Fungi	*Artemisia dracunculus*	Drought	Decreased leaf malondialdehyde (MDA) concentration, reduced hydrogen peroxide (H_2O_2) levels, increased leaf phosphorus (P) and potassium (K^+) content, and enhanced antioxidant system activity	Mansori *et al*., 2024

Conclusion

In the near future, the agricultural sector will face two fundamental and complex challenges that profoundly impact the industry's sustainability and efficiency. The first challenge is the continuous and relentless population growth, which significantly increases the demand for food resources. The second challenge is the widespread effects of climate change, leading to temperature fluctuations, irregular rainfall distribution, and severe floods and droughts. Low agricultural productivity is often attributed to environmental stress. The application of biostimulants in horticultural crops helps increase yield, accelerate growth, and improve resistance to biotic and abiotic stresses. Biostimulant formulations typically include substances such as humic acids, protein hydrolysate products, amino acids, seaweed extracts, and beneficial soil microorganisms, including mycorrhizal fungi and plant growth-promoting bacteria. One of the crucial inputs in organic agriculture is the utilization of seaweed extract, which can be a suitable alternative to chemical fertilizers. Seaweeds contain a combination of minerals like potassium and organic substances such as amino acids. These elements play an effective role in enhancing plant resistance to environmental stresses. Humic acid plays a significant role in managing water stress by strengthening plants' antioxidant capacity and reducing damage from water deficiency. It enhances plants' ability to cope with water-scarce conditions by stimulating root growth, improving water use efficiency, and promoting the activity of antioxidant enzymes. Plant growth-promoting rhizobacteria improve plant growth under stress conditions by activating specific metabolic pathways such as nitrogen, phosphorus, sulfur, magnesium, calcium, and other nutrient metabolisms. Additionally, plant symbiosis with mycorrhizal fungi enhances water and nutrient uptake, promoting plant growth in stressful environments. Therefore, this review directly demonstrates that the use of biostimulants under abiotic stress conditions, from germination to crop performance, can be a promising approach to improving food security, enhancing sustainability, and increasing agricultural productivity within the framework of a circular economy. Furthermore, the application of biostimulants in organic agriculture worldwide could be significant, assisting the scientific community in introducing these natural compounds as alternatives to synthetic chemicals, with considerable application in specialized areas of horticulture. Numerous benefits can be attributed to the use of these nature-based solutions, including:

1. Increased seed vigor and germination under abiotic stress conditions
2. Improved plant resilience by modulating physiological and biochemical processes
3. Enhanced growth and better yield performance of horticultural crops
4. Reduced use of synthetic chemical inputs
5. Increased soil health by enhancing microbial activity and soil fertility
6. Economic benefits in terms of cost savings

Challenges and Perspectives

Biostimulants have emerged as a promising strategy for enhancing plant resilience against abiotic stresses. However, several challenges persist, hindering their widespread adoption. These include the standardization of application rates due to the diverse composition of biostimulant products, inconsistent field performance, and regulatory hurdles for approval and utilization in different regions. Addressing these issues is crucial for the broader acceptance of biostimulants in sustainable agriculture. Further research is essential to elucidate the underlying molecular and physiological mechanisms associated with biostimulant activity. Additionally, educating and informing farmers and agricultural professionals about the benefits and proper application methods of these products is paramount. Continued research and development of optimized biostimulant formulations and investigation of their synergistic effects are vital for enhancing efficacy in diverse agricultural systems. A focus on utilizing environmentally compatible biostimulants can contribute to mitigating the problems associated with synthetic fertilizer use and promote sustainable agricultural practices.

Conflicts of Interest

The authors declare no conflicts of interest.

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