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Biostimulants as a Sustainable Strategy for Enhancing Vegetable Production: A Literature Review

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Abstract

Plant biostimulants have emerged as promising tools to enhance plant resilience against a wide range of abiotic and biotic stresses while simultaneously improving growth, yield, and product quality. This review critically evaluates the effects of various types of biostimulants including humic substances, protein hydrolysates, seaweed extracts, microbial inoculants, and silicon compounds on leafy vegetables cultivated under temperate and subtropical conditions. Amino acid–based biostimulants have demonstrated significant physiological and biochemical benefits, particularly in radish. Application of aspartic acid notably enhanced phenolic contents in the shoot (by 1.01%) and root (by 12.23%) compared with chemical fertilizer treatments. Total protein content increased in the shoot with glycine (by 251.81%) and in the root with aspartic acid (by 57.06%). Shoot ascorbic acid levels were markedly improved by aspartic acid (179.90%), vitamin B complex (159.91%), and lysine (139.92%). Similarly, plant fresh and dry weights increased substantially with vitamin B complex (478.31%) and aspartic acid (364.73%). Nitrogen and phosphorus concentrations in radish roots were higher with vitamin B complex (25.93%) and lysine (100%) treatments. Moreover, soil organic matter content improved with aspartic acid (61.51%), followed by vitamin B complex (60.13%). Emphasis is placed on the mechanisms of action, optimal timing of application, and crop-specific responses of biostimulants under stress conditions such as salinity, drought, heat, cold, and nutrient deficiency. Comparative insights are also provided regarding their roles in enhancing photosynthesis, nutrient uptake, biomass accumulation, and postharvest quality. Furthermore, this review highlights commercially available biostimulant formulations currently used in horticulture and summarizes recent findings through tabulated data. Overall, evidence suggests that biostimulants, when properly integrated with crop type and climatic conditions, represent a sustainable and effective strategy to mitigate environmental stresses and enhance the productivity, nutritional value, and overall quality of leafy vegetable production systems.

Keywords: Abiotic stress, Biostimulants, Nutrient uptake, Sustainable agriculture, Vegetables

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INTRODUCTION

Vegetables are an essential component of a healthy diet and play a critical role in food and nutritional security (Ebert, 2020). However, vegetable production is highly sensitive to bioenvironmental stresses such as drought, salinity, extreme temperatures, and nutrient imbalances, all of which adversely affect plant growth and yield (Solankey et al., 2021). Climate change has exacerbated these challenges, placing additional pressure on agricultural systems. Recent studies have shown that biostimulant priming treatments can increase tolerance to drought, salinity, and temperature stress. For instance, solid matrix priming of carrot seeds with seaweed extract, alone or in combination with karrikinolide, improved germination and seedling characteristics, suggesting the importance of identifying crop-specific biostimulant priming strategies (Muhie, 2021).Conventional agricultural practices, which often rely heavily on chemical inputs, have contributed to environmental degradation and a decline in soil health.

In this context, plant biostimulants have emerged as a promising approach to enhancing the resilience, productivity, and sustainability of vegetable crops. Biostimulants are substances or microorganisms that improve plant growth and development by enhancing nutrient uptake, stress tolerance, and overall plant vigor (De Vasconcelos et al., 2021). Plant bioactive compounds can vary significantly depending on harvest timing and plant parts. For example, studies have reported that essential oil, phenolic, and flavonoid contents are often higher in the upper regions of plants, with variations across successive harvests, highlighting the importance of optimizing harvest timing and plant parts to maximize bioactive yields (Tan&Gören, 2024)Unlike fertilizers, they do not directly supply nutrients but instead stimulate the plant's physiological processes to achieve improved performance. Biostimulants, which may be of natural or synthetic origin, can be applied to seeds, plants, or soil to enhance plant vitality and productivity. Although applied in small quantities, they can trigger significant physiological and biochemical responses. These include improved tolerance to abiotic stresses, enhanced nutrient assimilation, and increased yield and quality, making biostimulants a valuable tool in sustainable crop management (Du Jardin, 2015). Functioning independently of their nutrient content, biostimulants exert their effects through complex biological mechanisms. When applied exogenously, they may act similarly to plant hormones such as cytokinin's, auxins, and gibberellins—though they do not mimic or replace these hormones in structure or function (Yaronskaya et al., 2016).

