



REVIEW ARTICLE

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

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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 Absciscic 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 acids,

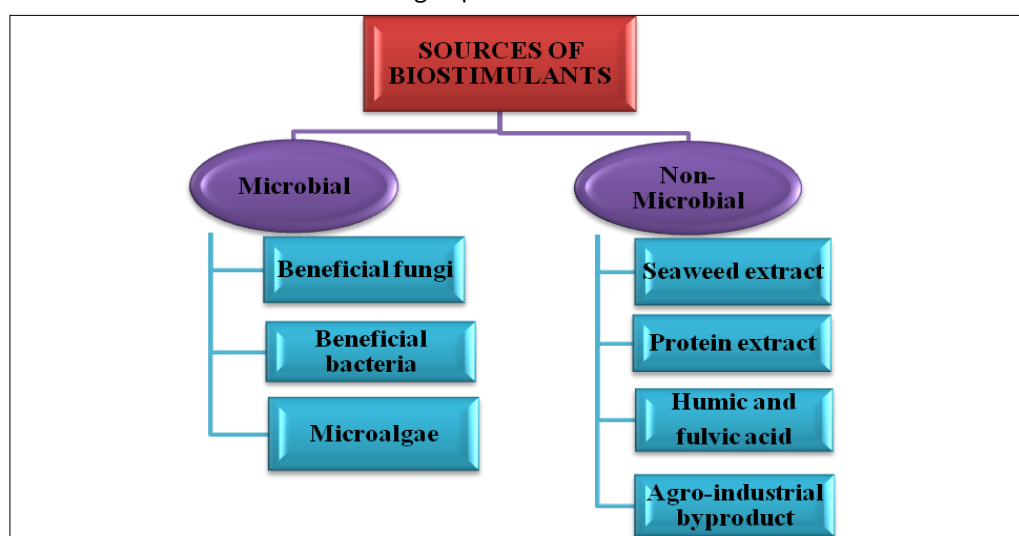


Fig. 1. Classified sources of biostimulants.

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 hot water bath at 45 °C for 30 mins and centrifuged for 15 min. The

