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REVIEW ARTICLE

Seaweed-based Biostimulants: Impacts on Quality and Health Value of Solanaceous Vegetables

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Abstract

Biostimulants extracted from nutrient-rich seaweed, which has emerged as a promising sustainable alternative to harnessing the power of chemical fertilizers and pesticides, can significantly enhance agricultural productivity and ensure healthier crops, enhancing their growth and longevity belonging to solanaceous vegetables. This review looks closely at the bioactive compounds found in algal-based seaweed extracts, such as Amino acids, phytohormones, polysaccharides, phenolic compounds, and other micronutrients. This also discuss about how these compounds work in different ways to improve nutrient absorption, hormonal balance, photosynthesis, root structure, and plant defense mechanism. The various applications of these biostimulants have significantly enhanced growth, yield, fruit quality, and the phytochemical composition (Phenolics, flavonoids, carotenoids, and capsaicinoids) of tomatoes, chillies, brinjals, and potatoes. They also cut down on the need of chemical fertilizers, which is good for the environment and the economy because it cuts down on the need for them.

Key words: Biostimulants, pharmaceutical applications, seaweed extract, solanaceous vegetables

INTRODUCTION

Biostimulants are defined as substances or microbes that, independent of their own nutritional value, promote plant nutrient uptake efficiency, stress tolerance, and crop performance.[1,2] Compared to traditional fertilizers that directly supply nutrients, biostimulants improve plant metabolism, root structure, photosynthetic activity, enzyme activity, and hormone balance, comprising humic substances, protein hydrolysates, microbial inoculants, chitosan, and seaweed extract. Biostimulants derived using seaweeds are of huge importance because they harbor bioactive compounds that regulate plant growth and development, including phytohormones (auxin, cytokinins, and gibberellins), amino acids, vitamins, polysaccharides, betaine, and micronutrients. These chemicals contribute to the enhancement of cell divisions, chlorophyll content, and enzyme activities. When used through either a foliar spray or soil application, they improved germination, Seedling vigor, flowering, fruit set, and stress tolerance on horticultural crops[3,4] and Can be considered a long-term strategy to boost crop yields and lessen reliance on chemical synthetic fertilizers.[5] This is particularly relevant for economically significant solanaceous vegetables such as Tomato, Brinjal, chilli, and Potato, which can play a crucial role in food security, income, and nutritional well-being. These crops are not only rich in vitamins and minerals but also constitute a major portion of vegetable production in

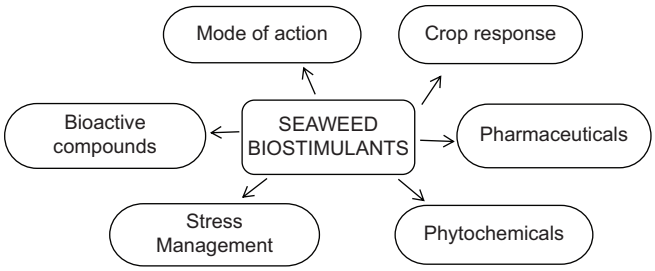
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Asian countries and India, with cultivation occurring year-round across various agro-climatic zones. However, their productivity is heavily influenced by balanced nutrition, effective water management, and resilience to biotic and abiotic stresses.

Since high-density farming may cause overuse of chemical fertilizers and pesticides, the sustainability of crop production is required to ensure high productivity without exhausting natural resources, enhancing the health of soil, and decreasing negative impact on the environment. Sustainable agriculture can be achieved using biostimulants, which is based on the efficiency of nutrients, the decrease in chemicals, and the enhancement of plant stress resistance.



BIOCHEMICAL PROFILE OF SEAWEED-DERIVED BIOSTIMULANTS

Phytohormonal constituents and their functional roles

A variety of bioactive substances found in seaweed extracts control plant growth, metabolism, stress tolerance, and defense systems. It contains important components such as phytohormones, organic metabolites, mineral nutrients, and elicitor molecules, which enhance the sustainability and production of crops.[6,7] Plant growth regulators, such as auxins, cytokinins, gibberellins, and brassinosteroids, control the growth of the roots, production of chlorophyll, flowering, and reproductive development.[8] Moreover, these chemicals improve the process of photosynthesis, nitrogen assimilation, and abiotic stress resistance of solanaceous plants against drought and salinity.[3]

