REVIEW ARTICLE

Seaweed-based Bio-stimulant as Multifunctional Bio-inputs: Agronomic Performance, Bioactive Composition, and Emerging Pharmaceutical and Nutraceutical Potential

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Abstract

Seaweeds in recent days have been turning out to be an extremely adaptable compound in the field of sustainable agriculture, plant stress research, and even human health. They offer a direct extraction of sea macroalgae, which captures a diversity of bioactive compounds such as phytohormone-like chemicals, sulfated polysaccharides, amino acids, antioxidants, vitamins and essential minerals into commercial preparations. Seaweed biostimulants in agricultural systems, particularly in perennial crops in adverse conditions, also assist crops to establish superior root systems, more effectively absorb nutrients, enhance photosynthesis, harmonize hormones, and overcome abiotic and biotic stress, but not merely deposit raw nutrients. In addition to pure agriculture, experimental and pre-clinical evidence is mounting that they are also pharmaceutical-ready due to excellent antioxidant, anti-inflammatory, antimicrobial, antiviral, immunomodulatory, metabolic-regulatory, and heart-protective properties. Fucoidan, laminarin, carrageenan, ulvan, alginates, and phlorotannins are major players in these therapeutic wins and can be included in functional foods, which depicts a good level of safety and bioavailability. This review summarizes the existing knowledge of the sources, bioactive makeup, mechanisms, health benefits, formulations, regulation, and research gaps in the field of seaweed biostimulants, and examines the potential way they might facilitate integrated agri-nutri-pharma systems and the circular bioeconomy.

Key words: Antioxidant activity, functional foods, nutraceuticals, pharmaceutical applications, seaweed biostimulants

INTRODUCTION

Biostimulants are one of the sustainable agricultural inputs that help increase nutrient uptake, enhance plant physiological processes, growth, yield, and tolerance without acting as direct nutrient sources.[1] Even when applied at low concentrations, biostimulant substances improve the metabolic processes of plants.[2] Bio-stimulants help increase and promote plant growth when they are applied in larger amounts.[3] Seaweed extract is well known for being used to promote growth, prevent pests and disease, and increase the quality of the product.[4] There are various biostimulant categories, but seaweed based biostimulant contain a rich composition of plant growth regulators, polysaccharides, amino acids,

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vitamins, and micronutrients, which jointly influence plant metabolism and stress–response pathways.[5,6] Seaweeds are a heterogenic community of organisms, consisting of about 9,000 species representing brown, green and red taxa of algae. Brown seaweeds are commercially extracted and used in agriculture.[7] Due to their content, such as macronutrients, amino acids, polyunsaturated fatty acids, vitamins, and types of polysaccharides.[5] These compounds enhance the biosynthesis activity of compounds such as auxin, cytokinins, and gibberellins and improve growth and development.[8] This molecular weight of this compound has a strong promotive action on the vegetative growth of the plant.[9] Chlorophyll content increases early and blocks chlorophyll degradation in the plant, also delaying senescence and increasing photosynthetic rate.[5] The extracts from brown seaweeds included *Ascophyllum nodosum*, *Ecklonia maxima*, and *Kappaphycus alvarezii*, and *Gracilaria edulis* are red seaweed.[10] Biostimulants contain naturally occurring bioactive compounds such as antioxidants, phenolics, and polysaccharides that exhibit antimicrobial, anti-inflammatory, and protective properties, making them valuable in pharmaceutical research. Certain components, such as chitosan, are widely used in drug delivery systems and wound-healing applications due to their biocompatibility and biodegradability. In addition, biostimulants enhance the production of secondary metabolites in medicinal plants, thereby increasing the yield of pharmaceutically important compounds and supporting the development of therapeutic and nutraceutical products. This review helps us to understand the seaweed-based biostimulants and their pharmaceutical value.

Definition and regulatory perspective of biostimulant

The biostimulant concept originated from the observation of the organic extracts and natural products that enhanced plant growth, explained using their mineral nutrient composition.[6] Biostimulants come in handy in perennial plantation crops such as coconut, where there is a long span of time, recurrent exposure to abiotic stressors, and depletion of soil biological activity with time.[18] Globally, it influenced research and product development in sustainable agriculture.[19] In India, biostimulants are greatly rising in fertilizer regulatory conditions; there is a problem of standardization of efficacy.[2]

Classification of plant biostimulants

Some of the biostimulants may be classified based on their source, their composition, and their mode of operation within the plant. Regulatory and scientific authorities define them as substances that are capable of causing plant activity, even without any adenoscent addition.[1] The most prevalent ones in plantation crops are the seaweed extracts, humic substances, protein hydrolysates, microbial inoculants, biopolymers, and inorganic stimulants. Research on horticultural crops has revealed that each of the classes has a specific physiological effect on growth, including hormone-like activity, increased nutrient uptake, and stress regulation.[3]

