PLANT SCIENCE TODAY
Vol 12(sp1): 1-11
https://doi.org/10.14719/pst.8499

eISSN 2348-1900

REVIEW ARTICLE

Impact of biostimulants on crop growth and soil health - A review

Kaviya Thennarasu[1], Ramah Kandasamy[2*], Sakthivel Nalliappan[2], Sivasakthivelan Panneerselvam[2] & Senthilvalavan Pitchamuthu[3]

[1]Department of Agronomy, Tamil Nadu Agricultural University, Coimbatore 641 003,Tamil Nadu, India
[2]Agricultural Research Station, Tamil Nadu Agricultural University, Bhavanisagar 638 451, Tamil Nadu, India
[3]Department of Soil Science and Agricultural Chemistry, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

*Correspondence email - kr74@tnau.ac.in

Received: 25 March 2025; Accepted: 17 July 2025; Available online: Version 1.0: 29 August 2025; Version 2.0: 29 September 2025

Cite this article: Kaviya T, Ramah K, Sakthivel N, Sivasakthivelan P, Senthilvalavan P. Impact of biostimulants on crop growth and soil health - A review. Plant Science Today. 2025; 12(sp1): 1-11. https://doi.org/10.14719/pst.8499

Abstract

Biostimulants are essential for advancing sustainable agriculture by promoting plant growth, soil health and crop productivity. It is derived from organic materials, including microbial and non-microbial components, which undergo an activated biological and physiological process that stimulates nutrient uptake, resists stressful conditions and also regulates plant metabolism. It includes microbial components such as Arbuscular Mycorrhizal Fungi (AMF) and Plant Growth Promoting Rhizobacteria (PGPR) and other non-microbial components like protein hydrolysates, seaweed extracts, humic acid, fulvic acid, chitin and chitosan based biostimulants, which plays a significant role through different mode of actions such as modulation in plant hormone, activating antioxidant responses, water and nutrient absorption in soil and crop resilience. Their applications across various agricultural and horticultural crops, where they exhibited enhanced nutrient efficiency, eliminated environmental stress and promoted eco-friendly farming methods. Furthermore, biostimulants showed promising solutions for problematic soils. This review explores the applications of biostimulants and their influence on ensuring food security, enhancing nutrient uptake and stimulating natural processes, improving crop quality, yield and reducing dependency on synthetic fertilizers. Further research should focus on the timely application of biostimulants and their formulations for different crops to increase their potential benefits across agricultural systems.

Keywords: biostimulants; crop productivity; soil health; stress tolerance; sustainable agriculture

Introduction

The green revolution and high-yielding varieties require excess chemical fertilizers, that has led to the degradation and a decline in soil health and microbial activity. Despite the large amounts of fertilizers applied to the soil, only a small portion is effectively absorbed by crop plants, while the remainder is lost to the environment, contributing to soil and water pollution. Soil fertility is also threatened by chemical pollutants such as trace iron residues from drinking water treatment, which adversely affect soil fertility and nutrient dynamics. Recent economic analyses have shown that even low concentrations of these contaminants can lead to sustained yield loss and increase input costs (1). Additionally, biotic and abiotic stressors suppress crop growth; in turn, there is a decrease in global agricultural production every year. Organic farming offers a sustainable approach to address these challenges; however, maintaining high productivity while minimizing chemical fertilizer use necessitates the adoption of alternative strategies. In this situation, Biostimulants serve as a practical approach in enhancing agricultural productivity as well as sustaining the soil health for future generations. The global market for biostimulants is valued at approximately 4.5-5.5 billion in 2024 and projected to reach USD 9 billion by 2030. Recently, North America and Europe hold a 61 % market share. This highlights that the Asia-Pacific region is expected to reach the highest CAGR (Compound Annual Growth Rate) by 2035, prompted by increasing demand for sustainable agriculture. This trend reflects the growing adoption of biostimulants for the growth and development of crops (2).

Biostimulants are substances or microorganisms that, when applied to the plants they enhance nutrient uptake, stimulate natural processes, improve stress tolerance and increase crop quality and yield without acting directly as fertilizers (3). They are classified into different categories, including plant extracts, protein hydrolysates, humic substances, seaweed-based products and microbe-based components. Each category of biostimulants has unique properties that influence plant hormone activity by modulating phytohormones like auxins, gibberellins and cytokinins and improving stress tolerance by promoting Osmo protectants, secondary metabolites and antioxidant activity (4). Protein hydrolysates serve as precursors for plant metabolism, promoting stress resistance and nutrient efficiency in crops. Humic and Fulvic acids improve soil structure, enhance nutrient availability and stimulate plant root growth. Microbial biostimulants include beneficial bacteria such as PGPR and fungi like Mycorrhizae, which will enhance the nutrient solubilization and uptake by crops (5).

Biostimulants offer multiple advantages in crop production and soil health by reducing the dependency on synthetic fertilizers while helping plants to withstand abiotic stresses. They promote microbial activity, increase organic matter content, improve soil structure and water retention capacity, enhance the shelf life of crops, maximize yield and minimize runoff, thereby reducing soil degradation and environmental pollution. Hence, the applications of biostimulants have a positive influence on both plant and soil ecosystems. Biostimulants are a promising approach for modern agriculture by improving crop performance and preserving soil health. Their wide range of sources and multifunctional benefits make them a valuable tool for modern farming, reducing the dependency on synthetic inputs and mitigating the environmental stress. Beyond biostimulants, the adoption of complementary technologies such as biochar, nutrient-rich byproduct from biogas systems and digestate-derived biochar not only facilitates nutrients but also acts as an efficient carrier material for microbial biostimulants. The studies have shown that phosphorus recovery from biogas fermentation residues can offer a promising economic return (6). A novel application of biochar can reduce nitrate leaching and greenhouse gas emissions (7). Additionally, silica nanoparticles, which are synthesized from Agroindustrial residues such as coir pith, have been shown to enhance bioactive compounds, increase germination efficiency, nutrient uptake and also offer benefits for both crop performance and economic viability and these integration approaches are prospective directions for future research (8). This review explores the different sources of biostimulants, applications of various biostimulants and their influence on crop growth, productivity and soil health.

Sources of biostimulants

Biostimulants are synthesised from various sources, *viz.*, microbial, non-microbial and waste derived products. They are classified into 2 important groups, namely microbial and non-microbial, as shown in Fig. 1. The waste-derived or byproduct-derived biostimulants come under the non-microbial group as they have identical production processes to non-microbial (9). Microbial biostimulants contain microorganisms or microbial-derived compounds that enhance plant growth and stress tolerance by improving root development, increasing nutrient uptake and promoting plant growth through the mechanisms of hormone production, such as auxins, gibberellins, stimulating enzyme activation and secondary metabolite synthesis (10). On the other , microbial biofertilizers contain living microorganisms, which enhance nutrient availability by fixing nitrogen, phosphorus, or potassium through nitrogen-fixing bacteria and Phosphate-Solubilizing/mobilizing bacteria (11). Non-microbial biostimulants are substances or formulations that do not contain living microorganisms but waste-derived products such as seaweed extracts, protein hydrolysate, humic and fulvic acid, used to improve the growth, development and productivity of plants and soil (12).

Microbial biostimulants

Microbial biostimulants are composed of PGPR, AMF and microalgae. The PGPR directly influences the mechanism of higher nutrition acquisition, osmolytes, phytohormone productions like Indole-3-Acetic Acid (IAA), Gibberellic Acid (GA_3) and cytokinin which indirectly influence the disease resistance, abiotic stress tolerance and also help in Reactive Oxygen Species (ROS) scavenging in crops (13). AMF play a major role through different modes of action such as modifications of root architecture, activating antioxidant responses, induction of Abscisic acid (ABA) plant hormone and increasing water and nutrient absorption by the plants. They also enhance plant nutrition availability by translocating and absorbing minerals and nutrients beyond the plant rhizosphere, improving nutraceutical compounds content such as polyphenols, flavonoids, polysaccharides and other bioactive compounds (5). The AMF protects the photosynthetic apparatus from drought stress, improves leaf water potential, osmolytes and photosynthetic efficiency (14, 15). Similarly, photo hormone level modulation, increasing antioxidant activity, nutrient enhancement antagonism and osmolyte production, which helps for better growth and yield as well as soil health. The microalgal biostimulants are extracted from microalgae, which are photosynthetic microorganism which has the ability to produce a greater number of beneficial compounds. It contains bioactive compounds like amino