Primary and secondary organic metabolites

Compounds present in seaweed extracts, such as amino acids, proteins, vitamins, phenolic compounds, and polysaccharides influence directly the metabolism and physiological functions of plants.[9] Vitamins and amino acids enhance metabolic function and oxidative stress resistance, while proteins boost the activity of enzymes and resistance to stress. Phenolic substances have antioxidant activity of enzymes and resistance to stress.[1,10] Phenolic substances have antioxidant activity and disease resistance through scavenging of reactive oxygen species.[11]

Essential mineral elements and their bioavailability

The seaweeds are rich in macro- and micronutrients in chelated form, including nitrogen, phosphorous, potassium, calcium, magnesium, sulfur, iron, zinc and boron.[12] These minerals help to make soil fertile and to take up nutrients, and help with metabolic activity. Potassium increases stomatal control and stress tolerance; calcium and micronutrients increase membrane stability and photosynthetic and respiratory enzyme function. Plant or soil application of seaweed extracts enhances the uptake of nutrients and yield of tomato, chilli and brinjal.[13]

Elicitor molecules and signal transduction compounds

Elicitors derived from seaweed activate defense-related enzymes such as peroxidase, polyphenol oxidase and phenylalanine ammonia- lyase, thus enhancing resistance to fungal, bacterial and viral infection. These chemicals also regulate salicylic acid, ethylene, and jasmonic acid signaling pathways, which increases plant immunity.[14]

PHYSIOLOGICAL AND MOLECULAR MODES OF ACTION

Improvement of nutrient uptake

Seaweed extracts enhance nutrient uptake by increasing root membrane permeability and enhancing nutrient chelation. Alginates are Polysaccharides that enhance the water retention and soil structure, enhancing nutrient availability in the rhizosphere. Consequently, there is a more efficient utilization of nitrogen and better absorption of other indispensable nutrients, including Potassium, calcium, and iron.[15] The overall effects of seaweed-based biostimulants on Nutrient Uptake are illustrated in Figure 2.

Modulation of hormonal balance

In seaweed extracts, natural plant growth regulators maintain the level of endogenous hormones. Auxins stimulate root formation, cytokinins retard leaf decay, and Gibberellins stimulate stem growth and flowering. This hormonal equilibrium enhances sink-source interactions and reproductive growth of solanaceous crops.

Regulation of photosynthesis and metabolism

Biostimulants are substances found in the seaweed that improve photosynthetic activity by increasing chlorophyll levels and stabilizing the thylakoid membrane. Photosynthetic machinery is safeguarded by compounds like betaines when stressed. This will cause increased synthesis of carbohydrates and an enhanced metabolic rate.

Rhizosphere interaction and root development

Bioactive compounds promote the growth of roots, such as lateral roots and root hair growth. Enhanced root structure increases nutrient and water uptake.[16] There is also the presence of seaweed polysaccharides, which promote favorable microbial activity in the rhizosphere, which further facilitates growth of plants.

Induction of defense mechanism

Seaweed-derived elicitors such as laminarin and fucoidan activate plant defense pathways, including Systemic Acquired Resistance (SAR).[5] Enhances the production of defense-related enzymes action and phenolic-based compounds, thereby strengthening tolerance to pathogen and environmental stress.[17]

APPLICATION STRATEGIES IN SOLANACEOUS CROPPING SYSTEMS

Seed priming and early stage conditioning

The extracts from the seaweed are utilized as seed treatment for enhancing germination, seedling vigor, and early root development by triggering phytohormones and micronutrients.[18,19] It has been demonstrated that seed treatments with seaweed produce better emergence and growth of the seedlings of the solanaceous crops.[20,21] Physiological performance and acclimation capacity were improved in the tomato and eggplant seedlings growing with *ascophyllum nodosum* extract, with larger biomass, root length, and chlorophyll content than the untreated seedlings.[22]

Soil-based delivery and rhizosphere activation

Seaweed biostimulants increase rhizosphere activity, root growth, nutrient availability, and microbial growth when applied to the soil. Bioactive polysaccharides like alginates can be used for improving soil structure and water-holding capacity, while auxin-like chemicals can stimulate root elongation and lateral root formation.[23] In tomato and eggplant trials, an extract concentration of 0.1–0.3% led to substantial increases in root biomass and growth from the seedlings, with 0.2% being most effective.[24]