Distinction between biostimulants and biofertilizers

Biostimulants are natural or synthetic materials or organisms that stimulate plant growth, nutrient-use efficiency, plant quality, and tolerance to stress, mainly by modulating plant physiological mechanisms and not by providing nutrients directly.[1] Biofertilizers are preparations containing living microorganisms that can colonize the rhizosphere, or plant tissues; they increase growth by primarily biological fixation of nitrogen, solubilization of phosphates, or mobilization of nutrients.[20] The main mechanism of action of biostimulants

Name of the Biostimulant	Description of biostimulant	Reference
Seaweed extracts	Marine macroalgae-based biostimulants contain phytohormones, polysaccharides, micronutrients, amino acids, vitamins, and antioxidants that enhance plant growth. The most widely used species is *Ascophyllum nodosum*, along with brown seaweeds such as *Sargassum* spp. known for growth-promoting activity. Red seaweeds such as *Kappaphycus alvarezii* and *Gracilaria* spp. are rich in polysaccharides and widely used in tropical agriculture. These extracts contain auxin- and cytokinin-like compounds that enhance chlorophyll content, photosynthesis, stress tolerance, and delay senescence.	[5,11-14]
Humic and fulvic substances	Oriented out of leonardite, peat, or vermicompost. They enhance the exchange capacity of soils Cation Exchange Capacity (CEC) in terms of cations and nutrient retention. Humic acids enhance the availability of *P* through the solubility of fixed P.	[15]
Amino acids and Hydrolysate of protein	Manufactured through the enzymatic degradation of plant/animal proteins. They provide organic acids and bioavailable nitrogen. Corn gluten hydrolysate increased the growth of lettuce by 28%.	[16]
Microbial and botanical biostimulants	Microbial: Plant growth-promoting rhizobacteria (*Bacillus subtilis, Pseudomonas fluorescens*) Botanical: *Allium sativum* extract (garlic), *Zea mays* extract (corn) (White and Thorpe, 2019).	[17]

is the stimulation of plant metabolism, hormonal balance, enzyme activity, and stress-response signaling pathways that are observed to have been stimulated in experimental studies where plant antioxidant activities and physiological regulated stimulation are reported.[3] On the other hand, biofertilizers act by microbial mechanisms that enhance the availability of nutrients in the soil, such as the fixation of nitrogen and phosphorus solubilization.[21] Biostimulants can be inanimate products such as seaweed extracts, humic compounds, or protein hydrolysates that manipulate plant metabolism,[22,23] but biofertilizers are necessarily made up of active microbial strains. Contrary to the biostimulants, biofertilizers do not directly influence the nutrition of the plant, but the microbial conversion of soil nutrients to make the plant nutritionally active.[20]

SEAWEED-BASED BIOSTIMULANTS: AN OVERVIEW

Seaweed-based biostimulants are derived from marine macroalgae, mainly adopting biostimulant categories in agriculture, and are most extensively studied.[11] These products give the complex composition of bioactive compounds that influence plant growth, development, and stress tolerance.[5] The composition and seaweed extract enhance root growth, photosynthetic performance, nutrient uptake, yield traits, and resistance against abiotic stresses in a great number of crops.[8] Seaweed-based biostimulants have been found to be especially compatible in the case of coconut and other plantation crops when it comes to perennial crops and prolonged stress exposure.[12]

Major seaweed groups used in agriculture

Brown algae (Phaeophyceae)

Brown algae are the most widely used seaweeds in commercial biostimulant formulations.[11] They are specified based on the presence of fucoxanthin, alginates, laminarin, mannitol, and high levels of cytokinin and auxin-like compounds.[24] Common brown algal genera used in agriculture include *Ascophyllum, Sargassum, Laminaria,* and *Fucus.*[5] Brown algae extracts have been demonstrated to improve root development and nutrient uptake, tolerance to stress, and stability in yields of multiple crops. Root development and nutrient uptake should be improved with the help of brown algae extracts.[8]

Red algae (Rhodophyceae)

The red algae are being increasingly used in the tropical biostimulant preparation because they are quite abundant and economical.[11] They are rich in sulphated polysaccharides such ascarrageenans andagarans, which act as elicitors of plant defense and stress-response pathways.[14]

Green algae (Chlorophyceae)

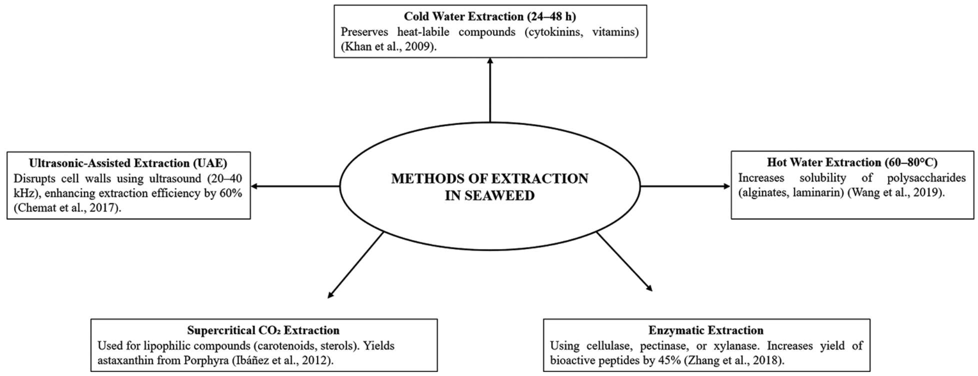
Green algae contain chlorophyll a and chlorophyll b and share biochemicals with related similarities in higher plants.[11] They are rich in ulvans, proteins, amino acids, vitamins, and minerals that help to improve plant growth stimulation.[16] *Ulva* spp. are commonly used green algae for agricultural biostimulant applications.[8] It isolates depicted prospective in enhancing nutrient uptake and endurance to stress. Compared to brown algae, it is not that commercialized.[5]