Non-microbial biostimulants are typically derived from various organic matrices using extraction techniques that concentrate bioactive substances. These bioactives support plant growth or enhance resistance to unfavorable environmental conditions (Ben et al., 2021; Michalak et al., 2015). Due to the complex and often undefined composition of raw materials, it is challenging to pinpoint the exact compounds responsible for bio stimulant activity. Nonetheless, non-nutritional minerals (e.g., silicon and selenium), vitamins, amino acids, chitin, chitosan, polysaccharides, oligosaccharides, and trace amounts of phytohormones have all been identified as potential contributors (Du Jardin, 2015; Xu et al., 2018). It is important to emphasize that the effectiveness of biostimulants must not depend solely on the presence of essential nutrients or phytohormones. The most well-known constituents include minerals, vitamins, amino acids, poly- and oligosaccharides, and minimal amounts of naturally occurring hormones. However, bio stimulant activity arises from their unique capacity to activate physiological responses rather than providing nutrients per se. The exact mechanisms of many biostimulants remain under investigation, often involving complex interactions at molecular, cellular, and whole-plant levels (Paul et al., 2019).

Despite the ongoing need for mechanistic clarity, the bio stimulant sector has gained momentum, attracting attention from both researchers and the agro-industry (Boukharit et al., 2020). Their growing application in agriculture reflects their potential to support sustainable vegetable production, particularly in the face of climate change and soil degradation. Moreover, biostimulants derived from agricultural or industrial by-products align with circular economy principles, offering economic and environmental benefits to producers, food processors, and consumers alike (Xu et al., 2018). The remarkable growth of the bio stimulant market is driven by several key factors, including the development of innovative products tailored to specific agronomic challenges, the increasing need to reduce chemical inputs and optimize fertilizer efficiency, and the heightened occurrence of environmental stresses that threaten crop yield and stability (Colla et al., 2014).

This chapter provides an in-depth overview of plant biostimulants, focusing on their classification, mechanisms of action, and potential role in enhancing the growth, quality, and resilience of vegetable crops under temperate and subtropical climates. Special attention is given to the integration of biostimulants into sustainable agricultural systems to address emerging environmental challenges.

To the best of our knowledge, no comprehensive reviews are currently available on the effects that microbial plant biostimulants' application showed to have on specific vegetable crops. This review thus aims to provide a state of the art overview of plant biostimulants' application to horticultural crops. Current research lines, challenges, and future perspectives of their application to vegetable crops are presented and discussed. We hypothesized that using biostimulants would reduce the application of chemical fertilizers and become an alternative and eco-friendly approach to sustainable agriculture. The objectives of our review study were to (i) Classification and Categories of Plant Biostimulants, (ii) Role of Biostimulants in Enhancing Vegetable Production under Abiotic Stress Conditions, and (iii) to assess the influence of biostimulants on vegetable performance, quality, and nutritional value.

Classification and Categories of Plant Biostimulants

Plant biostimulants are broadly categorized into microbial and non-microbial types, based on their origin and mode of action. This classification helps in understanding their distinct mechanisms and optimizing their application in agricultural systems (Parađiković et al., 2019). Both microbial and non-microbial biostimulants are widely recognized for their ability to enhance nutrient uptake, stimulate plant growth and development, and improve tolerance to both biotic and abiotic stresses. These effects are summarized in Table 1: Biostimulant Types and Their Effects on Plants, which provides representative examples from recent studies. Specifically, the impacts reported by Zhang et al. (2024), Kołodziejczyk et al. (2021), and Posmyk et al. (2009) are included in the table, illustrating the diverse mechanisms through which different biostimulants exert their beneficial effects on various vegetable crops. By linking these references to Table 1, readers can readily access both the biostimulant type and its corresponding observed physiological and biochemical effects.

Microbial biostimulants include beneficial microorganisms such as plant growth-promoting rhizobacteria (PGPR) and arbuscular mycorrhizal fungi (AMF). These microbes form symbiotic or associative relationships with plant roots, enhancing nutrient acquisition (especially nitrogen and phosphorus), promoting root growth, and boosting plant defense mechanisms. They also improve photosynthetic activity and overall plant vigor, while contributing to improved soil structure and biological fertility (Calvo et al., 2014; González González et al., 2020).

Non-microbial biostimulants encompass a diverse group of organic-based compounds such as seaweed extracts, humic and fulvic acids, and protein hydrolysates. For instance, seaweed extracts—particularly from Ascophyllum nodosum—are rich in bioactive compounds like phytohormones (auxins, cytokinins), betaines, and polysaccharides. These compounds are known to improve nutrient efficiency, enhance abiotic stress tolerance (e.g., salinity, drought, and cold), and stimulate plant metabolism (De Saeger et al., 2019; Boukhari et al., 2020).