Foliar-based nutrient and signal delivery

Foliar application is a common method used to apply seaweed biostimulants since the nutrients and bioactive compounds are readily taken up by the leaves.[25] The foliar application improves the photosynthetic rate, availability of nutrients, chlorophyll content, and enzyme activity.[26] In eggplant, vegetative growth, nutrient accumulation, and fruit production with the treatment of seaweed extract at 1000–2000 ppm were significantly enhanced.[27] The seaweed extracts possess betaines and micronutrients that help to preserve the integrity of chlorophyll and its efficiency during stress conditions.[28] In eggplant, the use of 0.2% *A. nodosum* extract resulted in increased root biomass and chlorophyll content in eggplant seedlings.[24]

Integration with irrigation systems (Fertigation approach)

Fertigation using seaweed biostimulants allows the nutrients to be distributed evenly in the root zone, resulting in better nutrient use, root growth, and rhizosphere microbial activity.[29] Application during vegetative and reproductive growth stages stimulates biomass build-up, flowering, and fruit set.[30] Use in combination with good bacteria enhances rhizosphere functions and responses of plants.[31]

Dosage optimization and application scheduling

Seaweed biostimulants are effective depending on the type of crop, its development stage, and environmental conditions. Application of 0.2% concentration by irrigation or foliar spray was beneficial in improving the development of tomato and eggplant.[24] In eggplant, foliar spray at 1000–2000 ppm at 2–3 week intervals significantly enhanced growth and yield, while 4000 ppm and above concentrations might have phytotoxic effects.[32] Applications during the transplanting, blooming, and fruit development phases are most beneficial for uniform crop performance.[33]

AGRONOMIC RESPONSES IN SOLANACEOUS VEGETABLES

Biostimulants that are produced using seaweeds are predominantly applied to solanaceous crops because they are a rich source of plant growth regulators, polysaccharides, and various bioactive compounds that support overall plant health and development. These chemicals trigger physiological activities including nutrient uptake, photosynthesis, root development, flowering, fruiting, and stress tolerance The major crop responses associated with seaweed-based biostimulant application are presented in. *A. nodosum, Ecklonia maxima, Sargassum* spp., *and Padina gymnospora* are brown seaweeds that are widely used in commercial preparations. It has been proven that seaweed extracts can enhance the growth, yield, quality, and tolerance to biotic and abiotic stresses in tomato, chilli, brinjal, and potato and the effect of seaweed extract on solanaceous vegetables are mentioned in Table 1.

MODULATION OF PHYTOCHEMICAL PROFILES

Seaweed-derived biostimulants significantly influence the synthesis and accumulation of Phytochemicals in solanaceous vegetables. These effects are mediated through enhanced nutrient uptake, improved photosynthetic efficiency, and activation of secondary metabolic pathways. As a result, treated plants exhibit higher concentrations of bioactive compounds with nutritional and functional importance. The major phytochemical groups influenced by seaweed biostimulants and their functional significance are presented in Table 2.

Phenolic compounds

Seaweed extracts enhance the production of phenolic by triggering important metabolic pathways with regard to plant defense.[46] The increase in nutrient uptake and photosynthesis rates only further favors phenolic accumulation, enhancing antioxidant ability and stress tolerance.[27]

Flavonoids and antioxidant systems

Seaweed bioactive compounds provoke better metabolic regulation and signaling that increases flavonoid production.[47] This leads to greater antioxidant activity, which helps in stress tolerance and enhances nutritional quality.[22]

Alkaloids and capsaicinoids

Seaweed biostimulants encourage the production of nitrogen-containing secondary metabolites, including alkaloids and capsaicinoids. These substances are crucial for plants defense and possess significant pharmacological properties.

Carotenoid and nutritional quality

Increased carotenoid concentration, especially lycopene and 2-carotene is caused by enhanced photosynthetic activity and metabolism.[48] The pigments improve the quality of fruit and help in improving the benefits of human health.

