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Sustainable Agriculture: The Role of Biostimulants in Enhancing Crop Growth and Resilience

Hasddin*,1, Ulyasniati[2], Jamal Mukaddas[1], Marjani[3], Mirad[4], Mustafa Kan[5] Abdul Aman Ega[6] and Musadia Afa[7]

[1]Departement of Urban and Regional Planning, Lakidende University, Unaaha, Indonesia; [2]Faculty of Agriculture, Lakidende University, Unaaha, Indonesia; [3]Department of Management, Faculty of Islamic Economics and Business, Muhammadiyah University of Kendari, Indonesia; [4]Faculty of Social and Business, Mandala Waluya University, Kendari, Indonesia; [5]Department of Agricultural Economics Kirsehir Ahi Evran University, Agricultural Faculty Kirsehir-Turkiye; [6]Forestry Service of Southeast Sulawesi Province, Kendari, Indonesia; [7]Faculty of Agriculture, Sembilan Belas November University, Kolaka, Indonesia
*Corresponding author's e-mail: hasddinjali@yahoo.com

Global population growth, climate change, and soil erosion threaten food security and agricultural production. Traditional farming methods using synthetic fertilisers and pesticides have worsened environmental issues, requiring sustainable solutions. Biostimulants such microbial inoculants, humic compounds, seaweed extracts, protein hydrolysates, and chitosan improve crop yield, soil health. By activating plant processes, these biologically generated compounds improve nutrient uptake, root development, and stress tolerance. *Azospirillum*, *Rhizobium*, and *Bacillus* biostimulants fix nitrogen and solubilize phosphorus, whereas seaweed extracts and protein hydrolysates modulate hormone activity and photosynthesis. Humic compounds modulate gene expression and activate antioxidant pathways to improve soil fertility and stress tolerance. Current biostimulant research, mechanisms of action, and sustainable agricultural potential are summarised in this study. Despite promising results, further research is needed to optimize biostimulant formulations, asses their long-term effects, and large-scale adoption in different agroecosystems.

Keywords: Biostimulants, agriculture, sustainability, microbial, fertility, soil, seaweeds, hormones.

INTRODUCTION

Due to population expansion, climate change, soil degradation, and crop yield declines, the global agricultural sector needs sustainable solutions to assure food security and environmental preservation (Hossain *et al.*, 2020). Over 820 million people are undernourished, and food demand is expected to rise by 50% by 2050 when the world's population reaches 9.8 billion (Searchinger *et al.*, 2019). Synthetic fertilisers and pesticides have degraded soil, lost microbial biodiversity, contaminated water, and released greenhouse gases, emphasising the need for resource-efficient alternatives (Paul and Bhatia, 2025). Climate change exacerbates abiotic stresses such drought, salt, severe temperatures, and nutrient deficits, lowering crop yields in arid and semi-arid countries (Saleem *et al.*, 2024).

Biostimulants stimulate natural plant processes without chemical inputs to boost crop yield, nutritional efficiency, and environmental resistance (Mandal *et al.*, 2023). It activates biosynthetic pathways and stimulates secondary metabolism in plants (Jmaili *et al.*, 2025). Multiple bioactive compounds work together to make them effective (Yakhin *et al.*, 2017). Figure 1 shows that microbial inoculants (e.g., mycorrhizal fungi, plant growth-promoting rhizobacteria (PGPR)), humic substances, protein hydrolysates, seaweed extracts, and chitosan each improve soil health, plant growth, and stress tolerance (Kumari *et al.*, 2022). *Azospirillum*, *Rhizobium*, and *Bacillus* improve nitrogen fixation, phosphorus solubilisation, root architecture, and plant immunity, lowering synthetic fertiliser use (Kumari *et al.*, 2023b). Bioactive chemicals in seaweed extracts drive photosynthesis, enzyme activity, and nutrient uptake, while humic substances

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and protein hydrolysates regulate hormone action, water retention, and root development (Garcia-Caparros *et al.*, 2025). Chemical fertilisers have degraded soil ecosystems, altered microbial diversity, and increased greenhouse gas emissions (Amin and Jilani, 2024). Biostimulants improve soil fertility, plant resilience, and lessen the environmental impact of conventional agriculture in sustainable agriculture (Sani and Yong, 2021). Biostimulants activate antioxidant enzymes, increase osmolyte accumulation, and modulate stress response gene expression, improving plant tolerance to drought, salt, and nutritional deficits (Bulgari *et al.*, 2019). Biostimulants like *Azospirillum brasilense* increase maize grain yield, Bradyrhizobium japonicum increase soybean nodule formation and nitrogen fixation, and mycorrhizal fungi *(Glomus faciculatum*) increase banana yield.