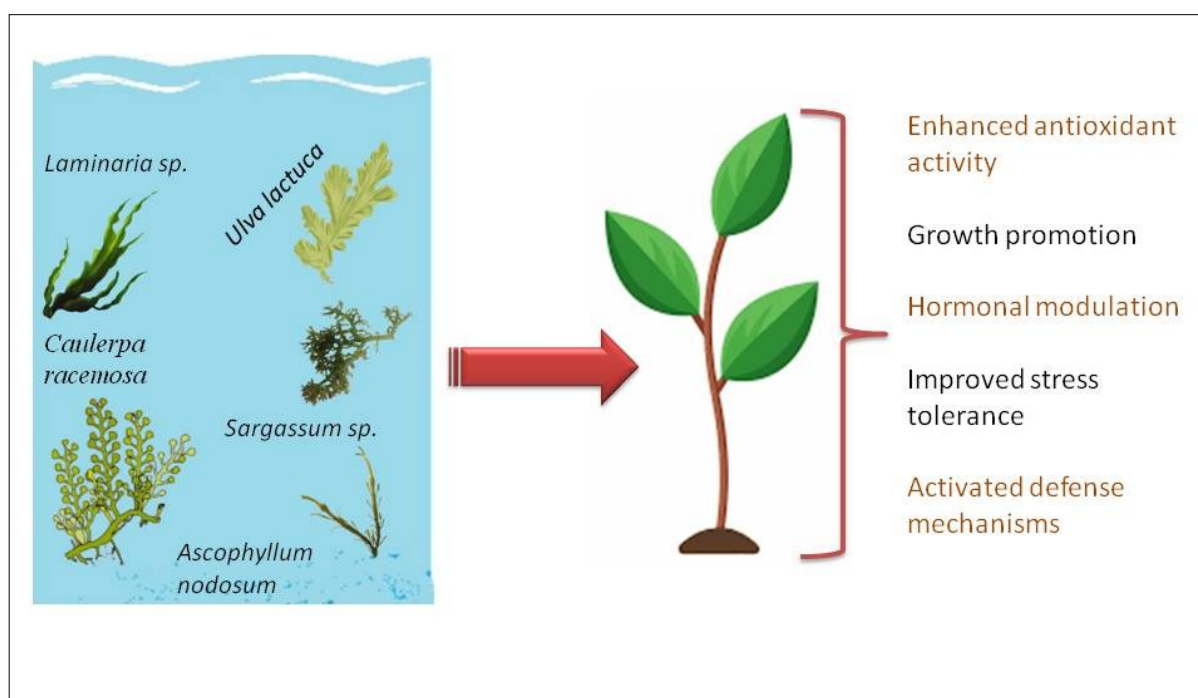


Fig. 2. Seaweed spp. with their mode of action.

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°C 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°C for 4 hr with constant stirring. After incubation, the mixture is placed in a boiling water bath at 100°C 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°C 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 is followed by treating chitin with concentrated NaOH at high

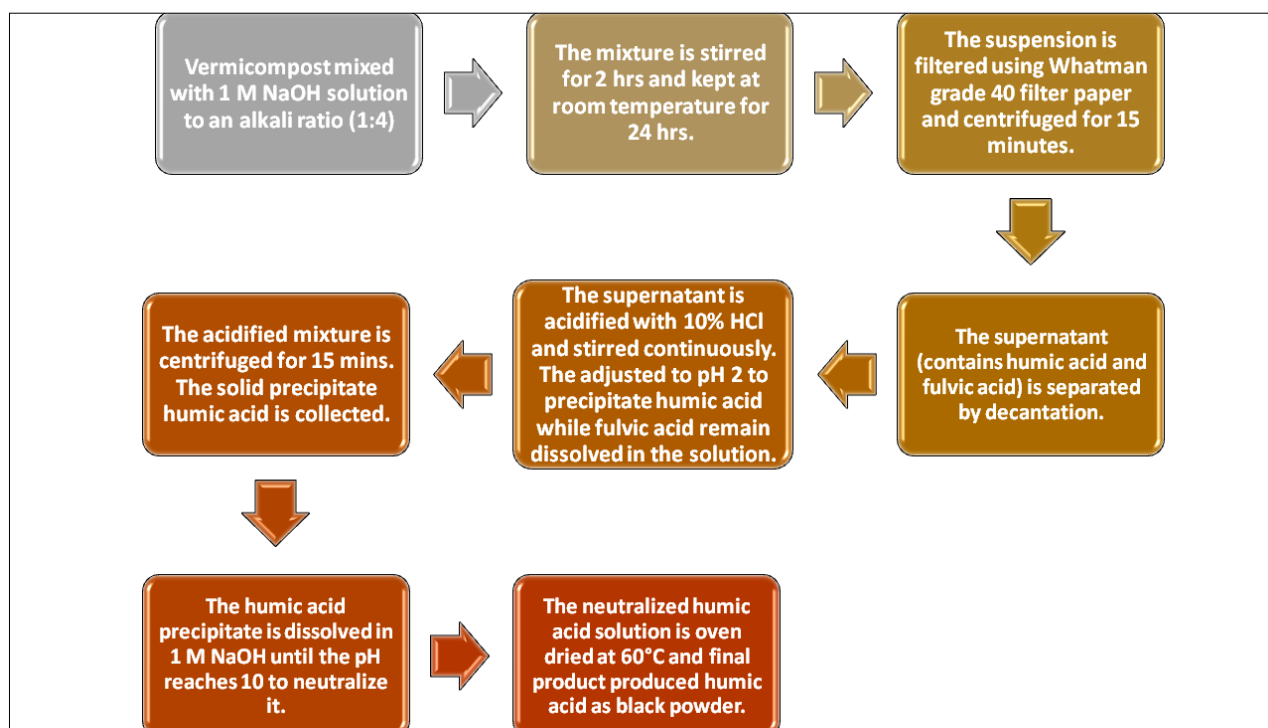


Fig. 3. Flow chart for the preparation of humic acid.