Regulation of secondary metabolism

Compounds produced by seaweeds are signaling molecules that control the expression of genes and enzyme activities that take part in secondary metabolism. This results in increased synthesis of phytochemicals, which increases the quality of crops and nutraceutical value.[49]

NUTRITIONAL AND FUNCTIONAL FOOD IMPLICATIONS

There is a broad spectrum of bioactive constituents in seaweed extracts, which include phytohormones, Polysaccharides, amino acids, micronutrients, and antioxidant present in seaweed derived of marine macroalgae. They affect plant physiological and biochemical, and result in the increase of nutrient uptake and metabolic activity, as well as in stimulation of the synthesis of secondary metabolites. Therefore, to a large extent, the nutritional content and nutraceutical value of solanaceous vegetables can be enhanced through the application of seaweed biostimulants.[50]

Biofortification of vitamins and mineral nutrients

The application of biostimulant-based seaweed has been widely documented to boost nutrient uptake, facilitated by naturally occurring plant growth regulators and micronutrients to promote uptake and accretion of vital vitamins and minerals in plants. Root development and enhancement of nutrient uptake in the soil are triggered by the presence of naturally occurring plant growth regulators, micronutrients, and organic compounds in the seaweed extracts. The result is a higher level of minerals (essential minerals like potassium, calcium, magnesium, iron, and zinc) in edible parts of plants. When tomato fruits are exposed to biostimulants in seaweed, the fruits tend to have high contents of ascorbic acid and carotenoids, which are factors in enhancing the quality of nutrition and antioxidant properties.[51]

The enhancement of mineral composition is especially outstanding since the issue of micronutrient deficiencies is a worldwide community health problem. Agronomic strategies like seaweed- based treatments can be a safe way of biofortifying the food intake of the most important nutrients through agronomic methods. Increased mineral nutrient in solanaceous vegetables does not only increase their nutritional value but improves human health outcomes as well.[52]

Enhancement of antioxidant capacity

The antioxidant compounds are important in shielding; they help biological systems combat oxidative stress caused by reactive oxygen species.[5] Antioxidants which naturally occur in solanaceous vegetables are phenolic acids, flavonoids, carotenoids, and vitamins.[48] The mentioned compounds are involved in preventing oxidative damages related to the chronic conditions, including cancer, cardiovascular disorders, and neurodegenerative conditions.[53]

Utilization of biostimulants made of seaweed was reported to have considerable positive effects on the antioxidant

Table 1: Effects of seaweed on solanaceous vegetables

Crop	Aspect	Effects	References
General (Solanaceous crops)	Overall impact	• Seaweed bio-stimulants are widely used as they are rich in plant growth regulators, polysaccharides, amino acids, micro-nutrients, and bio-active compounds.	[34]
		• They increase nutrient uptake, photosynthesis, development of root, flowering, and fruiting.	[35]
		• Common Seaweeds: *Ascophyllum nodosum, Ecklonia maxima, Sargassum spp., Padina gymnospora.*	[36]
		• Improve growth, quality and stress tolerance in solanaceous crop.	
Tomato	Growth and yield improvement	• Increases plant height, root biomass, total biomass and leaf and leaf area.	[37]
		• *Padina gymnospora* extract enhances shoot/root length, biomass, and fruit number under salinity stress.	[38]
		• Soil drench with seaweed polysaccharides increases vegetative growth, flowering, and yield under greenhouse conditions.	[39]
	Enhancement of fruit quality	• Improves fruit size, firmness, soluble solids, Vitamin C, and lycopene.	
		• Enhances sugar content and organoleptic quality. Increased chlorophyll boosts photosynthesis and higher carbohydrate accumulation in fruits.	
Chilli/Capsicum	Flowering and fruit set	• Promotes early flowering, better flower retention, and higher fruit set.	[34]
		• Improves reproductive efficiency and uniform flowering.	[40]
	Capsaicin accumulation	• Enhances capsaicin content, fruit color, size, and Vitamin C.	[36]
		• Improves secondary metabolite synthesis and antioxidant accumulation.	
Brinjal (Eggplant)	Plant development and crop production	• Improves seedling vigor, overall growth, branching, foliage density, and root growth.	[37]
		• Enhances nutrient uptake and biomass production.	[41]
	Fruit attributes and pest tolerance	• Increases flower retention, fruit number and fruit weight. Enhances resistance against pests and fungal diseases.	
Potato	Tuber quality	• Promotes stolon growth, tuber bulking and dry matter accumulation.	[42]
		• Enhances photosynthesis and carbohydrate translocation.	[43]
	Storage quality	• Reduces physiological losses, sprouting, and oxidative damage during storage. Improves membrane stability and antioxidant capacity.	[44] [45]