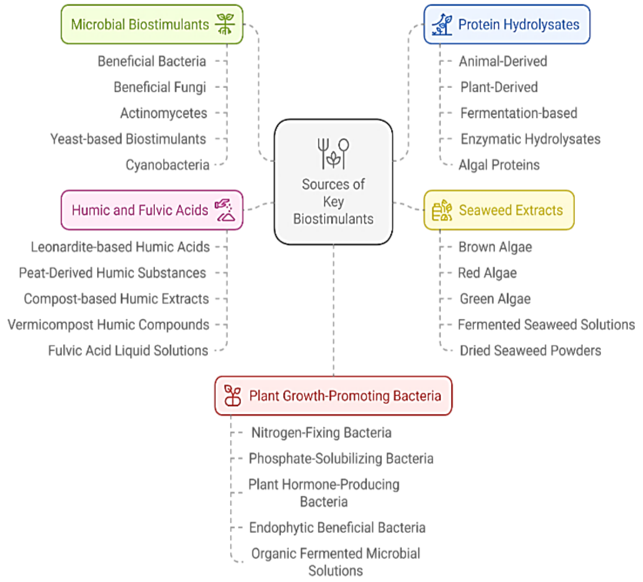

Figure 1. Sources of key biostimulants in agriculture.

Agricultural intensification without ecological consideration is unsustainable, necessitating a paradigm shift toward biological agriculture, agroecology, and permaculture, which emphasize the use of microbial biostimulants, composting, and organic amendments to improve soil structure and nutrient cycling (Sarangthem *et al.*, 2023). The role of *arbuscular mycorrhizal fungi* (AMF) and PGPR in enhancing plant resilience against abiotic stresses has been well-documented, with notable improvements in drought tolerance, heavy metal detoxification, and soil fertility restoration (Wahab *et al.*, 2023). Different biostimulants and their mechanism of action represented in Table 1. The adoption of these biologically integrated agroecosystems is critical for maintaining food security, particularly in regions vulnerable to climate change-induced productivity losses (Ahmed *et al.*, 2022). This review provides a comprehensive synthesis of current research on biostimulants and their applications in sustainable agriculture, exploring their mechanisms of action, potential in improving crop yield and quality, and their role in reducing environmental impact. It aims to highlight the importance of biostimulants in mitigating climate-induced stresses, discuss the limitations of current biostimulant technologies, and propose future research directions for their large-scale implementation. Addressing global food security challenges requires a shift towards climate-smart and sustainable farming solutions, with biostimulants offering a viable pathway to achieving resilient, productive, and environmentally responsible agriculture.

Microbial biostimulants in enhancing crop growth and resilience*:** Microbial biostimulants, including beneficial bacteria and fungi, play a crucial role in enhancing crop productivity, stress tolerance, and soil health by improving nutrient uptake, root development, and plant resilience under abiotic and biotic stresses. ***Glomus faciculatum and *Bacillus megaterium* increase banana yield by 30% through improved phosphorus solubilization and root colonization, promoting nutrient absorption and plant vigor (Patil *et al.*, 2002; Vasant, 2021). This effect is demonstrated in other crops, as represented in Fig. 2, where microbial inoculant enhance root, and shoot development through rhizobacteria and mycorrhizal fungi synergistic interaction. A consortium of *Bacillus firmus*, *Enterobacter spp.*, *Burkholderia spp.*, *Pseudomonas sp.*, and *Paenibacillus kribbensis* enhances paddy yield by optimizes nitrogen fixation, leading to higher grain production and improved soil fertility (Jain *et al.*, 2022). *Phosphobacterium variety SBS 1* boosts sword bean yield by solubilizing phosphate, thereby making essential nutrients more bioavailable for plant uptake (Misganaw, 2024). *Azotobacter chroococcum*, a nitrogen-fixing bacterium, increases wheat yield by 74% by enhancing root growth, nitrogen fixation, and microbial activity in the rhizosphere, improving soil structure and plant health (Wani *et al.*, 2016). Legume-specific microbial biostimulants significantly improve nitrogen availability and crop productivity. *Rhizobium lupini* enhances nitrogen shoot content, nutrient uptake, and biomass accumulation in alfalfa, promoting sustainable forage production (Ponmurugan and Gopi, 2006). *Pseudomonas cepacia R85* and *Pseudomonas fluorescens R22* improve wheat height and yield by optimizing plant growth-promoting hormone production and nutrient assimilation (Aftab Afzal and Asghari Bano, 2008) *Rhizobium phaseoli* facilitates increased root nodule formation in clover, significantly enhancing biological nitrogen fixation and reducing the dependence on synthetic fertilizers (Hayat *et al.*, 2010). Similarly, *Frateuria aurantia* isolate KSBD-58 enhances sunflower growth by improving head diameter, seed yield, and potassium uptake, contributing to better crop resilience and yield quality (Kammar *et al.*, 2016).