Common seaweed species used for biostimulant production

- Cold Water Extraction/Seaweed Biostimulants
- Hot Water Extraction
- Ultrasonic-Assisted Extraction
- Enzymatic Extraction
- Supercritical CO_2 Extraction

Method of seaweed extract preparation

Name of the species	Documented uses in plant systems	Primary research reference
Ascophyllum nodosum	These extracts contain hormone-like compounds, and they enhance root development, nutrient uptake, chlorophyll retention, and stress tolerance during crop development	[18,25]
Sargassum spp.	Bioactive metabolites and polysaccharides have been demonstrated to stimulate the growth of plants and enhance physiological performance	[16]
Kappaphycus alvarezii	They are abundant in sulphated polysaccharides such as carrageenans that are elicitors of plant defense and stress-response mechanisms in tropical crops.	[15]
Gracilaria spp.	Source of agar and bioactive polysaccharides, which facilitate plant growth and reduce stress.	[15]
Ulva spp.	ulvans and other bioactive products which increase nutrient uptake and stressing capacity in crops	[18]



Bioactive component	Documented physiological role	Primary research references
Auxins	Influence cell division, elongation, and differentiation in plant tissues. IAA activates auxin-responsive genes *(ARF1, ARF5).*	[22,25]
Cytokinins	Seaweed extracts enhance root initiation and lateral root growth, improving nutrient and water uptake. They suppress ethylene, delay senescence, increase chlorophyll content, and stimulate *IPT* gene expression.	[15,17]
Gibberellin-like compounds	Stimulate stem elongation, leaf expansion, and overall vegetative growth. GAs control the expression of GA20-oxidase.[15]	[15,26]
Laminarin	Act as elicitors that activate plant defense and stress–response pathways	[16]
Carrageenan	Trigger plant defense mechanisms and enhance stress tolerance	[14]
Ulvan	Improve stress resilience and act as signaling molecules in plants	[17]
Alginates	Contribute to nutrient chelation, improve root-zone chemistry, and enhance soil–plant interactions	[16]
Amino acids	Enhance metabolic activity, osmotic adjustment, and tolerance to abiotic stress	[3]
Proteins/peptides	Act as signaling molecules that stimulate enzyme activity and plant growth responses	[22]
Vitamins	Play roles in redox regulation and enzymatic activity	[17]
Primary, secondary, and micronutrients K, Ca, Mg, Fe, Zn, Mn	Essential cofactors in enzymatic and metabolic processes; support nutrient uptake and physiological efficiency. The Fe-use efficiency of calcareous soils was enhanced by *Ulva* extract, which regulated the gene yellow stripe 1	[16,27]

BIOACTIVE COMPONENTS OF SEAWEED-BASED BIOSTIMULANT

Seaweed-based biostimulants are effective due to all the various bioactive materials they contain, and this confounds plant physiology rather than being a nutrient.[15,22] In addition to growth regulators, it is analyzed that there are also polysaccharides, amino acids, vitamins, organic acids, and antioxidants that enhance better stress resistance in plants and also improve metabolism.[16] Experiments with tech indicate that those compounds increase chlorophyll construction, slow aging, and increase the efficiency of photosynthesis, which allows plants to endure stress in stressful conditions.[3,17] The betaines that we discovered in the extracts assist stabilize chlorophyll and prevent the leaves in crops from aging.[6]

MODE OF ACTION OF SEAWEED-BASED BIOSTIMULANT

Essentially, the biostimulants based on seaweed do not merely pour nutrients on the plants; they primarily adjust how a plant functions and lives. Extracts of brown seaweeds were discovered in the course of bioassay research to contain hormone-like compounds that interfere with cell division and ultimately determine the growth pattern of a plant.[22] Experimental studies on stress physiology also demonstrated that application of these biostimulants also pumps up antioxidant enzyme functioning and membrane stability when it is dry, which indicates that these biostimulants are also important actors in the metabolic regulation.[3] Overall, all these products are intersecting in terms of the root growth, photosynthesis, balance of hormones, stress reaction, and the dialogue between roots and soil.