Table 2: Influence of seaweed biostimulants on phytochemical composition

Phytochemical group	Major compounds	Mechanism of enhancement	Functional significance
Phenolics	Chlorogenic acid, Caffeic acid	Activation of phenylpropanoid pathway	Antioxidant stress defense
Flavonoids	Quercetin, Rutin	Enhanced metabolic activity and signaling	Antioxidant, Ultraviolet protection
Alkaloids	Solanine, Capsaicin	Improved nitrogen metabolism	Defense pharmacological activity
Carotenoids	Lycopene, β-carotene	Increased photosynthesis and pigment synthesis	Nutritional quality, Antioxidant

ability of plants due to the stimulation of the synthesis of secondary metabolites that enhance plant defense and stress tolerance.[1,32] Bioactive molecules in seaweed extract are polysaccharides, betains, and phytohormones that trigger antioxidant enzymes systems and metabolic pathways, including phenylpropanoid pathway that leads to the formation of phenolic compounds.[27]

Solanaceous crops have also been found to contain higher amounts of antioxidants like lycopene, β-carotene, chlorogenic acid, and flavonoids when treated with seaweed.[48] Lycopene is a key carotenoid in tomatoes that has been identified to possess very powerful antioxidant properties and the ability to lower the chances of the occurrence of cardiovascular disease and some types of cancer.[54] Phenolic

Table 3: Pharmacological properties of phytochemicals enhanced by seaweed biostimulants[59]

Bioactive compound	Source crop	Pharmacological activity	Health benefit
Lycopene	Tomato	Antioxidant	Reduces cancer risk
Capsaicin	Chilli	Anti-inflammatory	Pain relief, metabolism regulation
Chlorogenic acid	Brinjal	Antioxidant	Cardiovascular protection
Flavonoids	All crops	Anti-inflammatory	Reduces oxidative stress
Glycoalkaloids	Potato	Antimicrobial	Defense against Pathogens

Table 4: Role of seaweed biostimulants in stress management of solanaceous crops

Stress type	Mechanism of action	Key compounds involved	Physiological outcome
Drought	Osmotic adjustment, Improved root growth, stomatal regulation	Proline, betaines, cytokinins	Improved water-use efficiency and plant survival
Salinity	Ion homeostasis (K+/Na+balance), membrane stabilization	Polysaccharides, betaines	Reduced ion toxicity and improved growth[61]
Heat stress	Activation of antioxidant enzymes, heat shock proteins	Phenolics, antioxidants	Protection of cellular structures
Cold stress	Osmoprotection chloroplast stability	Sugars, amino acids	Reduced cellular damage
Pest and diseases	Activation of SAR and ISR pathways	Laminarin fucoidan	Enhanced resistance to pathogens[62]

SAR: Systemic acquired resistance, ISR: Induced systemic resistance

compounds assists in the increase of the radical scavenging properties and the overall antioxidant properties.[37] Seaweed Biostimulants improve the functional characteristics of solanaceous vegetables by raising the concentration of such compounds, hence becoming important dietary sources of natural antioxidants.

PHARMACOLOGICAL RELEVANCE OF SEAWEED-INDUCED PHYTOCHEMICALS

Oxidative stress modulation and protective biological effects

Seaweed biostimulants also raise antioxidant by boosting phenolics, flavonoids, and carotenoids synthesis. They are antioxidants and eliminate reactive oxygen species to ensure that biological systems are not damaged by oxidation.[55]

Regulation of inflammatory pathways by plant-derived compounds

Phytochemicals like flavonoids and carotenoids are able to modulate the process of inflammation by blocking the activity of important enzymes and decreasing the number of pro-inflammatory mediators.[56] This helps to prevent chronic diseases.

Chemopreventive potential of bioactive phytochemicals

Anticancer effects of bioactive compounds like lycopene and phenolic acids are reported to control the cell proliferation, induce apoptosis, and prevent tumor growth.

Inhibitory effects against microbial pathogens

Phytochemicals such as alkaloids, phenolics, and flavonoids have antimicrobial actions that cause destabilization of the cell structures and metabolism of microbes, which offer protection against pathogens.[57]

Role in metabolic regulation and cardiovascular protection

Phytochemicals, which are enhanced by seaweeds, enhance lipid metabolism, lessen oxidative stress, and maintain glucose levels. Lycopene and chlorogenic acid are examples of compounds that protect the heart and promote metabolism.[58] The pharmacological properties of selected phytochemicals enhanced by seaweed biostimulants are summarized in Table 3.