Table 1. Role of biostimulants and their key mechanisms.

Biostimulant	**Target Plant**	**Specific Action mechanism**	**Reference**
Protein hydrolysate	*Solanum lycopersicon* (Tomato)	Enhanced biomass, photosynthesis, root growth, and gene regulation for stress resistance.	(Caruso *et al.*, 2020; Di Mola *et al.*, 2020; Sun *et al.*, 2024)
Protein hydrolysate	*Zea mays* (Corn)	Stimulated root elongation, nutrient transport, and upregulated hormone metabolism genes.	(Rouphael *et al.*, 2020)
Protein hydrolysate	*Diplotaxis tenuifolia*	Increased yield, chlorophyll biosynthesis, and improved antioxidant enzyme activity.	(Caruso *et al.*, 2020)
Protein hydrolysate	*Olea europaea* (Olive)	Optimized gas exchange, improved photosynthetic rate, and increased olive oil yield.	(Psarras *et al.*, 2024)
Protein hydrolysate	*Lactuca sativa* (Lettuce)	Enhanced microbial growth, higher chlorophyll content, and improved nitrogen efficiency.	(Choi *et al.*, 2022)
Crambe abyssinica protein hydrolysate	*Vigna radiata* (Mung bean), *Zea mays* (Corn)	Stimulated lateral root formation, nitrogen uptake, and promoted chlorophyll accumulation.	(Ugolini *et al.*, 2023)
Whey protein hydrolysate	*Ipomoea batatas* (Sweet potato)	Increased shoot biomass, improved nutrient assimilation, and higher tuber yield.	(Elwaziri *et al.*, 2023)
Chicken feather hydrolysate	*Zea mays* (Corn), *Saccharum officinarum* (Sugarcane)	Boosted chlorophyll and protein synthesis, improved soil fertility, and microbial activity.	(Jagadeesan *et al.*, 2023)
Nitrogenous amino acid hydrolysate	*Cucumis sativus* (Cucumber)	Increased fruit size, nutrient transport efficiency, and metabolic activity.	(Drobek *et al.*, 2020)
Protein hydrolysates	*Zea mays* (Corn)	Overexpression of heat shock proteins and dehydration response genes under drought stress.	(Vaseva *et al.*, 2022)
Bacillus subtilis CG-6	*Medicago sativa* (Alfalfa)	Enhances alfalfa growth, inhibits pathogenic bacteria, and reduces root rot incidence.	(Chen *et al.*, 2024)
Bacillus amyloliquefaciens HZ-12	*Malus domestica* (Apple)	Effectively controls apple rot, improving fruit health.	(Zhang *et al.*, 2024)
Bacillus velezensis RC218; Bacillus nakamurai	*Hordeum vulgare* (Barley)	Suppresses *Fusarium poae* and mycotoxin production, reducing Fusarium head blight (FHB) severity.	(Zanon *et al.*, 2024)
Bacillus velezensis RC218		Controls *Fusarium* species and mycotoxins like nivalenol and deoxynivalenol, enhancing grain safety.	
Bacillus spp.	*Phaseolus vulgaris* (Bean)	Increases phosphorus and nitrogen concentration in leaves, improving nutrient availability.	(Yobo *et al.*, 2009)
Bacillus spp.	*Phaseolus vulgaris* (Bean)	Enhances plant biomass by improving dry weight of stems and roots.	(Gholami *et al.*, 2014)
Bacillus cereus AL-19; Bacillus megaterium AL-18	*Phaseolus vulgaris* (Bean)	Reduces the harmful effects of salinity, enhances phosphate uptake, plant growth, and photosynthetic pigments.	(Abdelmoteleb and Gonzalez-Mendoza, 2020)
		Mitigates salinity stress, enhancing plant growth and nutrient absorption.	
Glomus faciculatum, Bacillus megaterium	Banana	30% increase in yield by improving nutrient uptake and root colonization.	(Patil *et al.*, 2002)

Co-inoculation of various microbial strains boosts soil fertility and plant resistance. *Rhizobium meliloti*, *Paenibacillus polymyxa*, and *Bacillus megaterium* boost bean dry matter, nodule formation, and root biomass, improving nitrogen fixation and crop performance (Korir *et al.*, 2017). *Bradyrhizobium japonicum* increases soybean root nodule formation, yield, and nitrogen for crop rotations (Leggett *et al.*, 2017). *Azospirillum brasilense*, *Bacillus spp*., and *Pseudomonas fluorescens* increase sugarcane shoot output, phosphorus accumulation, and eco-friendly P fertilization by 75% (Rosa *et al.*, 2020).