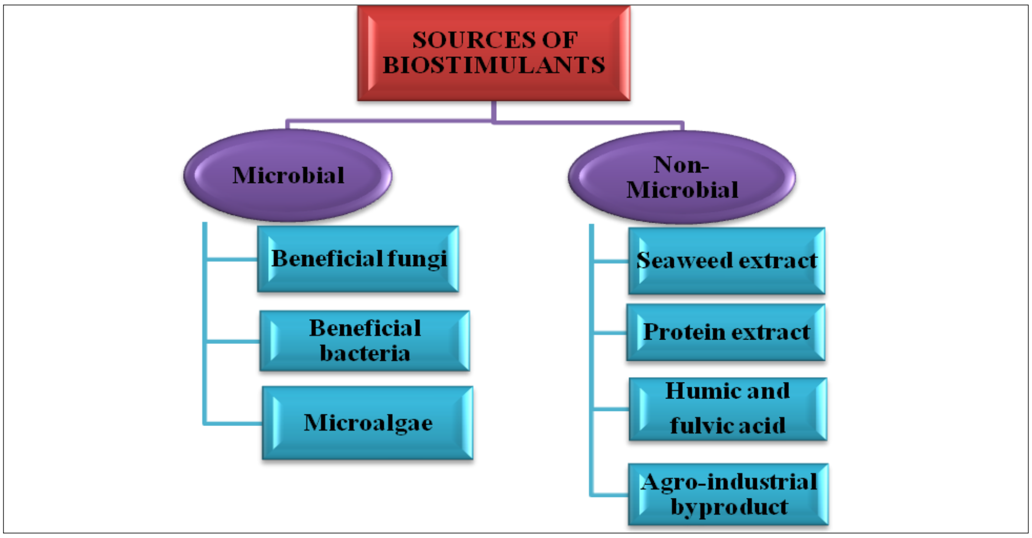

Fig. 1. Classified sources of biostimulants.

acids, polysaccharides, phytohormones and vitamins that enhance plant growth and development (16). The primary mechanism of microalgal biostimulants is that they act as stress tolerance to plants, particularly to reduce the effect of heavy metals and salinity by acting as Osmo protectants and also contributes its central role in increasing crop productivity, soil health and nutrient uptake (17, 18). Incorporating microalgae into hydroponics farming systems, results in nutrient recycling and enhance plant growth (19, 20). Microalgae species, such as *Chlorella spp., Spirulina platensis, Acutodesmus spp., Scenedesmus spp., Dunaliella spp.* and *Calothrix elenkini*, are commonly used as biostimulants. Recent studies have shown that *Chlorella vulgaris* extracts can improve root and shoot biomass, while *Spirulina platensis* has been reported to enhance chlorophyll content and photosynthetic activity. Similarly, *Scenedesmus obliquus* and *Acutodesmus dimorphus* exhibit plant growth-promoting effects through phytohormone production and nutrient enrichment of the soil (21).

Non-microbial biostimulants

Seaweed extract

Seaweeds, which are naturally derived biostimulants such as macroscopic, multicellular marine algae from coastal ecosystems. The most common seaweed extracts are prepared from red, green and brown macroalgae that are used for both agricultural and horticultural crops. Seaweed extract has become a prominent replacement to chemical fertilizers as a natural and biodegradable biostimulant. Seaweed extracts contain phytohormones like auxins, cytokinins and gibberellins along with enzymes, vitamins, hydrolyzed proteins polysaccharides and other nutrients as explained in Fig. 2. These natural plant growth modulators significantly enhance crop yield by stimulating plants metabolic functions. Seaweed extract is one of the finest substitutes for synthetic inputs, helping to sustain both yield and quality of the crop (22). It is well known for its ability to reduce abiotic stress and increase plant yield (23). Seaweed extracts can be applied in multiple ways, including soil applications, foliar spraying and seed treatment. Among these, foliar spraying is the most effective method for nutrient application in plant production. Additionally, seaweed extract plays a crucial role in reducing pesticide usage by utilizing organic molecules found in seaweed. Beyond its nutritional components, seaweed contains essential macronutrients like nitrogen, phosphorus, potassium, calcium, magnesium, sulphur and chlorine as well as micronutrients such as iron, zinc, copper, molybdenum, manganese and boron. Along with plant biostimulants, seaweed extract will be part of next-generation natural organic fertilizers that promote growth and productivity, supplying highly effective nutrients and strengthen crop resistance to biotic and abiotic stresses (24). Studies suggest that *Ascophyllum nodosum* is a commonly used seaweed, which is responsible for cold stress tolerance, plant defence mechanism against pests and pathogens. Seaweed species vary in mineral composition, making them suitable for agricultural and horticultural applications. For example, the high nitrogen content of *Mastocarpus stellatus* (3.8 %) and *Fucus serratus* (2.7 %) can mitigate nitrogen deficiency and promote plant growth. Similarly, high levels of potassium in *Laminaria hyperborea (*8.1 %) and *Halidrys siliquosa (*4.7 %) are suitable for recovering potassium deficiencies. *Ascophyllum nodosum (*42.5 %) and *Fucus serratus (*35.5 %) with high calcium content are ideal for calcium-deficient soils and enhance soil structure (25).

Methods of preparation

The water extraction method is a standard method for extracting seaweed. In this method, 100 g of a dried seaweed sample was collected and mixed with deionized water to achieve a final volume of 1 L. Then, the mixture was stirred continuously using a magnetic stirrer at 70 °C for 3 hr. After stirring, filter the mixture using cheesecloth and centrifuge for 15 min. Finally, the resulting supernatant is collected (26). Acid extraction method, 500 g of frozen sample is blended with deionized water using a laboratory blender and then make a final volume of 1 L. The pH of the mixture is adjusted to 3.0 ± 0.1 using sulfuric acid (H_2SO_4). Then the solution is placed in

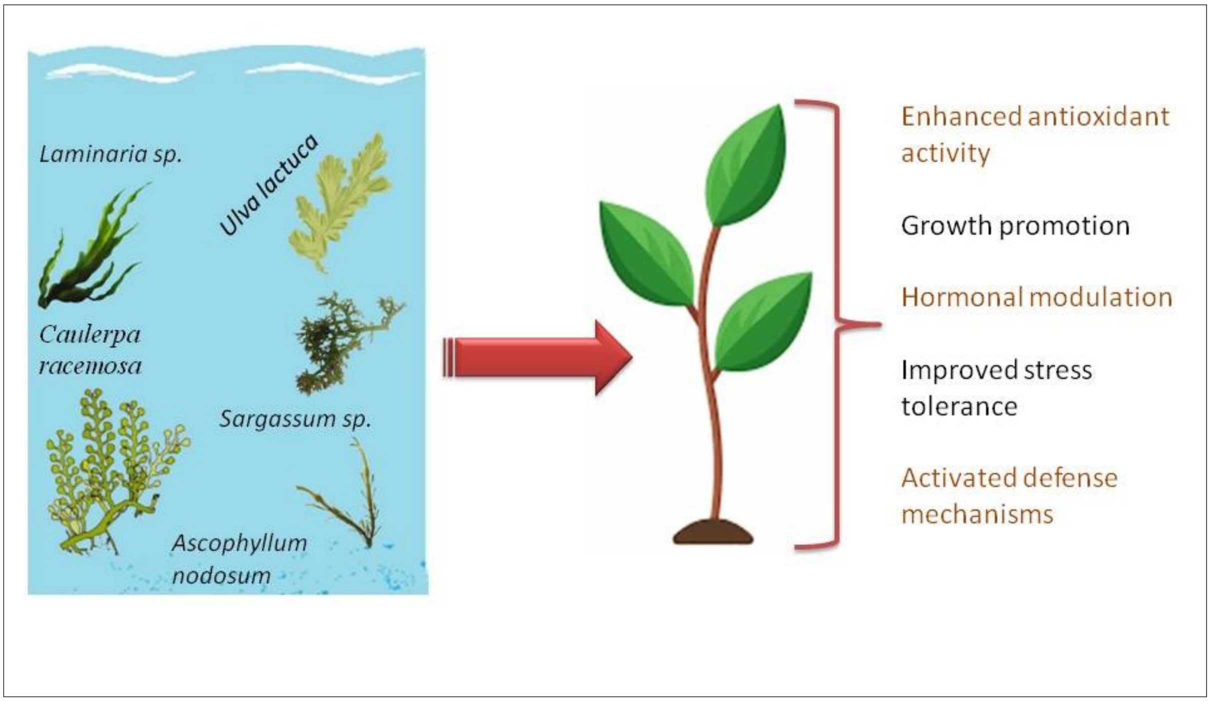

Fig. 2. Seaweed spp. with their mode of action.

hot water bath at 45 °C for 30 mins and centrifuged for 15 min. The supernatant is collected using cheesecloth and the pH is neutralized to 7.0 ± 0.1 using KOH (27). The alkali extraction method is widely used; the procedure was similar to acid extraction until the centrifugation step. Then the pH is adjusted to 12.0 ± 0.1 by using KOH. The solution is incubated in a hot water bath at 80℃ for 3 hr and centrifuged for 15 min. The final supernatants were collected (28).