Influence on root architecture and nutrient uptake

Seaweed extracts absolutely assist roots to become larger, and if distributed. It increases root length, gives rise to additional lateral roots, and advances the growth of the root hair, thereby increasing the total area of root surface. Bioassays of the hormones revealed that the extracts behave as auxin and cytokinin, stimulating meristem and root architecture.[9,22] Plants absorb more nutrients and water with an enhanced root system, particularly at times when there is a scarcity of stuff. This was supported by experimental research according to which the root growth after biostimulant application is more enhanced and results in increased uptake of nutrients and overall plant performance.[3] Treatment with *E. maxima* extract enhanced both root length density and transplant establishment of the treated crops.[28] The meristematic activity of roots was also stimulated by treatment with algal extracts, increasing root branching and soil exploration.[29]

Enhancement of photosynthesis and chlorophyll synthesis

Seaweed extracts increase the levels of chlorophyll and greenness of leaves. The experimental treatments registered increased chlorophyll retention and retarded senescence of leaves following the addition of the extracts.[6,17] The presence of the cytokinin-like activity is what preserves the chlorophyll and allows the photosynthesis to continue longer.[15] Increased photosynthetic capacity implies increased uptake of carbon and increased biomass production by plants, and the antioxidant systems activated by the biostimulant ensure that the photosynthetic tissues remain unaffected by oxidative stress.[3] Enhance stomatal conductance and CO_2 assimilation. *Kappaphycus* extract enhanced the stomatal opening in Arabidopsis through Open Stomata 1 Kinase.[30]

Hormonal regulation and growth promotion

Natural hormone-like compounds that are found in seaweed extracts do not replace the hormone balance in the plant but rather modify its hormone balance. Root initiation is initiated by auxin-like compounds, shoot growth is regulated by cytokinin-like compounds, and aging is delayed by gibberellin-like compounds.[15,22] Stimulates cell division in the meristematic area. Seaweed extract (5%), in this case coconut seedlings, improved the primordia count in the leaves by 25% (Sundararajababu *et al*., 2015). Promote flower initiation. Coconut: GA3 in ocean extract promoted the development of spikes by 7–10 days.[31] A combination of all these hormones will enhance vegetative growth, canopy development, and general plant vigor, which would be very beneficial in long-lived plantation crops that require constant control with time.

Activation of plant defense and stress tolerance mechanisms

Oligosaccharides and polysaccharides, such as laminarin in the seaweed, are elicitors that activate plant defenses. There is experimental evidence that biostimulant treatments increase the activities of antioxidant enzymes, assist the cells to adapt osmotically, and maintain the membranes stable, which reduces the amount of cellular injury in response to drought or salt stress in plants.[3] The systemic acquired resistance is caused by the accumulation of salicylic acid through seaweed extracts. *Ascophyllum* extract caused PR-1 to be expressed in tobacco, which cut tobacco mosaic virus infection by 70%.[32] The stress-responsive genes are dehydration-responsive element-binding protein-drought-induced. responsive to dehydration, 29-activated by salinity, heat shock protein 70-induced in heat stress.[33] Ganoderma basal stem rot was inhibited by 60% in coconuts with the use of seaweed extract through the stimulation of chitinases and b-1, 3-glucanases.[34] The increased production of protective metabolites also enhances the resistance of plants during difficult episodes in the environment.

PHARMACEUTICAL AND NUTRACEUTICAL POTENTIAL OF SEAWEED-BASED BIOSTIMULANTS: OVERVIEW

The value of seaweeds as rich sources of biologically active compounds is becoming widely recognised and is finding applications in agriculture, food science, pharmaceuticals, and nutraceuticals.[35,36] During the last decades, the world has been focusing on seaweed-based biostimulants due to their multifunctional bioactivity, environmental friendliness, and the possibility of producing them in a sustainable way.[12,37] Although their agronomic advantages, primarily the improvement of plant growth and stress resistance, proves that these biostimulants have significant pharmaceutical and nutraceutical properties that can be applied in relation to human health.[38,39] A wide range of bioactive molecules is produced by marine macroalgae, which include sulphated polysaccharides, polyphenols, carotenoids, sterols, peptides, vitamins, and minerals.[40,41] These substances exhibit antioxidant, anti-inflammatory, antimicrobial, antiviral, immunomodulatory, cardioprotective, and metabolic controls.[42-44] As a result, biostimulants in the form of seaweed are a special intersection between agricultural inputs and human health-promoting substances.[12,36] The current review is a synthesis of experimental evidence on the pharmaceutical and nutraceutical actions of seaweed-based biostimulants, in the context of bioactive composition, mechanism of action, therapeutic value, safety issues, and translational prospects.[38,39]