Microbial biostimulants also improve plant resilience to abiotic stress by optimizing photosynthetic efficiency, hormone regulation, and nutrient assimilation. *Azospirillum brasilense* increases maize chlorophyll index, stem girth, and grain yield by improving nitrogen metabolism and activating plant growth regulators (Galindo *et al.*, 2019b). Wheat seed inoculation with *Azospirillum brasilense* results in a 26.7% increase in grain yield and improved nutrient uptake, reducing dependency on chemical fertilizers (Galindo *et al.*, 2019a; Galindo *et al.*, 2019b). *Azospirillum sp.* enhances growth and productivity in finger millet by modulating root architecture and stimulating hormone production, improving drought resistance (Wang *et al.*, 2012). *Azospirillum brasilense Ab-V5* further enhances nitrogen use efficiency (NUE) in maize, leading to increased biomass, grain yield, and stress tolerance.

Figure 2. Role of biostimulants in plant growth and soil health.

Microbial inoculants also aid seed germination and early plant development. *Acinetobacter sp. RC04* and *Sinorhizobium sp. RC02* promote safflower seed germination and seedling vigor by optimizing water and nutrient uptake, ensuring uniform crop establishment under stress conditions (Zeffa *et al.,* 2019). A co-inoculation approach with *Bradyrhizobium*, *Azospirillum*, *Bacillus*, and *Pseudomonas* improves soybean nodule number by 11.40% and biomass accumulation in nodules (6.47%), roots (12.84%), and shoots (6.53%), demonstrating the potential of microbial synergy in enhancing crop resilience and productivity (Zeffa *et al.*, 2020). These findings highlight the critical role of microbial biostimulants in sustainable agriculture, reducing chemical input dependency while improving crop yields and resilience under varying environmental stresses.

Plant growth-promoting rhizobacteria (PGPR)**:** Including *Bacillus*, *Pseudomonas*, *Rhizobium*, *Azospirillum*, and others, enhance soil structure, nutrient cycling, organic matter decomposition, and plant resilience to abiotic stresses such as drought, salinity, and heavy metal toxicity (Sun *et al.*, 2019; Wenli *et al.*, 2020; Sun *et al.*, 2021). *Bacillus spp.* are particularly effective biostimulants due to their ability to secrete antimicrobial compounds, solubilize phosphate, produce phytohormones, and promote systemic resistance against pathogens like *Fusarium*, *Alternaria*, and *Bipolaris* (Scherm *et al.*, 2013; Todorov *et al.*, 2022; Kumari *et al.*, 2023b). Commercial *Bacillus*-based formulations such as **FZB24®, Inomix®, BactoFil B10®**, and **Symbion®** enhance nutrient uptake, root biomass, and stress tolerance in cereals, vegetables, and ornamentals (Le Mire *et al.*, 2016; Mishra and Arora, 2016; Aamir *et al.*, 2020; Hamid *et al.*, 2021; Zhu *et al.*, 2022). *Bacillus megaterium* improves photosynthesis and growth in saline soils, while *Bacillus subtilis GS3* inhibits *Listeria monocytogenes* biofilm formation (Kim *et al.*, 2013; Akram *et al.*, 2019; Alizadeh Behbahani *et al.*, 2024). Additionally, *Bacillus velezensis* exhibits strong nematode control and wastewater bioremediation potential (Ali *et al.*, 2023; Keshmirshekan *et al.*, 2024).