By reducing dependence on synthetic fertilizers and pesticides, plant biostimulants contribute significantly to sustainable agriculture. They support ecological farming practices by improving soil-plant interactions, promoting environmental resilience, and maintaining crop productivity under both optimal and stress-prone conditions (Calvo et al., 2014).

Table 1. Biostimulants types and their effects on plants

<table>
<tr><th rowspan="10">Bio stimulant Type</th><th colspan="2">Subcategory / Example</th><th>Source</th><th>Main Effects on Plants</th></tr>
<tr><td rowspan="4">Microbial</td><td>PGPR (Bacillus, Pseudomonas)</td><td>Soil bacteria</td><td>Improves root growth, N fixation, stress resistance</td></tr>
<tr><td>Arbuscular Mycorrhizal Fungi (AMF) (Glomus spp)</td><td>Symbiotic fungi</td><td>Enhances P uptake, drought tolerance</td></tr>
<tr><td>Trichoderma spp.</td><td>Fungi</td><td>Boosts chlorophyll, stress resistance, disease control</td></tr>
<tr><td>Yeasts, Algae, Filamentous Fungi</td><td>Microbial extracts</td><td>Induces systemic resistance, promotes hormone balance</td></tr>
<tr><td rowspan="4">Non-Microbial</td><td>Seaweed Extracts (A. nodosum)</td><td>Marine algae</td><td>Enhances growth, cold stress tolerance</td></tr>
<tr><td>Humic and Fulvic Acids</td><td>Decomposed organic matter</td><td>Improves nutrient uptake, root development</td></tr>
<tr><td>Protein Hydrolysates / Amino Acids</td><td>Enzymatically hydrolyzed proteins</td><td>Stimulates metabolism, enhances biomass accumulation</td></tr>
<tr><td>Melatonin</td><td>Tryptophan derivative</td><td>Improves germination under chilling stress</td></tr>
</table>

Microbial Biostimulants

Microbial biostimulants comprise beneficial microorganisms that form symbiotic or associative relationships with plants, resulting in enhanced root function, improved nutrient use efficiency, and greater tolerance to environmental stresses. Numerous commercial biostimulant products derived from microbial inoculants, seaweed extracts, protein hydrolysates, and humic substances are currently available to support sustainable crop production (Table 2 for selected commercial products used in agriculture and horticulture).

a. Plant Growth-Promoting Rhizobacteria (PGPR) and Arbuscular Mycorrhizal Fungi (AMF)

PGPR (e.g., *Rhizobium, Pseudomonas, Bacillus*) and AMF (e.g., *Glomus* spp.) play pivotal roles in facilitating nutrient uptake—particularly of nitrogen and phosphorus—enhancing root architecture, and mitigating abiotic stress conditions. These microorganisms establish beneficial interactions within the rhizosphere, promoting plant vigor, soil fertility, and overall crop resilience (Calvo et al., 2014; González González et al., 2020).

b. *Trichoderma spp.*

Members of the Trichoderma genus exhibit dual functionality as both plant biostimulants and biocontrol agents. These fungi are known to promote plant growth, increase chlorophyll content, and enhance tolerance to both biotic and abiotic stressors across a wide range of crop and ornamental plant species (Sesan et al., 2020; Vaio et al., 2021).

In horticulture, Trichoderma species have emerged as significant microbial biostimulants due to their multifaceted roles in supporting plant development and health (Harman, 2000). Beyond agricultural applications, Trichoderma is also employed in various industrial sectors, including biofuel production, and the synthesis of enzymes, antibiotics, and other bioactive metabolites. With the advancement of genomic technologies, several Trichoderma genome sequences are now publicly available, expanding the scope of their potential uses in both agricultural and non-agricultural fields (Blaszczyk et al., 2014). Nevertheless, further research is needed to improve the efficacy, safety, and species-specific optimization of Trichoderma-based applications.

In vegetable crops such as *Lactuca sativa* L. and Eruca sativa L., Trichoderma-based biostimulants have been shown to enhance yield performance (Sesan et al., 2020). Similarly, in ornamental species such as *Passiflora caerulea* L., application resulted in larger leaf size and increased chlorophyll content. Trichoderma has also demonstrated biostimulant effects in woody evergreen ornamental plants, including *Olea europaea* L., by improving resistance to abiotic stress factors (Vaio et al., 2021).

c. Other Beneficial Microorganisms

In addition to rhizobacteria and mycorrhizal fungi, various filamentous fungi, yeasts, and microalgae also act as effective microbial biostimulants. These microorganisms promote nutrient solubilization, stimulate the synthesis of phytohormones such as auxins and cytokinins, and activate plant defense mechanisms, leading to enhanced biomass accumulation and stress resilience (Baltazar et al., 2021; Franzoni et al., 2021). Microalgae and fungi exert their effects through metabolic processes in the soil, improving nutrient uptake via nitrogen fixation and solubilization, producing volatile organic compounds (VOCs), and modifying the plant's hormonal balance (Del Buono, 2021; Franzoni et al., 2021).