SEAWEED-BASED BIOSTIMULANTS: SOURCES AND BIOACTIVE COMPOSITION

These biostimulants are obtained by the extraction of marine macroalgae that are grown in coastal and open-oceanic ecosystems.[16,37] Brown seaweeds, including *A. nodosum*, *Sargassum* spp., and *Fucus* spp., are commonly used since they contain high levels of fucoidan, laminarin, alginates, and phlorotannins.[38,45] Carrageenans and agarans can be found in red seaweeds, such as, but not limited to: *K. alvarezii*, and *Gracilaria* spp.[46,47] Green algae, such as the species of the genus *Ulva*, include ulvans, proteins, as well as bioactive peptides with well-documented biological activity.[48] Sulphated polysaccharides, amino acids, vitamins (A, B-complex, C, and E), essential minerals, polyunsaturated fatty acids, and antioxidant compounds are included in the biochemical profile of seaweed biostimulants.[35,36] This combination has led to the complex health-promoting activities in experimental and pre-clinical studies.[39,44]

ANTIOXIDANT AND ANTI-INFLAMMATORY ACTIVITIES

Oxidative stress is identified as one of the key pathophysiological mechanisms of chronic diseases, such as cardiovascular disease, diabetes, neurodegeneration, and malignancy.[42,49] The biostimulants developed by the seaweed exhibit strong antioxidant properties through their capability of scavenging reactive oxygen species and enhancing endogenous antioxidant defence mechanisms.[39,50] Brown algal phlorotannins are also important in inhibiting lipid peroxidation and oxidative damage to cellular membranes.[40,42] Carrageenan fragments inhibit inflammatory edema and the production of prostaglandins in animals.[41,46] Another example is sulphated polysaccharides, which stimulate the activity of such antioxidant enzymes as catalase, superoxide dismutase, and glutathione peroxidase.[38,49] These results confirm the therapeutic significance of biostimulants produced by seaweeds in the treatment of conditions that manifest oxidative stress and inflammation.[39,43]

ANTIMICROBIAL AND ANTIVIRAL PROPERTIES

Biostimulants that are produced using seaweed have a wide-spectrum antimicrobial action against bacterial, fungal, and viral pathogens.[41,48] Sulphated polysaccharides have antimicrobial properties that inhibit microbial cell wall, enzyme systems, and also disrupt the mechanism of replication.[45,47] The extracts of *K. alvarezii* inhibit the growth of *Escherichia coli, Staphylococcus aureus*, and *Pseudomonas aeruginosa*.[35,46] Fucoidan extracted from brown seaweeds inhibits the adsorption and multiplication of herpes simplex and influenza viruses.[38,43] Interactions between envelope glycoproteins are blocked by viral entry by red seaweed polysaccharides (Jiao *et al*., 2011; Deville *et al*., 2007). These antimicrobial and antiviral properties indicate the pharmaceutical applicability of the seaweed-based biostimulants to the treatment of infectious diseases.[38,39]

IMMUNOMODULATORY AND ANTICANCER POTENTIAL

Bioactive compounds found in seaweed have an influence on immune response in the activation of macrophages, the increase of cytokine release, and the activity of natural killer cells (Maruyama *et al*., Ermakova *et al*.).[43,51] Fucoidin enhances cancer cell immune surveillance and promotes mitochondrial-mediated caspase activation and apoptosis.[38,43] There are experimental studies that support the antitumour effect of seaweed polysaccharides and inhibitory effect on angiogenesis in animal models.[41,51] All this indicates that seaweed-based biostimulants could find some use in immune health and as adjunctive cancer therapy, with their immunomodulatory and antiproliferative properties.[39,43]

METABOLIC REGULATION AND CARDIOPROTECTIVE EFFECTS

Biostimulants that are derived from seaweeds improve metabolic health by regulating lipid metabolism, preserving glucose homeostasis, and maintaining cardiovascular activity.[44,52] Alginates reduce serum cholesterol levels by binding bile acids and blocking the absorption of lipids into the intestines.[35,52] Phlorotannins suppress α-phosphatase and 8 glucosidases to enhance glycemic regulation.[40,44] The use of fucoidan supplements enhances insulin sensitivity and reduces hyperglycemia in diabetic models.[38,49] Dietary fibers in seaweed slow the emptying of the stomach and enhance the feeling of satisfaction, which is important during body-weight management.[48,52] These findings reveal the nutraceutical role of seaweed-derived biostimulants in the treatment of metabolic syndrome.[39,44]

GUT HEALTH AND PREBIOTIC FUNCTIONS

Seaweed polysaccharides are dietary fibers and prebiotics that selectively stimulate the beneficial gut microorganisms. *Lactobacillus* and *Bifidobacterium* are preferred microbes promoted by ulvans, laminarin, and alginates, thus improving microbial balance.[47,48] Nutraceuticals extracted from seaweed enhance the integrity of the intestinal barriers, reduce gut inflammation, and enhance the absorption of nutrients.[35,36] These characteristics make the seaweed biostimulants functional constituents in gut-health preparations.[39,48]

PHARMACEUTICAL AND NUTRACEUTICAL FORMULATION APPLICATIONS

The reason why seaweed bioactives are being used in pharmaceutical and nutraceutical products is due to their biocompatibility and functional properties.[36,38] Sulphated polysaccharides are excipients, stabilisers, and controlled-release agents in drugs.[41,46] Encapsulation technologies improve the bioavailability and target delivery of compounds from seaweed.[36,49] Antioxidants of seaweed provide nutraceutical preparations with shelf-life and oxidability.[39,50] Their multifunctional feature is the basis of use in functional foods, dietary supplements, and therapeutic products.[35,38]