Non-Microbial Biostimulants to stimulate Plants growth

***Seaweed extracts (SWE)*:** From *Rhodophyta*, *Phaeophyta*, *Chlorophyta*, and *Charophyta* improve soil fertility, plant growth, and stress tolerance by providing bioactive compounds such as polysaccharides, proteins, polyphenols, and plant hormones (Kumari *et al.*, 2022). Extraction methods like acid/alkaline treatment, high-pressure grinding, microwave, and ultrasound processing influence SWE composition, making them effective as standalone treatments or in combination with fertilizers (Sible *et al.*, 2021a; Asif *et al.*, 2023). As SWE mechanism explained in Fig. 3, it helps to activate antioxidant enzymes, reduce ROS, enhance nutrient uptake, and improve germination, biomass, and yield, contributing to sustainable agriculture (Del Buono, 2021; Asif *et al.*, 2023). Their phytohormones, including cytokinins (CKs), auxins (IAA), gibberellins (GA), and sterols, mimic synthetic hormones and stimulate plant metabolism (Asif *et al.*, 2023; Atero-Calvo *et al.*, 2024). SWE enhance micronutrient transporter gene expression in *Brassica napus* and increase Zn, Cu, and Fe uptake in strawberries, while also improving fruit size, polyphenol content, vitamin C, and antioxidant activity in cherries (Boutaleb; Drobek *et al.*, 2019; Malécange *et al.*, 2023). Brown algae-derived polysaccharides enhance wheat salinity tolerance, soybean drought resistance, and *Arabidopsis thaliana* cold stress adaptation through genetic regulations (Kulkarni *et al.*, 2019; Zou *et al.*, 2019; Ozi *et al.*, 2024).

***Ascophyllum nodosum*:** A North Atlantic brown alga, significantly improves seed germination, root colonization, biomass, and nutrient uptake, benefiting lettuce, tomato, bean, sugarcane, and wheat (Drobek *et al.*, 2019; Sible *et al.*, 2021a; Malécange *et al.*, 2023; Mandal *et al.*, 2023). It increases photosynthetic efficiency, CO_2 assimilation, stomatal conductance, and proline accumulation under heat stress, while enhancing nitrogen use efficiency and regulating flowering genes (Andreotti *et al.*, 2022; Atero-Calvo *et al.*, 2024). *A nodosum*-based biostimulants upregulate genes linked to carbohydrate metabolism, stress signaling, and antioxidant activity in *Arabidopsis thaliana*, improving resilience to oxidative stress (Nephali *et al.*, 2020). In vineyards, SWE application reduces lipid peroxidation, increases proline levels, and improves leaf thermoregulation, demonstrating their role in mitigating water stress (Drobek *et al.*, 2019; Boutaleb, 2024). *A. nodosum* extracts also enhance *Zea mays* biomass, nutrient accumulation, and phosphorus homeostasis under P-deficiency, while boosting rice salt tolerance through metabolic pathway activation (Nephali *et al.*, 2020; Ma *et al.*, 2022).

***Ecklonia maxima*:** A brown macroalga, improves salinity and water stress tolerance in tomato, potato, spinach, and lettuce by regulating biomass distribution, root/shoot ratio, and antioxidant defenses (Kulkarni *et al.*, 2019; Shahrajabian *et al.*, 2021; Righini *et al.*, 2023). Its extracts enhance chlorophyll content, phenolic production, and nitrogen use efficiency in common beans, chicory, and barley, while also extending lettuce shelf life by 21 days at 4°C (Kulkarni *et al.*, 2019; Miceli *et al.*, 2021; Righini *et al.*, 2023). E. maxima SWE boosts date fruit yield, soluble sugars, and antioxidant potential, increasing DPPH inhibition by 12.20%, further supporting its efficacy in enhancing fruit quality (Li *et al.*, 2022b; Abdelaaziz *et al.*, 2024).

***Kappaphycus alvarezii*:** A red macroalga, contains carrageenans, carotenoids, and ascorbic acid, which promote root formation, photosynthetic pigments, and osmoprotectant accumulation in drought- and salinity-stressed crops (Zou *et al.*, 2019). In maize, its extract reduces biomass loss, enhances lateral root volume, and activates antioxidant enzymes, mitigating oxidative damage (Luziatelli *et al.*, 2019; Del Buono, 2021; Ma *et al.*, 2022). Rice root application (2–3%) improves biomass by 60%, nutrient uptake, and stress adaptation, demonstrating *K. alvarezii*'s potential for sustainable agriculture (Zou *et al.*, 2019).

***Protein hydrolysates (PH)*:** Derived from enzymatic, chemical, or thermal hydrolysis of plant residues (legumes, fruits, vegetables) and animal by-products (feathers, casein, collagen, fish waste), stimulate germination, enhance growth, improve fruit quality, and boost crop productivity, particularly under stress conditions (Jagadeesan *et al.*, 2023; Malécange *et al.*, 2023). PH are widely used in horticulture and floriculture, available in powdered, granulated, or liquid forms, contributing to waste reduction and the circular economy (Jardin, 2015). Most commercial PHs are animal-based with high nitrogen (9–16%), slow-release properties, and amino acids such as proline and glycine (Kumari *et al.*, 2022; Ma *et al.*, 2022). Collagen-based PHs enhance nitrogen assimilation, while plant-derived PHs, rich in glutamic acid, optimize carbon and nitrogen metabolism and stress resilience (Paul *et al.*, 2019; Sun *et al.*, 2024).