ROLE OF ABIOTIC AND BIOTIC STRESS MANAGEMENT

Marine algal biostimulants are essential in improving plant tolerance to abiotic and biotic stresses, beneficial by the abundance of bioactive compounds like phytohormones, polysaccharides, betaines, and antioxidant which affect plant functions from the cellular to the molecular scale. These



Figure 1: Crop responses

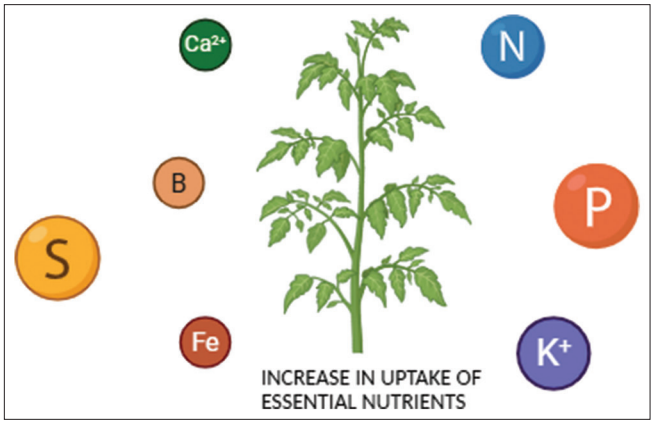


Figure 2: Effect of seaweed

compounds improve osmotic balance, antioxidant defense systems, and stress-responsive signaling pathways.[60-62] The major mechanisms associated with seaweed-mediated stress management in solanaceous crops are presented in Table 4.

Drought stress mitigation

These compounds enhance osmotic equilibrium, booster antioxidant defense mechanisms, and activate the stress-responsive signaling pathways, thereby boosting drought resistance by improving root structure and osmotic regulation.[63] The osmolytes (proline and soluble sugars) are accumulated to preserve turgor and stability of the membranes. Besides, high levels of antioxidant enzymes activity mitigate oxidative damages during water-deficit conditions.[19]

Salinity stress tolerance

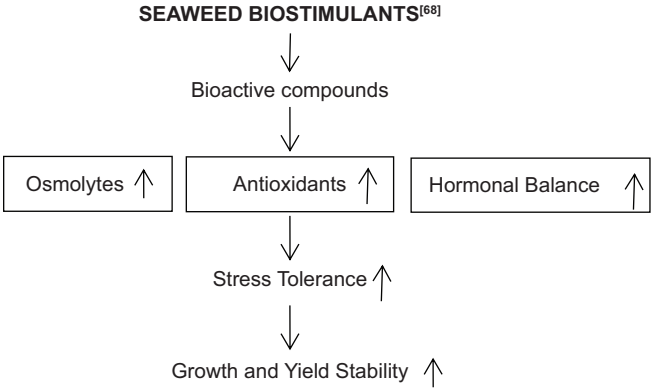
Seaweed biostimulants under saline conditions maintain ionic balance by decreasing the uptake of sodium and increasing potassium uptake.[64] Betaines are osmoprotectants that stabilize cell structures, and antioxidant systems that stabilize against oxidative stress lead to an increase in Growth and performance.[65]

Temperature stress adaptation

Seaweed biostimulants have the ability to enhance tolerance to thermal and cold stress by strengthening the antioxidant activity and stabilizing the membranes of the cells.[66] The result is an augmented production of protective molecules like phenolics and compatible solutes that enable the sustenance of physiological functions in the face of extreme temperatures.

Resistance to pests and diseases

Elicitors produced by seaweed trigger plant defense systems, such as SAR and induced systemic resistance. This results in a higher production of defense-related enzymes, phenolics, and pathogenesis-related proteins, hence enhancing resistance toward pathogens and pests.[67]



ENVIRONMENTAL AND ECONOMIC BENEFITS

Decrease in reliance on chemical fertilizers

Overuse of chemical fertilizers in growing vegetables causes soil erosion, imbalance of nutrients, erosion of nitrates, and greenhouse gases. Biostimulants, more particularly plant-based, microbial, and seaweed-derived biostimulants, provide a viable alternative as they enhance nutrient utilization efficiency and reduce dependency on fertilizers.[69] The addition of organic amendments (compost, digestate) to biostimulants can improve crops such as eggplant early yield, fruit quality, and less environmental harm. Likewise, foliar treatment of *A. nodosum* extract enhances nutrient absorption, metabolic rate, and stress tolerance in pepper and eggplant, allowing part of the chemical fertilizers to be replaced.[70]