SAFETY, TOXICOLOGY, AND BIOAVAILABILITY

Polysaccharides derived from seaweed are safe and non-toxic, as nutraceutical doses are performing toxicological studies.[35,38] There are no antibiochemical or histopathological effects that are attributed to seaweed-based nutraceuticals as demonstrated by long-term supplementation studies.[51,52]

BIOAVAILABILITY OF SEAWEED EXTRACT

Molecular weight and extent of sulphation are very influential factors that determine the bioavailability of sulphated polysaccharides produced by seaweed.[38] Low-molecular-weight fucoidan exhibited greater intestinal absorption as compared to original mass-high fractions in animal models.[45] Gut microbiota enzymatic degradation of polysaccharides in seaweed increases their bioavailability and biological action.[47] Phlorotannins in brown seaweeds were observed in plasma after oral administration, hence proving systemic bioavailability.[53] Seaweed bioactives were encapsulated to enhance the stability and absorption rate in the gastrointestinal tract.[36] Seaweed polyphenol metabolites had a protracted antioxidant effect following hepatic biotransformation.[49]

ROLE OF SEAWEED-BASED BIOSTIMULANTS IN FUNCTIONAL FOOD DEVELOPMENT

The addition of seaweed extracts to food matrices had a lot of impact on antioxidant activity and nutritional content.[50] Seaweed polysaccharides enhanced the texture, the water-retaining abilities, and shelf stability of the functional food products.[46] Oxidative-stress markers were minimized by dietary supplements with seaweed-enriched food in the human intervention research.[52] Fortified foods made with seaweed-based ingredients enhanced the bioavailability of minerals, especially calcium, iron, and iodine.[35] Experimental feeding experiments on functional foods fortified with bioactives in seaweeds enhanced lipid metabolism and glycemic response.[44] Nutraceutical foods derived from seaweed had high consumer acceptability and safety.[48]

SYNERGISTIC EFFECTS WITH OTHER NUTRACEUTICALS AND PHARMACEUTICALS

Polysaccharides in the seaweed improved the bioefficacy of polyphenols and vitamins in combination formulations.[40] Fucoidan synergistically enhanced the anticancer effect of the chemotherapeutic agents by sensitising tumour cells.[43] Oxidative toxicity due to drugs was alleviated using seaweed antioxidants in experimental pharmacological models.[42] Probiotics combined with a blend of seaweed bioactives enhanced gut and immune modulation.[47] A combination of seaweed compounds in synergistic formulations was associated with better therapeutic effects than individual treatments.[41]

CLINICAL AND HUMAN INTERVENTION EVIDENCE

In human trials, dietary supplementation with polysaccharides of seaweed enhanced lipid profiles and lowered serum cholesterol levels.[52] In human trials of the supplementation, it was reported that there was evidence of increased insulin sensitivity after taking seaweed bioactives.[44] Dietary interventions using seaweed improved the antioxidant enzyme activity of healthy volunteers.[42] The daily consumption of seaweed-enriched diets enhanced the immune parameters and lowered inflammatory markers in adults.[51] No side effects were reported in the long-term use of seaweed nutraceutical products.[35]

INDUSTRIAL, REGULATORY, AND COMMERCIAL PERSPECTIVES

Large-scale harvesting of seaweed bioactives has enabled the manufacturability of pharmaceutical-scale compounds.[38] The use of compounds derived from seaweed is gaining acceptance as generally recognized as safe ingredients in food and nutraceutical products.[35] The consumer demand for natural and sustainable health products is a major factor in the commercial adoption of seaweed-based nutraceuticals.[50] Regulatory harmonization and standardized processing are important to the commercialization of seaweed-derived products based on biostimulants across the world.[49]

KNOWLEDGE GAPS AND RESEARCH CHALLENGES

The insufficient knowledge of the long-term metabolic destiny of seaweed bioactives is one of the key research gaps.[38] The inconsistent bioactive profiles are due to variability among the seaweed species, harvest season, and extraction mechanisms.[40] Standardization of doses when used in pharmaceutical and nutraceutical applications needs additional controlled research.[43] There is a lack of large-scale human trials on the clinical validation of seaweed biostimulants.[44] The study would need advanced omics-based methods to explain the molecular pathways supporting the observed health outcomes.[49]

LIMITATIONS, OBSTACLES, AND EDUCATIONAL LACKINGS

However, in addition to their possible advantages, there are a variety of limitations to the application of seaweed-derived biostimulants in coconut cultivation.[8]

Fluctuation in the raw material and extract quality of seaweed

Seaweed biochemical content can change depending on the species, time of harvest, and environmental factors, and hence, extract quality is not consistent.[6] This variability leads to uneven field performance and restricts the possibility of results reproducibility across locations.[1]