PH application increases soil microbial activity, root density, branching, enzyme secretion, and nutrient uptake efficiency, positively impacting crop yields and stress resistance (Kumari *et al.*, 2022; Ugolini *et al.*, 2023; Boutaleb, 2024). PH-derived peptides and amino acids regulate photosynthesis, antioxidant production, and stomatal conductance, improving water use efficiency (Baltazar *et al.*, 2021; Kumari *et al.*, 2022). PH-

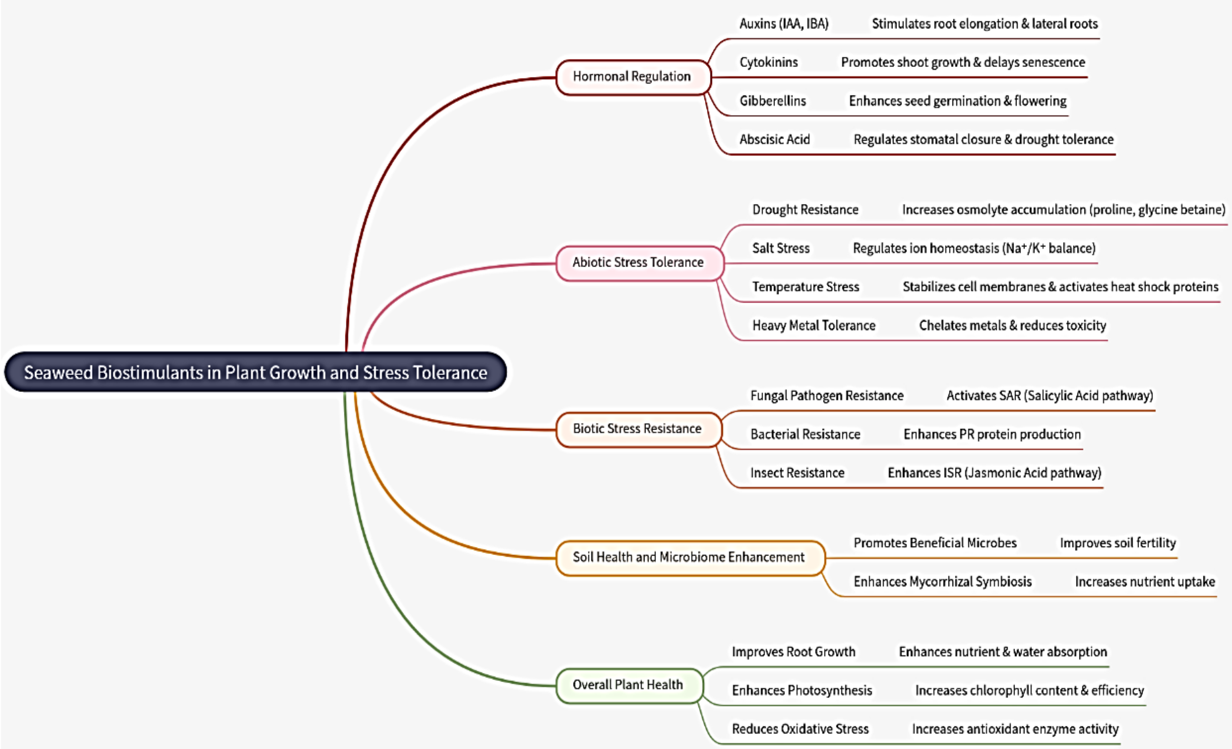

Figure 3. Role of Seaweed Biostimulants in plant growth and stress tolerance

based microgranules (0.5–4 $g\cdot L^{-1}$) increased shoot dry weight by 73% in aubergine, 61% in pepper, and 33% in tomato, while also enhancing root biomass by 37%, 34%, and 36%, respectively, though excessive doses decreased the chlorophyll a/b ratio (Di Mola *et al.*, 2020; Balan *et al.*, 2023). PHs significantly increased micronutrient uptake in spinach by 98.98% for Fe, 127.09% for Zn, 125.93% for Mn, 68.52% for Cu, and 230.76% for Se (Ugolini *et al.*, 2023). Plant-derived PHs extended the fruit-setting period, improved fruit firmness, and increased soluble solids in strawberries (Cardarelli *et al.*, 2024).