Among vegetable crops (e.g., tomato *Solanum lycopersicum*, cucumber *Cucumis sativus*, lettuce *Lactuca sativa*), microbial biostimulants enhance growth, nutrient uptake, and tolerance to abiotic stresses such as salinity and drought. In legumes (e.g., pea *Pisum sativum*, fava bean *Vicia faba*), *Rhizobium* species and other PGPR strains improve salt stress resilience and support symbiotic nitrogen fixation, with efficacy depending on the microbial strain (Pilar et al., 1999;

Egamberdiyeva et al., 2009; Gopalakrishnan et al., 2015). In ornamental plants (e.g., *Camellia japonica*, *Ficus benjamina*, spring bulbous species), PGPR inoculation has been shown to improve morphology, root development, and stress tolerance, thereby supporting growth under suboptimal conditions and reducing production costs (Prisa et al., 2021; Park et al., 2017; Sezen et al., 2014).

Plant Growth-Promoting Bacteria such as *Arthrobacter*, *Acinetobacter*, *Enterobacter*, *Ochrobactrum*, *Pseudomonas*, *Rhodococcus*, and *Bacillus* species are widely utilized across these crop groups (Efthimiadou et al., 2020). Their mechanisms include improving photosynthetic performance, increasing osmolyte accumulation, maintaining favorable potassium/sodium ratios, and stimulating antioxidant enzyme activity, thereby providing broad applicability of microbial biostimulants across vegetables, legumes, and ornamental plants (Bhise et al., 2019).

Non-Microbial Biostimulants

Non-microbial biostimulants are derived from organic or inorganic sources and contain biologically active compounds that indirectly support plant physiological processes.

a. Seaweed Extracts (SWE)

Seaweed extracts (SWEs), particularly those derived from brown algae such as Ascophyllum nodosum, are rich in biologically active compounds including phytohormones (e.g., cytokinins, auxins), betaines, and complex polysaccharides such as laminarin, fucoidan, and alginates. These compounds contribute to enhanced plant growth, improved nutrient use efficiency, and increased tolerance to various abiotic stresses (Battacharyya et al., 2015; De Saeger et al., 2019; Bradáčová et al., 2016).

SWEs are widely used as commercial biostimulants to improve crop productivity by promoting plant development and stress resilience. When applied as foliar sprays, they have been shown to enhance photosynthetic activity and confer tolerance to heat, drought, salinity, and biotic factors such as bacteria, viruses, and fungi (Norrie et al., 2006; Sharma et al., 2014). Despite numerous reports of positive effects on plant growth, the precise biochemical mechanisms of SWEs remain not fully understood, largely due to the complexity and variability of their constituents (Verkleij, 1992; Battacharyya et al., 2015).

Recent studies have begun to clarify the relationship between SWEs and cold stress tolerance. Specifically, SWEs enriched with micronutrients—particularly zinc and magnesium—have demonstrated the ability to improve cold tolerance in crops such as maize by enhancing the regulation of reactive oxygen species (ROS) (Rayirath et al., 2009; Bradáčová et al., 2016). These micronutrients act as cofactors in antioxidant enzymes, helping to mitigate oxidative damage under low-temperature stress. Thus, SWEs with high levels of essential micronutrients may effectively alleviate cold-induced nutrient deficiency stress and enhance plant resilience.

Supporting this view, previous studies showed that nutritional seed priming with micronutrients improved tolerance to root freezing stress in maize seedlings (Imran et al., 2013). Together, these findings highlight the dual role of SWEs as both a source of growth-promoting hormones and a means of micronutrient delivery to support plant defense systems under cold conditions.

b. Humic and Fulvic Acids

Humic and fulvic acids are naturally occurring organic compounds formed through the microbial and chemical decomposition of plant, animal, and microbial residues. They are key components of soil organic matter and play essential roles in promoting vegetable crop growth, such as in tomato (*Solanum lycopersicum*), cucumber (*Cucumis sativus*), and lettuce (*Lactuca sativa*), especially under stress conditions (Rouphael et al., 2018; Bulgari et al., 2015).