Dose and application methods standardization

There are no clear instructions on the dosage, the frequency, or the application of coconut palms.[54] Age of palm, soil type, and climate also contribute to making the application practices more difficult to standardize.[18]

Limited long-term and place-specific studies of coconut

The majority of studies on biostimulants that are made of seaweeds have been on short-term studies or annual crops.[8] Multi-location field research on the crop peculiar to coconuts, over a long period, remains rare, even though the crop has perennial rotation.[54]

Economic and adoption constraints

Potential limitations to using seaweed-based biostimulants are the high costs of the products and the lack of awareness among farmers.[18] The absence of extension support and cost-benefit information also slows down the mass adoption in the coconut-growing areas.[1]

FUTURE RESEARCH PRIORITIES AND PROSPECTS

The use of biostimulants derived from seaweeds is an important source to use to enhance the productivity and sustainability of coconuts in response to the changing climatic conditions.[55] The future of biotechnology and environmentally friendly methods of extracting bioactives of seaweed offers opportunities to boost the yield and purity of bioactives.[36] The use of seaweed-based biostimulants in the functional food and pharmaceutical pipeline promotes the concept of the circular bioeconomy.[37] The ability to develop personalised health solutions using precision nutraceutical preparations based on seaweed bioactives is an opportunity with potential.[39] Further interdisciplinary studies will boost the clinical application of seaweed-based therapeutic molecules.[41]

Molecular and physiological principles

Future research is required to be aware of stress tolerance, nutrient transportation, and hormone regulation molecular pathways in the coconut.[8] These will help to enhance the formulations and such application strategies of the perennial crops that are planted in a plantation.[1]

Quality control and standardization of the products

It is required to have standardized extraction methods and quality norms that will ensure that the seaweed-based biostimulants do the same thing in the same manner.[6] The regulatory systems will increase the confidence of farmers and product assurance.[5]

CONCLUSION

In fact, seaweed-based biostimulants represent a scientifically proven and environmentally safe form of input that does not go unnoticed in contemporary agriculture or the human health industry, in general. The agronomic kick they cause is largely of a kind of hormone-like chemicals, polysaccharides, amino acids, and micronutrients that fiddle with plant physiology, increase root growth, tighten photosynthesis, optimize nutrient utilization, and activate stress-defense mechanisms, all without the appearance of conventional fertilizers. That is why they are particularly suitable in perennial and climate-sensitive crops where long-term productivity and endurance are important. Meanwhile, the immense biochemical diversity of the seaweed is the force behind its tidal application in the pharmaceutical and nutraceutical industry. Sulphated polysaccharides, phlorotannins, alginates, and their buddies have been demonstrated to be antioxidants, anti-inflammatories, and antimicrobials, antivirals, immune modulators, metabolic controllers, and heart protectors, which supports their purpose in functional foods, dietary supplements, and treatment formulas. Their products qualify only by their safety profile, biocompatibility, and flexibility. Nonetheless, it is not smooth sailing. The raw material may still be everywhere, the process of extracting it is not yet perfected, establishing the optimal dose is a challenge, regulators are behind, and we do not have any large human studies. Addressing these gaps using the state-of-the-art omics studies, establishing a solid quality control, conducting long-term field and clinical trials, and obtaining a cohesive policy backing will be important, in case we wish to capture the full potential of seaweed biostimulants. Altogether, it can be stated that the future of sustainable crop production, functional nutrition, and therapeutics of nature-origin is hopeful with these bio-resources, and they increase their presence in the future of climate-resilient agriculture and the global bioeconomy.