PHs mitigate salinity, drought, and oxidative stress by activating antioxidant enzymes and secondary metabolites such as flavonoids, carotenoids, and phenolic compounds (Paul *et al.*, 2019; Sun *et al.*, 2024). A Malvaceae-derived PH (PH1, PH2, PH3) improved tomato biomass, photosynthesis, soluble solids, and lycopene accumulation under nitrogen-deficient conditions (Cardarelli *et al.*, 2024). Peptides in PH regulate stress-related genes, enhance root growth, and improve water retention, as observed in maize under salt stress (Ma *et al.*, 2022; Vaseva *et al.*, 2022). Animal-derived PHs, including gelatin hydrolysates, increase cucumber and maize growth by stimulating amino acid transporter genes (AAP3, AAP6) and modulating iron metabolism, outperforming $FeCl_3$ or FeEDTA treatments in Fe-deficient conditions (Rouphael *et al.*, 2020; Li *et al.*, 2022a).

Chicken feather-derived PHs (2 $g\cdot L^{-1}$) increased plant height, leaf number, root biomass, and chlorophyll content in tea plants, while hydrolyzed slaughterhouse sludge improved pepper growth, fruit number, and vitamin C content (Agliassa *et al.*, 2021; Jagadeesan *et al.*, 2023). PH application to tobacco adjusted metabolism towards amino acid accumulation, phenylacetic acid synthesis, and heat shock protein expression, increasing resilience to heat stress (Sun *et al.*, 2024). A 0.2 $g\cdot L^{-1}$ foliar PH spray in petunias increased flower number by 230%, leaf area by 1,487 cm^2, dry weight by 35 g, and enhanced P and K uptake by 21.6% and 41.0% (Rouphael *et al.*, 2020).

PH-based biostimulants significantly enhance lettuce and tomato growth under salinity stress, increase maize biomass in hydroponic conditions, and improve seed yield in *Cannabis sativa*. PHs activate stress-responsive genes (CAT3, OXI1), regulate nitrogen metabolism, and enhance osmolyte accumulation, improving drought tolerance in tomato and canola (Mandal *et al.*, 2023; Sun *et al.*, 2024). Foliar PH applications in *Arabidopsis thaliana* and *Cucumis sativus* induced systemic resistance, upregulating genes involved in antioxidant and salicylic acid pathways (Zou *et al.*, 2019; Choi *et al.*, 2022). PHs rich in glycine betaine and glutamic acid improved tomato pollen viability, yield, and antioxidant capacity (Francesca *et al.*, 2021). A commercial PH (Kaishi®) induced heat tolerance in maize by overexpressing heat shock proteins (HSPs) and dehydrins (RAB18), while

Table 2. Research gaps, recommendations, and future directions

Research gaps	Recommendations	Future directions
Limited understanding of mode of action	Employ advanced omics technologies (genomics, proteomics, metabolomics) to elucidate biochemical pathways.	Conduct molecular-level studies to understand how biostimulants interact with plant metabolic pathways.
Variability in efficacy across crops and environments	Develop standardized protocols for testing biostimulant efficiency across diverse agroecosystems.	Investigate soil-specific and crop-specific responses to different biostimulants.
Synergistic effects and optimal formulations	Explore optimal combinations of microbial and non-microbial biostimulants for maximum plant growth benefits.	Conduct extensive field trials to determine the best biostimulant blends for different climatic conditions.
Long-term soil health and microbial ecology	Study the impact of repeated biostimulant applications on soil microbial diversity and ecosystem sustainability.	Implement long-term trials to monitor changes in soil biodiversity and fertility over multiple growing seasons.
Scalability and cost-effectiveness	Develop cost-effective production methods and harmonize regulatory guidelines for global market acceptance.	Promote large-scale manufacturing and affordable pricing models for small-scale farmers.
Integration with precision agriculture	Integrate biostimulants with digital farming technologies, remote sensing, and AI-driven decision-making tools.	Develop AI-driven predictive models to optimize biostimulant application based on real-time environmental data.

another PH-based biostimulant improved nitrogen metabolism and osmolyte accumulation in lettuce, increasing biomass by 40% under optimal conditions and 20% under drought (Vaseva *et al.*, 2022; Malécange *et al.*, 2023).

Humic substances (HS)**:** Comprising humic acids (HA), fulvic acids (FA), and humins, constitute ~60% of global soil organic matter, originating from plant and animal decomposition and microbial activity, with sources including soil, compost, peat, and vermicompost (Rouphael *et al.*, 2020; Sible *et al.*, 2021a; Kumari *et al.*, 2023b). HA are soluble in alkaline media, FA in both acidic and alkaline media, and humins form macromolecular complexes with humic and non-humic materials (Sible *et al.*, 2021a; Kumari *et al.*, 2023b). HS improve soil productivity, enhance microbial activity, and facilitate nutrient availability, with efficacy depending on origin, as HA from compost enhance chicory growth more than lignite-derived HA, while HA from municipal waste benefit maize (Sible *et al.*, 2021b; Canellas *et al.*, 2024). Commercial HS are more concentrated than those in natural soils, and agricultural by-products can be processed into humic-like substances under controlled conditions (Jardin, 2015; Sible *et al.*, 2021a).