Humic and fulvic acid

Humic and fulvic acids are naturally occurring organic substances derived from the decomposition of organic matter, resulting in a blend of acids that comprise phenolate and carboxyl groups (29). Both humic and fulvic acids are organic molecules, which are known as humic substances. While the chemical and physical properties of fulvic and humic are distinct, both play a significant role in the physical and biological properties of the soil, improving nutrient availability and enhancing plant growth and development (30). The humic acids are present in the medium with molecular weight and it is insoluble in water. It has the ability to form complex soil structure, enhance the water retention process and improve microbial activity. Additionally, they function as chelating agents, enhancing the accessibility of essential micronutrients in the soil (31). The fulvic acid, which is smaller in molecular weight and soluble in both acid and alkali. It plays a vital role in nutrient translocation from the plant surface to various tissues and also acts as a plant growth regulating pathway to promote growth and stress resistance of the plant (32). Humic acid was extracted from vermicompost, which is an organic material resulting from organic waste decomposed by earthworms and the process of extraction method is explained in Fig. 3 (33).

Protein hydrolysate

Protein hydrolysate biostimulant is the mixture of peptides and amino acids, which were produced through enzymatic, chemical, thermal hydrolysis of animal or plant- derived protein (34). Protein hydrolysates help in improving crop productivity by influencing physiological processes. The protein hydrolysate has the potential to enhance plant health under environmental stress conditions and influence microbial interactions described in Fig. 4. Further, this involves the mechanism of improving hormonal activity, stimulating metabolism and regulating nutrient transport to enhance plant growth and development (35). In the method of protein hydrolysate preparation, a mixture of protein source and enzyme is mixed in 1:300 (w/w) ratio. Then the mixture is incubated at 37 ℃ for 4 hr with constant stirring. After incubation, the mixture is placed in a boiling water bath at 100 ℃ for 10 mins to inactivate the enzyme. The mixture is then centrifuged to remove insoluble fragments. Then, the supernatant is collected and preserved by the lyophilization (freeze-drying) method and stored at - 20 ℃ until further use (36).

Chitin and Chitosan-based biostimulants

Chitin and chitosan-based biostimulants are natural compounds derived from crustaceans and insects. Chitosan is derived from the deacetylation of chitin, which has gained attention in recent decades for its beneficial impacts on crops. This is a commercially produced substance, enhancing plant growth by inducing the production of protective molecules against pathogens, as shown in Fig. 5. Chitosan is an eco-friendly polymer, which is effective in controlling environmental pollutants (37). It is involved in promoting plant growth by stimulating the production of secondary metabolites (38). In the method of chitosan preparation, the first step involves removing proteins by deproteinization from crustacean shells using a concentrated NaOH solution. The deproteinized shells are then immersed in a dilute HCl solution to eliminate minerals, such as calcium carbonate, through demineralization. Following demineralization, pigments or any impurities are removed using organic solvents to obtain pure chitin. To convert chitin to chitosan, the deacetylation process

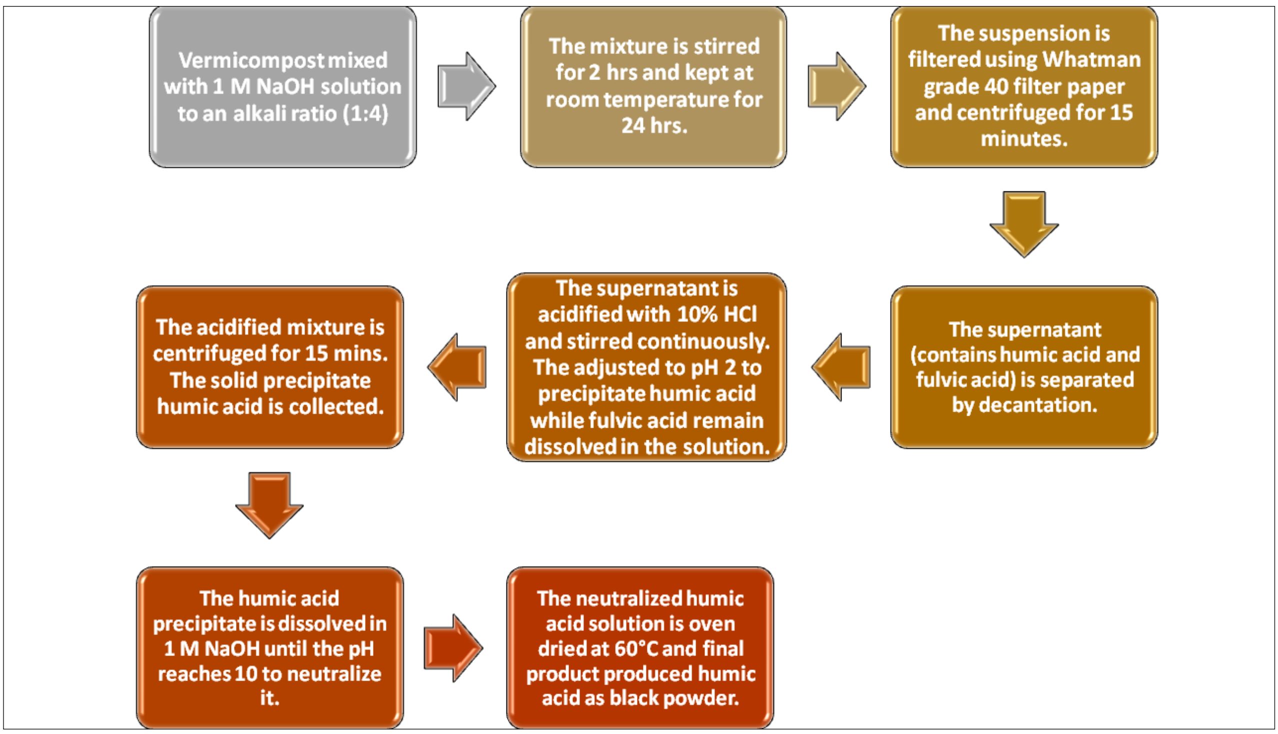

Fig. 3. Flow chart for the preparation of humic acid.

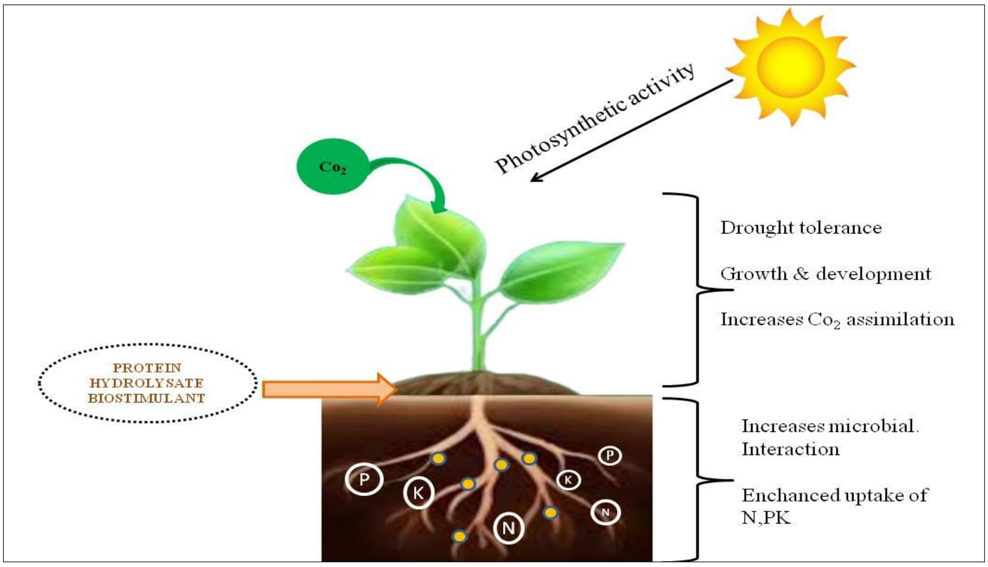

Fig. 4. Protein hydrolysate biostimulant and its influence on the plant.

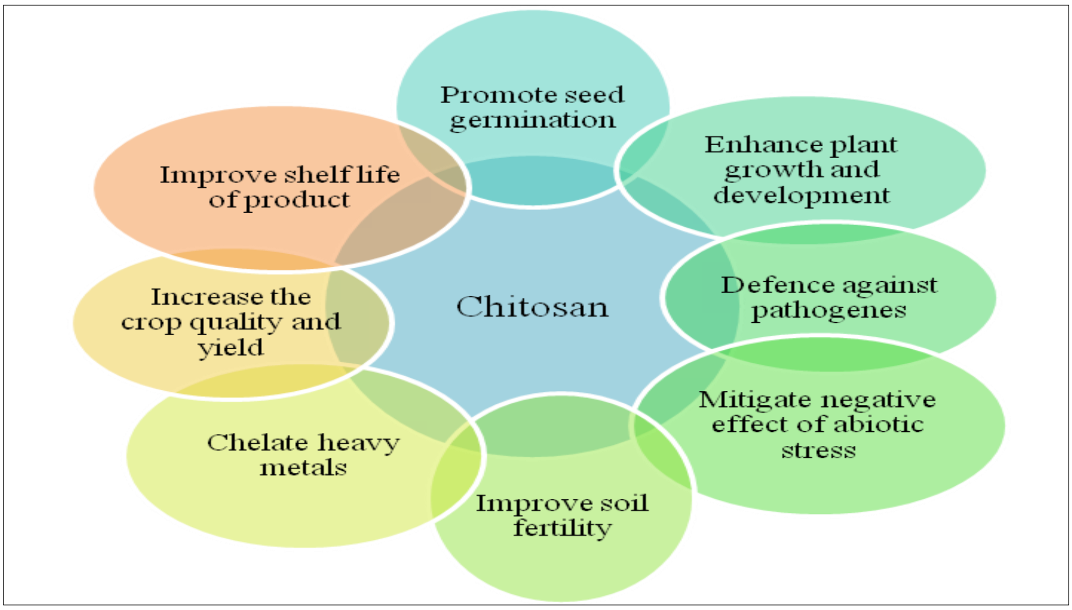

Fig. 5. Chitosan with its functions towards plants.

is followed by treating chitin with concentrated NaOH at high temperature. The obtained chitosan form of solution is dissolved in dilute acidic solutions. Chitosan has the potential to increase plant growth and prolong the storage life by decreasing heavy metals and also improves soil properties (39).