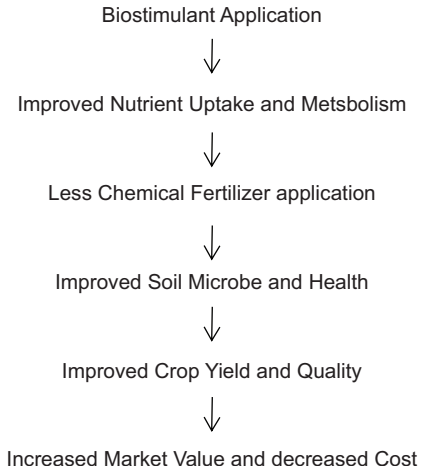
Eco-friendly and sustainable production of crops

Biostimulants also help enable sustainable agriculture by making soils health, increasing stress resilience, and facilitating environmentally-friendly inputs. The fact that products are made out of recycled biomass compounds aligning with circular economy principles because it is used to transform waste materials in agriculture to useful bioactive compounds.[71]

Adoption is dependent on economic feasibility. Biostimulants can potentially lower production costs by decreasing fertilizer

usage and enhancement of yield stability.[72] Systems based on biostimulants cost less to run than traditional systems that require high input levels of fertilizers. Early harvest and high quality of fruits enhance market value. A higher number of fruits per plant will lead to stability in yield and decrease production risks.

Role of biostimulants in sustainable agriculture



LIMITATION AND CHALLENGES

The Biochemical composition of seaweeds (according to species, time of harvesting, location, maturity, and methods of harvesting) is variable, making it very difficult to reproduce, which leads to variability in the yields of phytohormones, polysaccharides, phenolics, and other bioactive compounds, which in turn causes inconsistency in seaweed biological reactions and impairment of prediction of dose-response. In addition, Poor shelf life and stability by microbial degradation, oxidation, and sensitivity to storage conditions often lead to bio-loss, and barriers to adoption include high cost, limited technical know-how, absence of support to provide extension, and poor cost benefits ratios have kept many bioactive compounds in restricted use, especially by smallholder farmers.

FUTURE PERSPECTIVES AND RESEARCH DIRECTIONS

Future developments in seaweed biostimulants technology must be interdisciplinary in nature to include molecular studies (Transcriptomics, proteomics, and metabolomics) to comprehend how the specific processes of plant-biostimulants interactions take place as well as to develop nano-biostimulants that are more stable, bioavailable and delivered. It will be incorporated with accurate agricultural instrumentation, including internet of things sensors, Remote sensing, and decision-support system, to enable optimization and implementation based on location specificity and crop specific study by using multi-location field trails should be emphasized to come up with trustworthy guidelines to apply to solanaceous crops such as tomato, chilli, brinjal, and capsicum, depending on genotype variability, developmental phase, and integration with sustainable.

CONCLUSION

Seaweed extract biostimulants offer a sustainable solution to enhance the productivity resilience of solanaceous vegetable crops, including tomato, chilli and brinjal is seaweed extract biostimulants. Their complex activity of enhancing nutrient uptake, root development, photosynthesis, and stress tolerance leads to high yield, improved fruit quality, and life time in the shelf. Notably, these are marine-based inputs that are eco-friendly because they minimize by reducing the need for synthetic fertilizers and pesticides while promoting soil health and microbiological activity.

Although these benefits exist, issues like composition variability and standardization are some of the major constraints to their general use. Molecular characterization, better methods of extraction, and standardization of products will be vital in the elimination of these problems that have been associated with a lack of uniformity in field performance. With respect to future studies, long-term field studies on the evaluations, creating more sophisticated formulations like nano-biostimulants, and integrating seaweed extracts with precision agriculture and other biological inputs should be addressed. On the whole, biostimulants in seaweed have great potential as a foundation of sustainable agriculture. As more research and collaboration between scientists, industry, and farmers are undertaken, they can also contribute significantly toward high productivity, environmental sustainability, as well as food security as climatic conditions change.

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