Humic acids, which have higher molecular weights and complex structures, enhance root elongation, nutrient uptake, and water retention capacity. Fulvic acids, being of lower molecular weight and higher oxygen content, are more mobile in soil and easily absorbed by plants. They influence various physiological and biochemical pathways that contribute to improved stress tolerance (Canellas et al., 2015; Nardi et al., 2016).

Applications of humic substances have been shown to stimulate plant root development and enhance water and nutrient absorption efficiency, ultimately improving plant resilience under abiotic stress (Canellas et al., 2002; Trevisan et al., 2020). Moreover, monocotyledonous crops such as rice (*Oryza sativa* L.) can particularly benefit from humic acid treatments. For instance, vermicompost-derived humic extracts applied to rice plants increased antioxidant enzyme activities—such as ROS scavenging enzymes—which are vital in mitigating oxidative damage caused by salinity and drought stress (García et al., 2012). One of the potential mechanisms involves the differential regulation of proton ATPases in vacuolar and plasma membranes, which may enhance ion balance and energy regulation in stressed plants.

c. Protein Hydrolysates and Amino Acids

Protein hydrolysates are biostimulant products obtained through enzymatic or chemical hydrolysis of animal- or plant-derived proteins. These formulations are rich in peptides and free amino acids, which act as signaling molecules and metabolic precursors in vegetable crops (Colla et al., 2017). By mimicking hormone-like activity, they enhance growth and development, particularly under stress conditions.

Amino acids contribute to the regulation of key physiological processes such as nitrogen assimilation, antioxidant defense, and osmotic adjustment. For instance, glycine and glutamic acid enhance chlorophyll synthesis and photosynthetic activity, while proline and arginine accumulate under stress conditions to help maintain cellular homeostasis (Botta, 2013; Ertani et al., 2013).

Field and greenhouse trials have shown that protein hydrolysates can increase nutrient uptake efficiency, root growth, and stress tolerance in vegetables such as lettuce (*Lactuca sativa*), tomato (*Solanum lycopersicum*), and cucumber (*Cucumis sativus*). Products like Terra-Sorb® have been reported to improve biomass accumulation and cold tolerance in lettuce by enhancing stomatal conductance and water-use efficiency (Halpern et al., 2019).

Furthermore, application of protein hydrolysates has been associated with the upregulation of antioxidant enzyme activities (e.g., catalase, peroxidase, superoxide dismutase), protecting vegetable tissues from oxidative damage caused by abiotic stresses such as salinity and drought (Khalis et al., 2023). Their effectiveness depends on factors such as amino acid profile, peptide size distribution, and the origin of raw protein material (Colla et al., 2015).

Recent advances highlight their potential in sustainable vegetable production as eco-friendly tools for enhancing crop quality and yield while reducing dependency on chemical fertilizers (Yakhin et al., 2017; Rouphael and Colla, 2020).

d. Melatonin and Related Derivatives

Melatonin is biosynthesized via the shikimate pathway from tryptophan and has been shown to prime seeds against unfavorable environmental conditions by modulating stress-responsive pathways. For example, maize (Zea mays) seeds treated with melatonin exhibited increased cold tolerance during germination, suggesting a priming effect that enhances seedling vigor under chilling stress (Kołodziejczyk et al., 2016). Melatonin, a derivative of tryptophan, functions in vegetables as a potent antioxidant and signaling molecule. It plays a crucial role in enhancing tolerance to abiotic stresses, particularly during early developmental stages. Recent studies highlight its efficacy in seed priming and improving resistance to chilling stress during germination and seedling establishment in crops such as lettuce, tomato, and cucumber (Kołodziejczyk et al., 2016; Posmyk et al., 2016).

e. Protein Hydrolysates and Amino Acids

Protein hydrolysates, produced through chemical, enzymatic, or thermal hydrolysis of plant or animal proteins, consist of mixtures of free amino acids, peptides, polypeptides, and denatured proteins (Nardi et al., 2019). Hydrolysates derived from agro-industrial by-products or animal tissues (e.g., collagen) have demonstrated beneficial effects on plant growth by stimulating hormone-like activities and regulating metabolites involved in developmental processes (Halpern et al., 2019; Colla et al., 2017; Petropoulos, 2020).