Application of biostimulants in agricultural and horticultural crops

Cereals : The rice plant was treated with seaweed extract of *Ascophyllum nodosum* at a concentration of 0.5, 1.0 and 1.5 ml/ L of water along with growth regulators. The concentration of 2.5 ml resulted in the highest leaf area index, chlorophyll content, dry matter production and also mitigated water stress (40). Biostimulants such as Soligro, Opterine Liquid and Biozyme, made from the Ascophyllum nodosum, recorded higher yield, increased nutrient uptake and enhanced beneficial microbial population in soil (41). Seed treatment of rice with *Bacillus megaterium* at the rate of 10 g/kgseeds improved seed germination, seed vigour, shoot length, root length and number of leaves at the seedling stage (42). Rice plants under greenhouse conditions in Northern Malaysia treated with *Bacillus tequilensis* improved plant height, grain yield and stomatal conductance while reducing the transpiration rate (43). The bio efficacy of various foliar applications of biostimulants such as silife, humic acid, triacontanol and vermi wash for nutrient uptake and yield of rice crop under lateritic soils of Konkan region during the *kharif* season, foliar spray of silife at a concentration of 0.4 % significantly enhanced panicle length, number of grains per panicle and yield of rice, followed by humic acid at a concentration of 1 % (24). Seaweed extract-based products, such as seaweed liquid @ 0.25 % and seaweed granules 25 kg ha^{-1}, derived from *Rhodophyta* and *Phaeophyceae* algae, effectively increased rice yield and nutrient uptake (22). The effect of foliar application of sea grow powder at a concentration of 1.5 g/L significantly increases rice growth and yield in Maharashtra (44). The impact of microbial biostimulants on growth and yield of wheat (*Triticum aestivam L*) and oats (*Avena sativa*) were examined using probiotics such probiohumus and naturgel with concentration of 2 μL/g was used for seed priming, results in an increased yield by 0.5 t/ha - 1.09 t/ha and increased protein accumulation in the grains (45). The application of Zn+ fulvic acid and Zn+ amino acid enhanced Zn concentration in grain, compared to foliar application of Zn alone in wheat (46). Seaweed extract (phytozyme) at different growth stages in maize significantly improved yield attributes and economics (47). Microbial-treated maize performed well under both irrigated and drought conditions and increased amino acid levels (48). The effect of protein hydrolysates on the amino acid profile of maize seedlings was studied using a mixture of humic substances. The results showed that the protein hydrolysates stimulated amino acid production and improved maize growth. Hence, humic substances enhanced the effect of biostimulants. Similarly, evidence indicates that the protein hydrolysate-based products positively influenced wheat productivity, improving both yield and quality parameters (49). On the other hand, nitrogen fertilizer usage was also reduced (50).

Pulses : The application of fish amino acid and seaweed sap in green gram (*Vigna radiata*) resulted in higher yield and better economic returns during summer (51). Chickpea treated *(Cicer arietinum L*) treated with 2 % seaweed extract *(Ascophyllum nodosum)* showed increased growth and yield parameters (52). An experiment on two common bean (*Phaseolus vulgaris L.*) cultivars (Toska and Kelpak SL) with the foliar spray at the rate of 0.2 and 0.4 %, resulted in an increased number and weight of pods, as well as higher protein content in the grains (53). The application of fulvic acid as seed priming and foliar spray at 1.5 and 3g/L significantly improved seed yield and growth parameters in pea (*Pisum sativum*) (54). In pea (*Pisum sativum L. var. Meteor*), improved chlorophyll content, increased number of pods, higher fresh and dry weight of pods were recorded (55). Humic acid as foliar application at 300 mg L^{-1} during mid-vegetative influenced the plant height, harvest index and nutrient content (56). In *Vigna aconitifolia,* through foliar spray and soil application of *Ascophyllum nodosum* derived seaweed extract at different concentrations of 0.01 %, 0.02 %, 0.05 % 0.10 %, 0.50 % and 1.00 % were evaluated. The application of 0.5 % and 0.10 % as foliar spray and soil application resulted in increased number of pods, organic matter content, moisture percentage, number of leaves, leaf area and photosynthetic pigments (57). The foliar application of Quantis biostimulant at 2.5 ml/L in black gram and seed treatment of Epivio Energy at 200 ml/100 kg recorded higher growth and yield in black gram and soybean, respectively (58).

Oilseeds : The combination of sulphur and seaweed extract from *Kappaphycus alvarezii* resulted in higher yield parameters, including dry weight, number of pods/plants, seed index and kernel yield in Groundnut (59). Extracts from *Gracilaria tenuistipitata var. liui* seaweed increased growth and yield while also influencing drought tolerance in soybean (60). Foliar application increased growth and economic yield in soybean (61) and also improved the nutritional quality, functional compounds and productivity of soybean under greenhouse cultivation (62). The combined application of seaweed and humic acid on rapeseed (*Brassica napus L.*) increased seedling length, root length, relative water content, total phenolic compounds and superoxide dismutase. Also, it induced the antioxidant protective mechanism against stress conditions (63). *Bacilli rhizobacteria* helped sesame plants to mitigate the water deficit effect by improving physiological and biochemical responses (64).

Horticultural crops : The seaweed extract (*Ecklonia maxima*) applied to spinach increased Molybdenum concentration and quality @ 8 µmol/L (65). Humic and fulvic acid positively influenced the growth and flowering in *Achillea millefolium L* (66). In tomato plants, protein hydrolysates mitigated drought stress, two protophyte plant-derived protein hydrolysates, enhancing plant resistance to water stress (67). Similarly, the legume-derived protein hydrolysate improved growth and productivity in tomato and cucumber, even under Fe deficiency conditions (68). The use of chitosan nanoparticles at 0.4 mg m/L improved yield, enzymatic activity and bioactive compounds in lettuce (*Lactuva sativa L.*) (69). The application of humic acid in pumpkin increased the germination percentage and seed vigor under cadmium stress (70). In brinjal, biostimulants such as tryptophan and silicic acid were evaluated with foliar spray of tryptophan @ 200ppm, enhanced chlorophyll content, plant growth and water retention capacity (71). The eggplant treated with biostimulant of *Bacillus spp.* and brown seaweed extract as *Sargassum vulgare* resulted in significantly improved eggplant growth and productivity (72).

Applications of biostimulants to problem soils

Soil is a natural resource that supports the life of plants, animals and humans by maintaining ecosystem health. However, not all soils are healthy and productive. Such soils are known as problem soils due to their limitations on physical and chemical properties such as low pH, high salinity, toxic metal content, compaction and loss of organic matter. These issues negatively impact agriculture by causing poor crop yields, nutrient deficiencies, soil erosion and reduced productivity (73).

Saline soil : Saline soil is defined as the soil that has a higher level of soluble salts with an EC of > 4 dS/m @ 25 ^{0}C (74). Irregular rainfall, poor drainage facilities and irrigation water quality are the main reasons for soil salinity (75). Biostimulants improve shoot length, chlorophyll and carotenoid contents by mitigating salt stress and simultaneously reducing $Na+$ accumulation (76). Tomato plants treated with plant-based biostimulants have shown improved growth and influenced biochemical responses in tomatoes (77). Biostimulant of Trainer® as a protein hydrolysate, increased chlorophyll content, hydrophilic antioxidant activity and improved yield of spinach (78). Protein hydrolysate promoted tomato yield under salinity stress conditions and enhanced osmotic adjustment (79). Microbial biostimulants increase the salinity tolerance of transplanted vegetables up to 50 mM NaCl (13). Aqueous seaweed extract (*C. antennina*) increases germination, growth and yield in rice by enhancing their physiological attributes by reducing the saline toxicity (80). Seaweed liquid extract fosters the plant growth and enhance the salinity stress tolerance in *Vigna sinensis* and *Zea mays* seeds (81). *Ascophyllum nodosum,* as a seaweed extract, enhanced the relative water content and root growth in transplanted watermelon in field conditions (82).