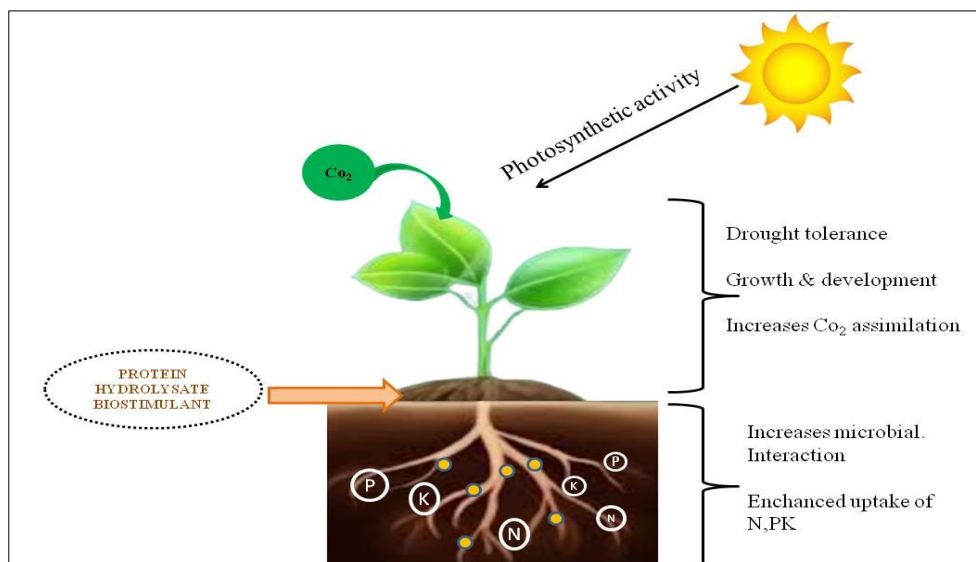


Fig. 4. Protein hydrolysate biostimulant and its influence on the plant.

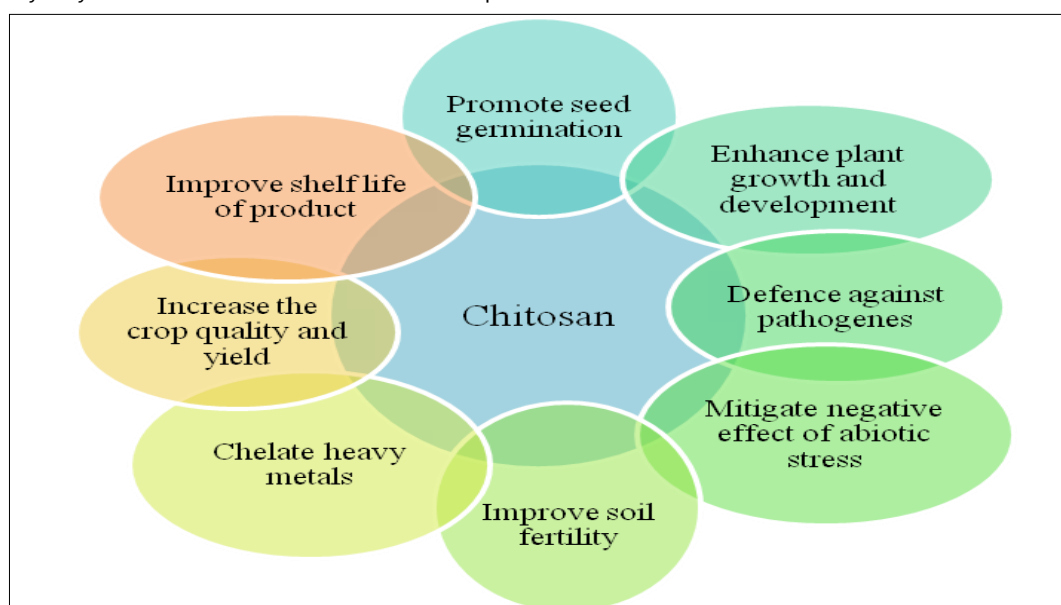


Fig. 5. Chitosan with its functions towards plants.

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/kg seeds 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 aestivum* L) and oats (*Avena sativa*) were examined using probiotics such as 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 (*Lactuca 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 °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 chaffiness 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 $\mu\text{S}/\text{cm}$ and exchangeable sodium percentage level from 62 to 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 *Penicillium digitatum* (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

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)

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	<i>Bacillus subtilis</i>
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

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.

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.

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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

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