Amino acid-rich formulations, such as Terra-Sorb®, have been shown to enhance biomass production and improve physiological traits under stress conditions. For instance, lettuce (*Lactuca sativa*) treated with Terra-Sorb under cold stress exhibited increased stomatal conductance and fresh weight, indicating improved cold tolerance (Botta et al., 2013).

f. Integration and Synergy of Biostimulants

Understanding the functional classification and mechanisms of action of plant biostimulants is essential for their effective application in sustainable agriculture. The combined use of microbial and non-microbial biostimulants, including melatonin and protein hydrolysates, offers a synergistic strategy to enhance crop performance, especially in the face of climate change and soil degradation.

Table 2. Commercial bio stimulant products used in the agriculture and horticulture industries.

Category	**Types**	**Example Organism / Compound**	**Commercial Product Name**	**Benefits**	**References**
Microbial Biostimulants	PGPR (Plant Growth Promoting Rhizobacteria)	*Bacillus subtilis*, *Pseudomonas fluorescens*	**Rhizovital**, **Companion**, **Quantum Light**	Root growth, nutrient solubilization, disease suppression	du Jardin (2015); Calvo et al. (2014)
	Arbuscular Mycorrhizal Fungi (AMF)	*Glomus intraradices*, *G. mosseae*	**MycoApply**, **Symbivit**, **AgriMycorrhiza**	P uptake, root architecture improvement, drought resistance	Rouphael & Colla (2020); Yakhin et al. (2017)
	Trichoderma spp.	*T. harzianum*, *T. viride*	**RootShield**, **Trianum** **Binab TF-WP**	Biocontrol, root stimulation, pathogen suppression	Woo et al. (2014); Lorito et al. (2010)
	Yeasts, Algae, Filamentous Fungi	*Saccharomyces cerevisiae*, *Chlorella vulgaris*	**Lalstim Osmo**, **Algaphon**, **AgriAlga**	Osmotic protection, antioxidant activity, metabolic enhancement	Sharma et al. (2020)
Non-Microbial Biostimulants	Seaweed Extracts	*Ascophyllum nodosum*, *Laminaria spp.*	**Kelpak**, **Seasol**, **Acadian**	Hormonal regulation, stress tolerance, growth promotion	Khan et al. (2009); Rouphael & Colla (2020)
	Humic and Fulvic Acids	Humic acid, fulvic acid (from leonardite)	**Blackjak**, **HumiSolve**, **FulvAgra**	Nutrient uptake, chelation of minerals, soil structure improvement	Canellas et al. (2015); Nardi et al. (2002)
	Protein Hydrolysates / Amino Acids	Plant-derived or animal-based peptides	**Trainer**, **AminoQuelant**, **Pepton**	Stimulate nitrogen metabolism, enzyme activity, stress mitigation	Colla et al. (2014); Ertani et al. (2013)
	Melatonin	Synthetic or plant-derived melatonin	**Melagro** (conceptual), **PlantMelatonin™** (experimental)	Antioxidant, growth regulation, heat and drought stress reduction	Arnao & Hernández-Ruiz (2014); Zhang et al. (2017)

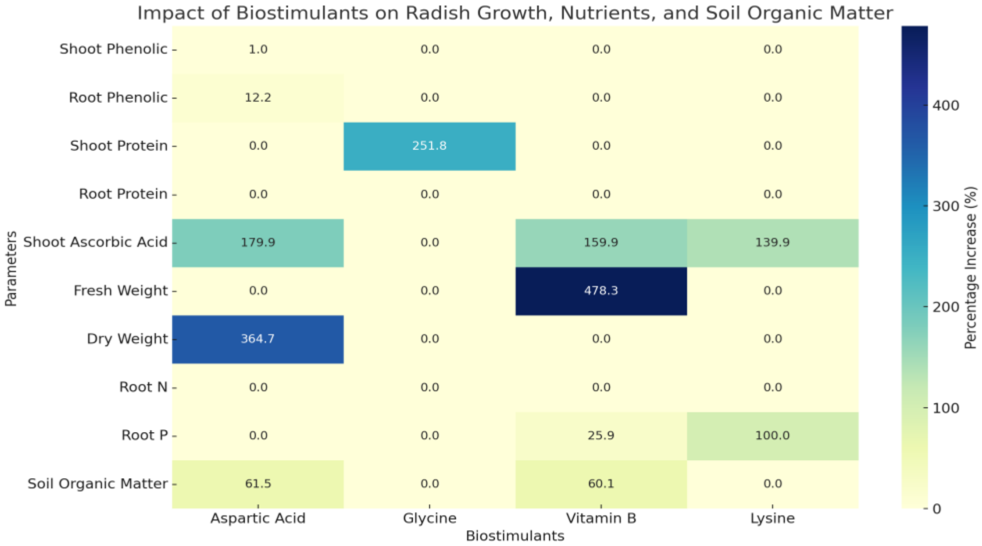

Figure 1. Effects of amino acid and vitamin-based biostimulant applications on radish growth, biochemical composition, and soil organic matter under abiotic stress conditions.