Sodic soil N: Sodic soil is soil that has a high sodium content and is characterized by a high level of Exchangeable Sodium Percentage [ESP], poor soil structure, decreased water infiltration, porosity, reduced microbial activity and soil fertility (83). Humic acid-treated sodic soil was more effective in the cultivation of rice plant, with increased quality parameters, micronutrients for yield and reduced chaffyness in grains (84). In *Vigna radiata,* application of *Halimeda microloba* as seaweed extract in sodic soil resulted in a reduction of pH from 9.8 - 8.0, electrical conductivity from 713.8 - 234.3 μs/cm and exchangeable sodium percentage level from 62 t- 21 %. Additionally, seaweed has been proven to be one of the promising biostimulants with a wide range of benefits (85). Application of *Ascophyllum nodosum* seaweed extract at the concentration of 0.25 kg/ha in soybean under greenhouse conditions positively influenced resistance to water scarcity and reduction in yield loss (86). Mechanisms of biostimulants are listed in Table 1.

Biostimulants as biocontrol agents

The foliar application of humic substances acts as a biocontrol agent against pathogens (87). The *Bacillus* genus of plant growth-promoting bacteria has demonstrated potential as a biocontrol agent in sustainable agriculture (88). Plant growth-promoting fungi of *Aspergillus flavus, Aspergillus niger, Mucor circinelloides* and *Penicillium oxalicum* act as a tool against *Fusarium wilt* in Tomato (89). PGPR and Humic acid reduce pesticide use by promoting pest resistance in plants (29, 90). Biostimulants from *Ascophyllum nodosum*, alfalfa and sugarcane extract, along with a low dose of synthetic fungicide, were effective against post-harvest green mold in orange fruits infected by *Penicilliumdigitatum* (91). Seaweed extract (*Ascophyllum nodosum*) with mycorrhizae controlled Rhizoctonia root rot and promoted the growth of pea and the seaweed extracts have phyto-stimulatory properties that act as a resistance to pests, diseases and abiotic stresses (92, 93). Cyanobacteria, nanochitosan and fulvic acid controlled the leaf rust disease in wheat (94). Commercial products available in the market are listed in Table 2.

Future aspects

Biostimulants are one of the best approaches for crops to achieve higher yields and quality. Based on the recent research publications, biostimulant is a more profitable way to mitigate the climatic changes and face the challenges to reduce the risk of hunger. Specifically, the use of fulvic acid and seaweed extracts in wheat has increased zinc concentration in grains, while organic biostimulants in rice cultivation have significantly improved grain and straw yields. While numerous instances demonstrate that biostimulant application has led to positive impacts on plant growth and yield, further research is necessary to refine application methods. Additionally, biostimulant use is more common in horticultural crops than in field crops, highlighting the need for more studies focused on field crops. On the other hand, application of biostimulants to problem soil also needs further research work. Agro-industrial byproducts related to biostimulants that need to be considered and adverse or negligible effects have also been documented. Increasing awareness and acceptance among farmers and consumers are important for the widespread adoption of biostimulants.

Table 2. Biostimulant products available in the market (101)

Trade name	Company name	Composition
Samras	Multiplex	Seaweed extract + humic substance
Greenmore-L	Multiplex	Seaweed extract
Biocure B Liquid	T.Stanes	*Bacillus subtilis*
EcoHume®	MARGO	Humic substance
Samrath Humisan	Samrath BioTech Ltd	Liquid humic acid
Vigore	Geolife Agritech India Pvt Ltd.	Amino acids + seaweed extract + humic substances
Black Dragob Gel	Hifield organic	Humic acid + seaweed extract + fulvic acid
Pioneer ProBio	Pioneer Agro	Microbial based
Seacal	Janatha Agro Products	Seaweed extract
AgroGain	Sea6 Energy	Red seaweed extract
Katyayani Premium	Katyayani organics	Seaweed extract

Conclusion

Biostimulants offer a sustainable alternative not only by promoting plant growth but also by influencing specific physiological pathways that enhance nutrient use efficiency and activate stress tolerance signaling compounds. Applications of biostimulants have shown promising results in various agricultural contexts. For instance, the application of humic acid and seaweed extracts in sodic and saline soils improves ion exchange capacity, mitigates the adverse effects of high salt concentrations and supports microbial activity that promotes the growth and development of crops such as rice. In wheat, protein hydrolysates have been shown to upregulate nitrate transporter genes, thereby increasing nutrient use efficiency under field conditions. Elucidating these mechanisms reveals the unique value of biostimulants as targeted, functional inputs. By enhancing soil health and plant resilience, biostimulants offer a promising approach to an economically scalable, environmentally sustainable solution for increasing agricultural productivity in the face of a growing global population.

Table 1. Biostimulants as plant growth promotor

Biostimulants	Mechanism	Benefits	Reference
Microbial	Metabolic regulations, hormone modulation and symbiotic interactions stimulate secondary metabolites and siderophores.	Improves available nutrients, stress tolerance, activates beneficial microbes, improves soil quality and promotes plant growth.	(95,96)
Seaweed extract	Altering the physiological processes such as phytohormones, polysaccharides, polyphenols and defense pathway through ROS	Enhance nutrient uptake, plant productivity and stress protection	(95)
Humic acid	Modulation of auxin, cytokinin pathways and ABA signaling pathways	Enhancement of nutrient uptake, root activity, stress tolerance and improving soil properties	(95, 96)
Fulvic acid	Increasing enzyme activity, hormone regulation, enhancing photosynthesis and metabolism.	Enhance plant growth, nutrient uptake and stress resistance.	(97)
Protein hydrolysates	Microbiome stimulation, antioxidant activity, hormonal activity and gene expression.	Enhance nutrient uptake, plant development, enhance beneficial microbes and stress tolerance.	(35,98)
Chitin and chitosan	Activate symbiotic signaling, enzymatic activity, cell division, cell elongation, induce secondary metabolites biosynthesis and protein synthesis	Stimulate beneficial microbes, vegetative growth and development, protect from plant pathogens, maintain chlorophyll and increase yield and quality.	(38,99)

Acknowledgements

Authors acknowledge the Agricultural Research Station, Tamil Nadu Agricultural University, Bhavanisagar - 638 451, Erode District, Tamil Nadu, India

Authors' contributions

KT collected the literature and designed the framework of the article. RK conceived the study and drafted the manuscript. SN reviewed and provided suggestions for improvement. SSV participated in the study design and corrected the article. SVP participated in the study design and coordination. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: The authors declare no conflicts of interest.