HS contain sugars, polypeptides, fatty acids, and aromatic compounds, held together by hydrophobic and hydrogen bonds, with functional groups like hydroxyls, carboxyls, and phenols increasing their reactivity in soil (Cha *et al.*, 2020; Ma *et al.*, 2022). HA mimic IAA, stimulating root elongation and nutrient uptake by increasing membrane permeability and chelating cations, while also improving soil structure by enhancing aggregate stability and water retention (Braziene *et al.*, 2021; Sible *et al.*, 2021a). It facilitate soil-atmosphere carbon exchange and regulate nutrient bioavailability by binding Fe and reducing nutrient leaching (Braziene *et al.*, 2021). It reduce heavy metal toxicity by complexing metals, limiting plant uptake, and enhancing Fe and P absorption when combined with FeEDDHA, improving nutrient status in tomatoes (Shahrajabian *et al.*, 2021; Kumari *et al.*, 2023a). Humic acid application increases K, P, Ca, Mg, and Si in strawberries, enhancing yield, while FA penetrate cell membranes due to their low molecular weight, improving seed germination and root growth in wheat and barley (Capstaff *et al.*, 2020; Andreotti *et al.*, 2022). FA also activate nitrogen metabolism and nutrient transport genes in *Medicago sativa*, improving Mg uptake and boosting chlorophyll levels, enhancing photosynthetic efficiency in *Vigna radiata* (Cha *et al.*, 2020; Bayat *et al.*, 2021).

HS modify rhizosphere microbial activity, supporting plant growth by stimulating photosynthetic pigments, carotenoids, phenols, flavonoids, and N, P, K uptake (Rai *et al.*, 2021; Rosolem *et al.*, 2024). HA exhibit hormone-like activity by interacting with plant hormone signaling, inducing nucleic acid, vitamin, amino acid, and phytohormone synthesis (Rouphael and Colla, 2020; Francesca *et al.*, 2021; Shahrajabian *et al.*, 2021; Asif *et al.*, 2023). HS increase stress tolerance by enhancing osmotic adjustment, antioxidant activity, and secondary metabolism, mitigating salinity- and drought-induced ROS accumulation through activation of SOD, CAT, APX, and GR enzymes, and promoting osmoprotectants like proline ((Del Buono, 2021; Ma *et al.*, 2022). HS reduce oxidative stress and enhance salt tolerance in maize, while improving NO_3- metabolism and the TCA cycle in lettuce and pepper under saline conditions (Cha *et al.*, 2020; Nephali *et al.*, 2020). HS increase chlorophyll production, photosynthetic rate, and water use efficiency in *Brassica napus* and *Hibiscus sabdariffa*, while also upregulating drought-responsive genes like *DREB2A* and *HsfA6a*, enhancing heat tolerance in *Arabidopsis thaliana* (Braziene *et al.*, 2021; Ma *et al.*, 2022). HA protect sorghum from salt stress, FA enhance nutrient uptake under salinity, and both improve hormonal pathways, regulating stress responses in maize (Cha *et al*., 2020; Del Buono, 2021).

Conclusion: Biostimulants offer a promising path towards sustainable agriculture, their widespread adoption remains hindered by scientific, economic, and regulatory challenges. The inconsistent efficacy across different soil types and climatic conditions raises concerns regarding their reliability. Additionally, the lack of standardized regulatory frameworks limits their large-scale commercialization and farmer adoption. Although biostimulants can reduce dependency on synthetic fertilizers and pesticides, their cost-effectiveness compared to conventional agrochemicals needs further validation. Future agricultural strategies must integrate biostimulants within a holistic framework that includes precision farming, soil health restoration, and climate-smart agricultural practices. Investments in biotechnological research, long-term field studies, and interdisciplinary collaborations are essential to refine biostimulant formulations and enhance their predictability and effectiveness. Furthermore, policymakers must establish clear regulations and incentive structures to encourage biostimulant adoption while ensuring environmental safety. Ultimately, biostimulants should not be viewed as a standalone solution but rather as part of a broader sustainable agricultural approach. By addressing the current research gaps and implementation barriers, biostimulants can play a crucial role in transforming global agriculture into a more resilient, resource-efficient, and environmentally sustainable system as explained in Table 2.

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SDGs addressed: Zero Hunger, Responsible Consumption and Production, Climate Action.

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