Biostimulants have been shown to mitigate various abiotic stresses, including drought, salinity, and cold, thereby improving crop growth and yield across diverse species (Table 3 for a summary of their effects under different stress conditions).

Heat Stress

High temperatures cause oxidative stress, enzyme deactivation, and structural damage, impairing growth and yield. In tomatoes, heat stress leads to reduced fruit set and pollen viability (Camejo et al., 2005). Mungbean seedlings treated with exogenous glutathione showed lower oxidative stress under high temperatures (Nahar et al., 2015).

Salinity Stress

Salinity causes osmotic stress, nutrient imbalance, and ion toxicity, especially in coastal regions (Viégas, 2006; Colla, 2010). PGPR inoculation improved root-shoot development and CO_2 assimilation in chickpea and faba bean. Moringa oleifera leaf extract and honey-derived biostimulants improved osmoprotectant levels, photosynthetic pigments, and bulb biomass in onions (Semida et al., 2019).

Cold or Chilling Stress

Cold stress disrupts membrane stability and photosystem II activity. Psychrotolerant soil bacteria improved cold resistance in tomatoes (Subramanian et al., 2015, 2016). Amino acid-based biostimulants like Terra-Sorb® Foliar and Asahi SL helped lettuce and coriander adapt to low temperatures by enhancing antioxidant defenses (Botta, 2012; Pokluda et al., 2016).

Drought Stress

Drought reduces photosynthesis and transpiration, thereby lowering yield. Seaweed extracts (Ascophyllum nodosum) improved gas exchange and chlorophyll retention in spinach and tomato (Xu et al., 2015; Goñi et al., 2018). PGPR such as Azospirillum brasilense and Pseudomonas sp. enhanced xylem conductivity and antioxidant activity in tomato and basil under drought (Romero et al., 2014; Heidari et al., 2012).

Nutrient Deficiency

Biostimulants improve nutrient solubility, root architecture, and nutrient transport (Halpern et al., 2015). Garlic and okra showed enhanced growth with reduced fertilizer inputs when treated with seaweed extracts or protein hydrolysates (Anjum et al., 2014; Papenfus et al., 2013). Humic substances also promoted seedling growth in Salvia splendens (Vujošević et al., 2007).

Plant Growth and Development

Biostimulants have shown effectiveness in rooting of woody cuttings (Rosa sp.) and biomass increase in annual ornamentals (Para et al., 2017; Florijančić and Lužaić., 2009). Alfalfa-derived biostimulants improved chlorophyll content, while humic acids accelerated seedling development in various crops (Bákonyi et al., 2020).

Biostimulants in Improving Food Quality and Nutritional Value

Biostimulants not only improve growth and yield but also enhance the nutritional and sensory qualities of fruits and vegetables. They elevate levels of bioactive compounds such as vitamins, phenolics, and antioxidants (Francesca et al., 2020; Godlewska et al., 2021). These changes lead to better taste, color, and shelf life.

According to Kocira et al. (2020), biostimulants positively affect all aspects of plant development, including root/shoot growth, leaf area, chlorophyll content, protein synthesis, and stress resilience. Applications of products like Ascophyllum nodosum extract or protein hydrolysates have consistently shown improvements in biomass accumulation, fruit set, and physiological efficiency (Ertani et al., 2014).

In summary, biostimulants are essential components of sustainable agriculture, offering benefits such as improved nutritional quality, stress tolerance, and reduced chemical input dependency (Calvo et al., 2014). Their multifunctional role highlights their potential to address global agricultural challenges under climate change and resource constraints.