Ethical issues : None

References

1. Marousek J, Marouskova A, Zoubek T, Bartos P. Economic impacts of soil fertility degradation by traces of iron from drinking water treatment. Environ Dev Sustain. 2022:1–10. https://doi.org/10.1007/s10668-021-01636-1
2. Roots Analysis. 2024. Biostimulants market: industry trends and global forecast, 2024–2035 [Internet]. Roots Analysis. [cited 2025 Jul 23]. Available from: https://www.rootsanalysis.com/reports/biostimulants-market.html
3. Du Jardin P. Plant biostimulants: definition, concept, main categories and regulation. Sci Hortic. 2015;196:3–14. https://doi.org/10.1016/j.scienta.2015.09.021
4. Sible CN, Seebauer JR, Below FE. Plant biostimulants: A categorical review, their implications for row crop production and relation to soil health indicators. Agron. 2021;11(7):1297. https://doi.org/10.3390/agronomy11071297
5. Sun W, Shahrajabian MH. The application of arbuscular mycorrhizal fungi as microbial biostimulant, sustainable approaches in modern agriculture. Plants. 2023;12(17):3101. https://doi.org/10.3390/plants12173101
6. Marousek J, Gavurova B. Recovering phosphorous from biogas fermentation residues indicates promising economic results. Chemosphere. 2022;291:133008. https://doi.org/10.1016/j.chemosphere.2021.133008
7. Stavkova J, Marousek J. Novel sorbent shows promising financial results on P recovery from sludge water. Chemosphere. 2021;276:130097. https://doi.org/10.1016/j.chemosphere.2021.130097
8. Marousek J, Marouskova A, Periakaruppan R, Gokul G, Anbukumaran A, Bohata A, et al. Silica nanoparticles from coir pith synthesized by acidic sol-gel method improve germination economics. Polymers. 2022;14(2):266. https://doi.org/10.3390/polym14020266
9. Zuzunaga-Rosas J, Boscaiu M, Vicente O. Agroindustrial by-products as a source of biostimulants enhancing responses to abiotic stress of horticultural crops. Int J Mol Sci. 2024;25(6):3525. https://doi.org/10.3390/ijms25063525
10. Roy D. Role of Biostimulants towards sustainable agriculture: A review. Food Sci Rep. 2024;5(1):47–52.
11. Kumari M, Swarupa P, Kesari KK, Kumar A. Microbial inoculants as plant biostimulants: A review on risk status. Life. 2022;13(1):12. https://doi.org/10.3390/life13010012
12. Ciriello M, Fusco GM, Woodrow P, Carillo P, Rouphael Y. Unravelling the nexus of plant response to non-microbial biostimulants under stress conditions. Plant Stress. 2024:100421. https://doi.org/10.3390/life13010012
13. Kaushal P, Ali N, Saini S, Pati PK, Pati AM. Physiological and molecular insight of microbial biostimulants for sustainable agriculture. Front Plant Sci. 2023;14:1041413. https://doi.org/10.3389/fpls.2023.1041413
14. Miceli A, Moncada A, Vetrano F. Use of microbial biostimulants to increase the salinity tolerance of vegetable transplants. Agron. 2021;11(6):1143. https://doi.org/10.3390/agronomy11061143
15. Soussani FE, Boutasknit A, Ben-Laouane R, Benkirane R, Baslam M, Meddich A. Arbuscular mycorrhizal fungi and compost-based biostimulants enhance fitness, physiological responses, yield and quality traits of drought-stressed tomato plants. Plants. 2023;12(9):1856. https://doi.org/10.3390/plants12091856
16. Parmar P, Kumar R, Neha Y, Srivatsan V. Microalgae as next generation plant growth additives: functions, applications, challenges and circular bioeconomy based solutions. Front Plant Sci. 2023;14:1073546. https://doi.org/10.3389/fpls.2023.1073546
17. Miranda AM, Hernandez-Tenorio F, Villalta F, Vargas GJ, Saez AA. Advances in the development of biofertilizers and biostimulants from microalgae. Biology. 2024;13(3):199. https://doi.org/10.3390/biology99130301
18. Marin-Marin CA, Estrada JA, Delgado-Naranjo JM, Zapata-Ocampo PA, Penuela-Vásquez M. Cyanobacteria and microalgae as potential sources of biofertilizers: A review. Actualidades Biologicas. 2024;46(120).
19. Morillas-Espana A, Perez-Crespo R, Villaro-Cos S, Rodriguez-Chikri L, Lafarga T. Integrating microalgae-based wastewater treatment, biostimulant production and hydroponic cultivation: A sustainable approach to water management and crop production. Front Bioeng Biotechno. 2024;12:1364490. https://doi.org/10.3389/fbioe.2024.1364490
20. Renganathan P, Puente EOR, Sukhanova NV, Gaysina LA. Hydroponics with microalgae and cyanobacteria: emerging trends and opportunities in modern agriculture. BioTech. 2024;13(3):27. https://doi.org/10.3390/biotech13030027
21. Colla G, Rouphael Y. Microalgae: new source of plant biostimulants. Agron. 2020; 10(9):1240. https://doi.org/10.3390/agronomy10091240
22. Leena Banjare DRB, Jataw GK, Shrivastav LK. Effect of seaweed extract on yield and nutrient uptake of rice in a vertisol. Pharm Innov. 2022;11(3):2193–98.
23. Raja B, Vidya R. Application of seaweed extracts to mitigate biotic and abiotic stresses in plants. Physiol Mol Biol Plants. 2023;29(5):641–61. https://doi.org/10.1007/s12298-023-01313-9
24. Mote G, Mane M, Bodake P, Thorat T, Mane A, Wahane M, et al. Bio efficacy of foliar applied biostimulants on nutrient uptake, yield and economics of rice (*Oryza sativa* L.) under lateritic soils of Konkan region. Pharm Innov. 2022;11(12):318–22.
25. Thaimei T, Bokado K, Bera B. Seaweed extract for sustainable rice production-A review. Int J Plant Soil Sci. 2024;36(7):147–60. https://doi.org/10.9734/ijpss/2024/v36i74716
26. Sharma HS, Fleming C, Selby C, Rao J, Martin T. Plant biostimulants: A review on the processing of macroalgae and use of extracts for crop management to reduce abiotic and biotic stresses. J Appl Phycol. 2014;26:465–90. https://doi.org/10.1007/s10811-013-0101-9
27. Ertani A, Francioso O, Tinti A, Schiavon M, Pizzeghello D, Nardi S. Evaluation of seaweed extracts from *Laminaria* and *Ascophyllum nodosum* spp. as biostimulants in *Zea mays* L. using a combination

of chemical, biochemical and morphological approaches. Front Plant Sci. 2018;9:428. https://doi.org/10.3389/fpls.2018.00428

28. Shukla PS, Mantin EG, Adil M, Bajpai S, Critchley AT, Prithiviraj B. Ascophyllum nodosum-based biostimulants: sustainable applications in agriculture for the stimulation of plant growth, stress tolerance and disease management. Front Plant Sci. 2019;10:462648. https://doi.org/10.3389/fpls.2019.00655

29. Wang Y, Lu Y, Wang L, Song G, Ni L, Xu M, et al. Analysis of the molecular composition of humic substances and their effects on physiological metabolism in maize based on untargeted metabolomics. Front Plant Sci. 2023;14:1122621. https://doi.org/10.3389/fpls.2023.1122621

30. Canellas LP, Canellas NO, da S, Irineu LES, Olivares FL, Piccolo A. Plant chemical priming by humic acids. Chem Biol Technol Agric. 2020;7:1–17. https://doi.org/10.1186/s40538-020-00178-4

31. Ampong K, Thilakaranthna MS, Gorim LY. Understanding the role of humic acids on crop performance and soil health. Front Agron. 2022;4:848621. https://doi.org/10.3389/fagro.2022.848621

32. Lv D, Sun H, Zhang M, Li C. Fulvic acid fertilizer improves garlic yield and soil nutrient status. Gesunde Pflanzen. 2022;74(3):685–93. https://doi.org/10.1007/s10343-022-00644-z

33. Maguey-Gonzalez JA, Nava-Ramirez MdJ, Gomez-Rosales S, Angeles MdL, Solis-Cruz B, Hernandez-Patlan D, et al. Humic acids preparation, characterization and their potential adsorption capacity for aflatoxin B1 in an in vitro poultry digestive model. Toxins. 2023;15(2):83. https://doi.org/10.3390/toxins15020083

34. Aktsoglou DC, Kasampalis DS, Sarrou E, Tsouvaltzis P, Chatzopoulou P, Martens S, et al. Protein hydrolysates supplement in the nutrient solution of soilless grown fresh peppermint and spearmint as a tool for improving product quality. Agron. 2021;11(2):317. https://doi.org/10.3390/agronomy11020317

35. Monterisi S, Garcia-Perez P, Buffagni V, Zuluaga MYA, Ciriello M, Formisano L, et al. Unravelling the biostimulant activity of a protein hydrolysate in lettuce plants under optimal and low N availability: A multi-omics approach. Physiol Plant. 2024;176(3):e14357. https://doi.org/10.1111/ppl.14357

36. Elwaziri E, Ismail H, Abou El-Khair E-S, Al-Qahtani SM, Al-Harbi NA, Abd El-Gawad HG, et al. Biostimulant application of whey protein hydrolysates and potassium fertilization enhances the productivity and tuber quality of sweet potato. Not Bot Horti Agrobot Cluj-Na. 2023;51(2):13122.https://doi.org/10.15835/nbha51213122

37. Stasinska-Jakubas M, Hawrylak-Nowak B. Protective, biostimulating and eliciting effects of chitosan and its derivatives on crop plants. Molecules. 2022;27(9):2801. https://doi.org/10.3390/molecules27092801

38. Sun W, Shahrajabian MH, Petropoulos SA, Shahrajabian N. Developing sustainable agriculture systems in medicinal and aromatic plant production by using chitosan and chitin-based biostimulants. Plants. 2023;12(13):2469. https://doi.org/10.3390/plants12132469

39. Shahrajabian MH, Chaski C, Polyzos N, Tzortzakis N, Petropoulos SA. Sustainable agriculture systems in vegetable production using chitin and chitosan as plant biostimulants. Biomolecules. 2021;11(6):819. https://doi.org/10.3390/biom11060819

40. Abdel Megeed T, Gharib H, Hafez E, El-Sayed A. Effect of some plant growth regulators and biostimulants on the productivity of Sakha108 rice plant (*Oryza sativa* L.) under different water stress conditions. Appl Ecol Environ. 2021(19):2859–78. https://doi.org/10.15666/aeer/1904_28592878

41. Rahaman M, Murmu K, Khandakar J, Bordolui SK, Hedayetullah M. Crop productivity and soil health in relation to the microbial population as influenced by different organic biostimulants in summer rice cultivation. Oryza- Int J Rice. 2022;59(2):194–204. https://doi.org/10.35709/ory.2022.59.2.9

42. Vaishnavi D, Ravichandran V, Sritharan N, Anandakumar S, Kumar GP, Latha M. Biopriming of seeds with microbial biostimulant (*Bacillus megaterium*) on improvement of seedling growth, biochemical and root traits of rice (*Oryza sativa* L.). Plant Sci Today. 2024;11(sp4):1–8. https://doi.org/10.14719/pst.5541

43. Shultana R ZA, Rana MM, Naher UA, Paul PLC, Akter M, Shupta SA, Roy TK. Exploring indigenous *Bacillus* spp. as a biostimulant to enhance the growth and yield of rice under glasshouse conditions. Asian J Agric. 2025;9(1).

44. Ghodake SS, Thorat TN, Rajemahadik VA, Bodake PS, Khobragade NH, Desai SS, et al. Effect of foliar application of biostimulants on growth, yield and yield attributing characters of rice (*Oryza sativa* L.). J Pharm Innov. 2022;11(11):2134-37.

45. Gavelienė V, Jurkoniene S. Probiotics enhance cereal yield and quality and modify agrochemical soil properties. Microorganisms. 2022;10(7):1277. https://doi.org/10.3390/microorganisms10071277

46. Wang S, Tian X, Liu Q. The effectiveness of foliar applications of zinc and biostimulants to increase zinc concentration and bioavailability of wheat grain. Agron. 2020;10(2):178. https://doi.org/10.3390/agronomy10020178

47. Ramah K, Shanthi P, Ponnusamy K. Productivity enhancement in maize (*Zea mays* L.) through seaweed extract (Phytozyme) foliar spray. Int J Agric Hortic Allied Sci. 2009;2(8):526–7.

48. Nephali L, Moodley V, Piater L, Steenkamp P, Buthelezi N, Dubery I, et al. A metabolomic landscape of maize plants treated with a microbial biostimulant under well-watered and drought conditions. Front Plant Sci. 2021;12:676632. https://doi.org/10.3389/fpls.2021.676632

49. Canellas LP, Canellas NA, Val F, Spaccini R, Mazzei P, Olivares FL. Changes in amino acids profile and uptake on maize seedlings treated with protein hydrolysates and humic substances. Nitrogen. 2024;5(2):439–54. https://doi.org/10.3390/nitrogen5020028

50. Mironenko GA, Zagorskii IA, Bystrova NA, Kochetkov KA. The effect of a biostimulant based on a protein hydrolysate of rainbow trout (*Oncorhynchus mykiss*) on the growth and yield of wheat (*Triticum aestivum* L.). Molecules. 2022;27(19):6663. https://doi.org/10.3390/molecules27196663

51. Priyanka Priya , Shikha Singh, Murari Mohan. Influence of organic nutrients on growth and yield of summer greengram (*Vigna radiata*). J Exp Agric Int. 2024;46(6):333–39. https://doi.org/10.9734/jeai/2024/v46i62485

52. Mohammed S, El-Sheekh MM, Hamed Aly S, Al-Harbi M, Elkelish A, Nagah A. Inductive role of the brown alga *Sargassum polycystum* on growth and biosynthesis of imperative metabolites and antioxidants of two crop plants. Front Plant Sci.2023;14:1136325. https://doi.org/10.3389/fpls.2023.1136325

53. Kocira S, Kocira A, Kornas R, Koszel M, Szmigielski M, Krajewska M, et al. Effects of seaweed extract on yield and protein content of two common bean (*Phaseolus vulgaris* L.) cultivars. Legume Res Int J. 2018;41(4):589–93. https://doi.org/10.18805/LR-383

54. Mahdy RM, Al-Saif AM, Ahmed ME, El-Bary TSA, Sharma A, El-Sheshtawy A-Na, et al. Evaluation of two different methods of fulvic acid application (seed priming and foliar spray) on growth, yield and nutritional quality of pea (*Pisum sativum* L.). Plants. 2024;13(23):3380. https://doi.org/10.3390/plants13233380

55. Kamran A, Mushtaq M, Arif M, Rashid S. Role of biostimulants (ascorbic acid and fulvic acid) to synergize Rhizobium activity in pea (*Pisum sativum* L. var. Meteor). Plant Physiol Biochem. 2023;196:668–82. https://doi.org/10.1016/j.plaphy.2023.02.018

56. Roudgarnejad S, Samdeliri M, Mirkalaei AM, Moghaddam MN. The role of humic acid application on quantitative and qualitative traits of faba bean (*Vicia faba* L.). Gesunde Pflanzen. 2021;73(4):603–11. https://doi.org/10.1007/s10343-021-00581-3

57. Verma N, Sehrawat KD, Mundlia P, Sehrawat AR, Choudhary R, Rajput VD, et al. Potential use of ascophyllum nodosum as a

biostimulant for improving the growth performance of *vigna aconitifolia* (Jacq.) marechal. Plants. 2021;10(11):2361. https://doi.org/10.3390/plants10112361