Table 3. Effect of biostimulants under different stress condition on different crops

Stress Type	Bio stimulant or Strategy	Crop Studied	Effect Observed	Reference
Heat Stress	Exogenous glutathione	Mungbean	Reduced oxidative stress and methylglyoxal levels; improved antioxidant defense	Nahar *et al*., 2015
Salinity Stress	Rhizobium inoculation	Chickpea, Faba bean, Sweet pepper	Increased root/shoot development, dry weight, and CO_2 assimilation	Cordovilla *et al*.; Pilar *et al*., 1999
Salinity Stress	Moringa leaf extract + Salicylic acid	Various vegetables	Improved photosynthetic pigments, antioxidants, osmoprotectants	Semida *et al*., 2019
Cold Stress	Psychrotolerant soil microbes	Tomato	Increased germination, decreased membrane damage, improved antioxidant activity	Subramanian *et al*., 2016, 2015
Cold Stress	Amino acid-based (Terra-Sorb®)	Lettuce	Improved fresh weight and stomatal conductance	Botta, 2012
Drought Stress	Ascophyllum nodosum	Spinach, Broccoli	Improved gas exchange and water stress resilience	Xu *et al*., 2015; Kałuzewicz *et al*., 2017
Drought Stress	Azospirillum brasilense	Tomato	Delayed wilting, increased xylem vessel area	Romero *et al*., 2014
Nutrient Deficiency	Seaweed-based product (Kelpak®)	Okra	Improved shoot/root growth under P and K deficiency	Papenfus *et al*., 2013
Nutrient Deficiency	Protein hydrolysates and amino acids	Rocket, Baby leaf	Improved root biomass, nutrient uptake	Vernieri *et al*., 2005

Biostimulants and Soil Carbon Sequestration

Biostimulants, including microbial inoculants such as Plant Growth-Promoting Rhizobacteria (PGPR) and arbuscular mycorrhizal fungi (AMF), as well as non-microbial agents like humic substances, seaweed extracts, and protein hydrolysates, have been shown to enhance soil organic matter and promote carbon sequestration. These products improve nutrient availability, stimulate root growth, and increase microbial biomass, which together facilitate the stabilization of organic carbon in the soil through aggregate formation and enhanced microbial diversity (Dębska et al., 2016; Rukaitė et al., 2024; Rouphael et al., 2018). The application of humic substances, for example, increases cation-exchange capacity and promotes the formation of stable soil organic matter, while microbial biostimulants enhance carbon cycling via root exudation and microbial activity. Integrated use of microbial and non-microbial biostimulants has been reported to synergistically improve soil aggregation, increase organic carbon persistence, and contribute to long-term soil fertility and climate change mitigation (Dubey et al., 2025; Baltazar et al., 2021). Overall, biostimulants represent a promising strategy for improving soil carbon stocks and supporting sustainable agricultural practices.

Strategies and Conclusions for Bio stimulant Adoption

Plant biostimulants have demonstrated substantial potential in enhancing growth, stress resilience, nutrient uptake, yield, and overall productivity in horticultural crops, as evidenced by the studies reviewed.

As emphasized in the reviewed literature, biostimulants can positively influence nutrient uptake efficiency, plant vigor, yield, and tolerance to abiotic stressors such as drought, salinity, and temperature extremes.

Among future strategies, breeding stress-resilient plant varieties remains a high-priority approach to ensure food security and sustainable crop production. The identification of stress-responsive genes and a deeper understanding of molecular mechanisms—especially the role of transcription factors—will be vital for developing genotypes with improved adaptability to environmental constraints.

Emerging classes of biostimulants, including microbial consortia (e.g., PGPR and AMF), protein hydrolysates, humic substances, seaweed extracts, and signaling molecules such as melatonin, are expected to play a central role in sustainable horticultural practices. Their application not only promotes crop quality and growth but also enhances the soil microbiome and contributes to ecological balance without adverse effects on human or environmental health.

However, the efficacy of biostimulants largely depends on application method, dosage, crop species, and developmental stage. Therefore, future research must focus on:

- Elucidating the specific modes of action of different bio stimulant categories,
- Determining optimal application timing and formulation strategies,
- Developing regulatory frameworks to ensure product consistency and farmer trust,
- And quantifying long-term impacts on yield stability and product quality under real field conditions.

Of particular importance is the role of algae-based biostimulants in boosting antioxidant defense mechanisms and the synergistic effects of plant-derived protein hydrolysates and microbial formulations in enhancing growth parameters.

Overall, biostimulants offer a promising, environmentally friendly approach for sustainable horticultural production, but continued scientific investigation is essential to maximize their practical benefits.

Compliance with Ethical Standards

Peer Review

This article has been reviewed by independent experts in the field using a rigorous double-blind peer review process.

Conflict of Interest

The authors declare no conflicts of interest.

Author Contributions

Ceren Ayşe Bayram: Performed the initial literature screening and drafted the first version of the manuscript.
Kanu Murmu: Revised and expanded the literature content and finalized the manuscript.
Both authors contributed to the critical review and approved the final version of the manuscript.

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