58. Vishwanatha S, Shwetha B, Koppalkar B, Ashoka N, Ananda N, Umesh M, et al. Response of blackgram (*Vigna mungo* L.) and soybean (*Glycine max* L.) to novel bio stimulants in north eastern dry zone of Karnataka. Legume Res Int J. 2022;45(9):1130–36. https://doi.org/10.18805/LR-4858
59. Bahekar K, Singh K, Dawson J. Effect of Sulphur and Seaweed (*Kappaphycus alvarezii*) Extract Spray on Growth and Yield of Groundnut. Int J Plant Soil Sci. 2024;36(6):183–87. https://doi.org/10.9734/ijpss/2024/v36i64620
60. Mannan MA, Yasmin A, Sarker U, Bari N, Dola DB, Higuchi H, et al. Biostimulant red seaweed (*Gracilaria tenuistipitata* var. liui) extracts spray improves yield and drought tolerance in soybean. Peer J. 2023;11:e15588. https://doi.org/10.7717/peerj.15588
61. Meyer FR, Junior VO, Bernardes JVS, de Miranda Coelho VP. Aplicacao foliar de bioestimulante a base de extrato de alga marinha na cultura da soja. Revista Caatinga. 2021;34(1):99–107. https://doi.org/10.1590/1983-21252021v34n111rc
62. Engel DCH, Feltrim D, Rodrigues M, Baptistella JLC, Mazzafera P. Application of protein hydrolysate improved the productivity of soybean under greenhouse cultivation. Agriculture. 2024;14(8):1205. https://doi.org/10.3390/agriculture14081205
63. Gursoy M. Alone or combined effect of seaweed and humic acid applications on rapeseed (*Brassica napus* L.) under salinity stress. J Soil Sci Plant Nutr. 2024;24(2):3364–76. https://doi.org/10.1007/s42729-024-01759-0
64. Lima GBPd, Gomes EF, Rocha GMGd, Silva FdA, Fernandes PD ,et al. *Bacilli rhizobacteria* as biostimulants of growth and production of sesame cultivars under water deficit. Plants. 2023;12(6):1337. https://doi.org/10.3390/plants12061337
65. La Bella S, Consentino BB, Rouphael Y, Ntatsi G, De Pasquale C, Iapichino G, et al. Impact of Ecklonia maxima seaweed extract and Mo foliar treatments on biofortification, spinach yield, quality and NUE. Plants. 2021;10(6):1139. https://doi.org/10.3390/plants10061139
66. Bayat H, Shafie F, Aminifard MH, Daghighi S. Comparative effects of humic and fulvic acids as biostimulants on growth, antioxidant activity and nutrient content of yarrow (*Achillea millefolium* L.). Sci Hortic. 2021;279:109912. https://doi.org/10.1016/j.scienta.2021.109912
67. Leporino M, Rouphael Y, Bonini P, Colla G, Cardarelli M. Protein hydrolysates enhance recovery from drought stress in tomato plants: phenomic and metabolomic insights. Front Plant Sci. 2024;15:1357316. https://doi.org/10.3389/fpls.2024.1357316
68. Celletti S, Astolfi S, Guglielmo N, Colla G, Cesco S, Mimmo T. Evaluation of a legume-derived protein hydrolysate to mitigate iron deficiency in plants. Agron. 2020;10(12):1942. https://doi.org/10.3390/agronomy10121942
69. Ramirez-Rodriguez SC, Preciado-Rangel P, Ortega-Ortiz H, Gonzalez -Morales S. Chitosan nanoparticles as biostimulant in lettuce (*Lactuca sativa* L.) plants. Phyton-Int J Exp Bot. 2024;93:777–87. https://doi.org/10.32604/phyton.2024.048096
70. Asadi Aghbolaghi M, Sedghi M, Sharifi RS, Dedicova B. Germination and the biochemical response of pumpkin seeds to different concentrations of humic acid under cadmium stress. Agriculture. 2022;12(3):374. https://doi.org/10.3390/agriculture12030374
71. Dobaria J, Dhruv J, Pandya M. Evaluation of biostimulants effect on various parameters and its relation to insect-pest infestation on two genotypes of Brinjal. Int. J Adv Biochem Res. 2024;8(6):373–80. https://doi.org/10.33545/26174693.2024.v8.i6Se.1312
72. Aydi-Ben-Abdallah R, Ammar N, Ayed F, Jabnoun-Khiareddine H, Daami-Remadi M. Single and combined effects of Bacillus spp. and brown seaweed (*Sargassum vulgare*) extracts as bio-stimulants of eggplant (*Solanum melongena* L.) growth. Adv Hortic Sci. 2021;35(2):151–64. https://doi.org/10.36253/ahsc-9624
73. Sarangi SK, Mainuddin M, Maji B. Problems, management and prospects of acid sulphate soils in the Ganges Delta. Soil Systems. 2022;6(4):95. https://doi.org/10.3390/soilsystems6040095
74. Zaman M, Shahid SA, Heng L, Shahid SA, Zaman M, Heng L. Introduction to soil salinity, sodicity and diagnostics techniques. Guidel Salin. Assess Mitig. Adapt Using Nucl Relat Tech. 2018:1–42. https://doi.org/10.1007/978-3-319-96190-3_1
75. Ramamoorthy P, Ramamoorthy M, Nirubana V. Management of saline and sodic soils. . Int J Agric Sci Technol. 2021;1(1):24–7. https://doi.org/10.51483/IJAGST.1.1.2021.24-27
76. D'Amato R, Del Buono D. Use of a biostimulant to mitigate salt stress in maize plants. Agron. 2021;11(9):1755. https://doi.org/10.3390/agronomy11091755
77. Zuzunaga-Rosas J, Silva-Valdiviezo D, Calone R, Lupuţ I, Ibanez-Asensio S, Boscaiu M, Moreno-Ramon H, et al. Biochemical responses to salt stress and biostimulant action in tomato plants grown in two different soil types. Hortic. 2023;9(11):1209. https://doi.org/10.3390/horticulturae9111209
78. El-Nakhel C, Cozzolino E, Ottaiano L, Petropoulos SA, Nocerino S, Pelosi ME, et al. Effect of biostimulant application on plant growth, chlorophylls and hydrophilic antioxidant activity of spinach (*Spinacia oleracea* L.) grown under saline stress. Horticulturae. 2022;8(10):971. https://doi.org/10.3390/horticulturae8100971
79. Ikuyinminu E, Goni O, O Connell S. Enhancing irrigation salinity stress tolerance and increasing yield in tomato using a precision engineered protein hydrolysate and Ascophyllum nodosum-derived biostimulant. Agron. 2022;12(4):809. https://doi.org/10.3390/agronomy12040809
80. Chanthini KM-P, Senthil-Nathan S, Pavithra G-S, Malarvizhi P, Murugan P, Deva-Andrews A, et al. Aqueous seaweed extract alleviates salinity-induced toxicities in rice plants (*Oryza sativa* L.) by modulating their physiology and biochemistry. Agriculture. 2022;12(12):2049. https://doi.org/10.3390/agriculture12122049
81. Hussein MH, Eltanahy E, Al Bakry AF, Elsafty N, Elshamy MM. Seaweed extracts as prospective plant growth bio-stimulant and salinity stress alleviator for *Vigna sinensis* and *Zea mays*. J Appl Phycol. 2021;33:1273–91. https://doi.org/10.1007/s10811-020-02330-x
82. Bantis F, Koukounaras A. Ascophyllum nodosum and silicon-based biostimulants differentially affect the physiology and growth of watermelon transplants under abiotic stress factors: The case of salinity. Plants. 2023;12(3):433. https://doi.org/10.3390/plants12030433
83. Neupane A, Jakubowski D, Fiedler D, Gu L, Clay SA, Clay DE, et al. Can Phytoremediation-Induced Changes in the Microbiome Improve Saline/Sodic Soil and Plant Health? Agron. 2023;14(1):29. https://doi.org/10.3390/agronomy14010029
84. Fathima F, Suma R, Asha N, Ananthakumar M, Keshavaiah K. Exploiting biostimulants and micronutrients for optimal rice yield in sodic soil: A strategic approach to salt stress resilience. Plant Arch. 2024;24(1):768–74. https://doi.org/10.51470/PLANTARCHIVES.2024.v24.no.1.105
85. Ravichandran M, Chinnadurai S, Subha B, Muthulaxmi V, Sivakumar SR, Subbiah S, et al. Ameliorated reclamation potential of Halimeda microloba on sodic soil and its impact on the *Vigna radiata*. Arab J Geosci. 2023;16(7):404. https://doi.org/10.1007/s12517-023-11509-8
86. Do Rosario Rosa V, Dos Santos ALF, da Silva AA, Sab MPV, Germino GH, Cardoso FB, et al. Increased soybean tolerance to water deficiency through biostimulant based on fulvic acids and *Ascophyllum nodosum* (L.) seaweed extract. Plant Physiol Biochem. 2021;158:228–43. https://doi.org/10.1016/j.plaphy.2020.11.008
87. Jindo K, Olivares FL, Malcher DJdP, Sanchez-Monedero MA, Kempenaar C, Canellas LP. From lab to field: role of humic

substances under open-field and greenhouse conditions as biostimulant and biocontrol agent. Front Plant Sci. 2020;11:426. https://doi.org/10.3389/fpls.2020.00426

88. Pellegrini M, Pagnani G, Bernardi M, Mattedi A, Spera DM, Gallo MD. Cell-free supernatants of plant growth-promoting bacteria: A review of their use as biostimulant and microbial biocontrol agents in sustainable agriculture. Sustainability. 2020;12(23):9917. https://doi.org/10.3390/su12239917

89. Attia MS, Abdelaziz AM, Al-Askar AA, Arishi AA, Abdelhakim AM, Hashem AH. Plant growth-promoting fungi as biocontrol tool against fusarium wilt disease of tomato plant. J Fungi. 2022;8(8):775. https://doi.org/10.3390/jof8080775

90. Pereira RV, Filgueiras CC, Doria J, Penaflor MFG, Willett DS. The effects of biostimulants on induced plant defense. Front Agron. 2021;3:630596. https://doi.org/10.3389/fagro.2021.630596

91. La Spada F, Aloi F, Coniglione M, Pane A, Cacciola SO. Natural biostimulants elicit plant immune system in an integrated management strategy of the postharvest green mold of orange fruits incited by *Penicillium digitatum*. Front Plant Sci. 2021;12:684722. https://doi.org/10.3389/fpls.2021.684722

92. Rashad YM, El-Sharkawy HH, Elazab NT. Ascophyllum nodosum extract and mycorrhizal colonization synergistically trigger immune responses in pea plants against Rhizoctonia root rot and enhance plant growth and productivity. J Fungi. 2022;8(3):268. https://doi.org/10.3390/jof8030268

93. Ali O, Ramsubhag A, Jayaraman J. Biostimulant properties of seaweed extracts in plants: implications towards sustainable crop production. Plants. 2021;10(3):531. https://doi.org/10.3390/plants10030531

94. Elkhwaga AA, Eldakar HA, Abdelmaksoud HM, Ahmed NE, Gad MA. Biopotential of cyanobacteria, fulvic acid and nano-chitosan in controlling leaf rust of wheat. Asian J Res Crop Sci. 2024;9(2):156–67. https://doi.org/10.9734/ajrcs/2024/v9i2276

95. Sun W, Shahrajabian MH, Soleymani A. The roles of plant-growth-promoting rhizobacteria (PGPR)-based biostimulants for agricultural production systems. Plants. 2024;13(5):613. https://doi.org/10.3390/plants13050613

96. Tran TLC, Callahan DL, Islam MT, Wang Y, Arioli T, Cahill D. Comparative metabolomic profiling of *Arabidopsis thaliana* roots and leaves reveals complex response mechanisms induced by a seaweed extract. Front Plant Sci. 2023;14:1114172. https://doi.org/10.3389/fpls.2023.1114172

97. Rathor P, Upadhyay P, Ullah A, Gorim LY, Thilakarathna MS. Humic acid improves wheat growth by modulating auxin and cytokinin biosynthesis pathways. AoB Plants. 2024;16(2):plae018. https://doi.org/10.1093/aobpla/plae018

98. Liang Y, Wang J, Wang Z, Hu D, Jiang Y, Han Y, et al. Fulvic acid alleviates the stress of low nitrogen on maize by promoting root development and nitrogen metabolism. Physiol Plant. 2024;176(2):e14249. https://doi.org/10.1111/ppl.14249

99. Raguraj S, Kasim S, Md Jaafar N, Nazli MH. Growth of tea nursery plants as influenced by different rates of protein hydrolysate derived from chicken feathers. Agron. 2022;12(2):299. https://doi.org/10.3390/agronomy12020299

100. Shibana S, Nair DS, Sreekala G, Pillai S, Alex S, Joseph A. Application of Chitin Improves Growth, Yield and Secondary Metabolite Production in Turmeric (*Curcuma longa* L.). Int J Environ Clim Change. 2023;13(12):1108–17. https://doi.org/10.9734/ijecc/2023/v13i123775

101. Agriplex India. Biostimulants [Internet]. Bengaluru (IN): Agriplex India; [cited 2025 Jul 23]. Available from: https://agriplexindia.com/collections/biostimulant

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

Publisher information: Plant Science Today is published by HORIZON e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.