REFERENCES

1. Du Jardin P. Plant biostimulants: Definition, concept, main categories and regulation. Sci Hortic 2015;196:3-14.
2. Calvo P, Nelson L, Kloepper JW. Agricultural uses of plant biostimulants. Plant Soil 2014;383:3-41.
3. Zhang X, Schmidt R. Hormone-containing products' impact on antioxidant status of tall fescue and creeping bentgrass subjected to drought. Crop Sci 2000;40:1344-9.
4. Verkleij FN. Seaweed extracts in agriculture and horticulture: A review. Biol Agric Hortic 1992;8:309-24.
5. Khan W, Rayirath UP, Subramanian S, Jithesh MN, Rayorath P, Hodges DM, *et al*. Seaweed extracts as biostimulants of plant growth and development. J Plant Growth Regul 2009;28:386-99.
6. Craigie JS. Seaweed extract stimuli in plant science and agriculture. J Appl Phycol 2011;23:371-93.
7. Atzmon N, Van Staden J. The effect of seaweed concentrate on the growth of *Pinus pinea* seedlings. New For 1994;8:279-88.
8. Ali O, Ramsubhag A, Jayaraman J. Biostimulant properties of seaweed extracts in plants: Implications towards sustainable crop production. Plants (Basel) 2021;10:531.
9. Stirk WA, Van Staden J. Effects of seaweed-derived compounds of different molecular weights on plant growth. J Appl Phycol 1996;8:503-8.
10. Wang L, Liu F, Wang A, Yu Z, Xu Y, Li R, *et al*. Hot water extraction of polysaccharides from seaweeds. J Appl Phycol 2019;31:1123-32.
11. Shukla PS, Sharma AK, Singh NP. *Ascophyllum nodosum*-based biostimulants: Sustainable applications in agriculture. Trends Plant Sci 2019;24:321-34.
12. Stirk WA, Van Staden J. Comparison of cytokinin- and auxin-like activity in some commercially used seaweed extracts. J Appl Phycol 1996;8:503-8.
13. Blunden G, Jenkins T, Liu YW. Enhanced leaf chlorophyll levels in plants treated with seaweed extract. J Appl Phycol 1997;8:535-43.
14. Whapham CA, Blunden G, Jenkins T, Hankins SD. Significance of betaines in the increased chlorophyll content of plants treated with seaweed extract. J Appl Phycol 1993;5:231-4.
15. Ahmad M, Lee SS, Dou X, Mohan D, Sung JK, Yang JE, *et al*. Effects of humic acid on root growth and gene expression related to nutrient uptake in plants. Geoderma 2019;337:749-62.
16. Colla G, Nardi S, Cardarelli M, Ertani A, Lucini L, Canaguier R, *et al*. Protein hydrolysates as biostimulants in horticulture. Sci Horticul 2015;196:34-43.
17. White PJ, Thorpe MR. Botanical biostimulants in agriculture: Mechanisms and applications. J Plant Sci Biotech 2019;12:145-58.
18. Rouphael Y, Colla G. Biostimulants in agriculture. Front Plant Sci 2020;11:40.
19. Yakhin OI, Lubyanov AA, Yakhin IA, Brown PH. Biostimulants in plant science: A global perspective. Front Plant Sci 2017;7:2049.
20. Vessey JK. Plant growth promoting rhizobacteria as biofertilizers. Plant Soil 2003;255:571-86.
21. Adesemoye AO, Torbert HA, Kloepper JW. Enhanced plant nutrient use efficiency with plant growth-promoting rhizobacteria. Appl Soil Ecol 2008;40:97-104.
22. Crouch IJ, Van Staden J. Evidence for the presence of plant growth regulators in commercial seaweed products. Plant Growth Regul 1993;13:21-9.
23. Canellas LP, Falcao AC, Rumjanek VM. Humic acids as bioactive compounds affecting root physiology. Plant Soil 2002;249:263-73.
24. Stirk WA, Tarkowská D, Turečová V, Strnad M, Van Staden J. Plant growth regulators in seaweeds: Occurrence, regulation and physiological responses. J Appl Phycol 2014;26:1373-85.
25. Tao Y, Ferrer JL, Ljung K, Pojer F, Hong F, Long JA, *et al*. Rapid synthesis of auxin via a new tryptophan-dependent pathway is required for shade avoidance in plants. Plant Physiol 2018;176:1890-904.
26. Yamauchi Y, Takahashi M, Miyazaki S, Kuroha T, Nagai K, Seo M. Gibberellin biosynthesis and regulation in plants. Plant Physiol 2004;134:1100-10.
27. Lucena C, Romera FJ, Alcántara V. Seaweed extracts enhance iron acquisition in calcareous soils by activating YS1 transporter in pepper. Plant Soil 2020;456:213-27.
28. Mattner S, Wite D, Riches D, Porter I, Arioli T. The effect of kelp extract on seedling establishment of broccoli on contrasting soil types in southern Victoria, Australia. Biol Agric Hortic 2013;29:258-70.
29. Rayorath P, Jithesh MN, Farid A, Khan W, Palanisamy R, Hankins SD, *et al*. Rapid bioassays to evaluate the plant growth promoting activity of *Ascophyllum nodosum* (L.) Le Jol. Using a model plant. *Arabidopsis thaliana* (L.) Heynh. J Appl Phycol 2008;20:423-9.
30. Ishikawa Y, Iwatani M, Takeno K. *Kappaphycus alvarezii* extract enhances stomatal opening via OST1 kinase activation in *Arabidopsis thaliana*. Plant Signal

Behav 2021;16:1-9.
31. Raghavan G, Kumari R, Sahoo D, Reddy CR, Jha B, Prasad K, *et al.* Seaweed extracts as biostimulants for crop productivity and quality improvement. J Appl Phycol 2019;31:3747-60.
32. Vallad GE, Goodman RM, Ji P, Tally A, Collins A, Cooperband L, *et al.* Induced systemic resistance and plant defense responses triggered by plant activators. Phytopathology 2003;93:356-62.
33. Yamaguchi-Shinozaki K, Shinozaki K. Transcriptional regulatory networks in cellular responses and tolerance to dehydration and cold stresses. Annu Rev Plant Biol 2006;57:781-803.
34. Sundararajababu S, *et al.* Effect of Seaweed Extract on Growth and Physiological Parameters of Coconut Seedlings. Proceedings/Institutional Report; 2015.
35. Gupta S, Abu-Ghannam N. Bioactive potential and possible health effects of edible brown seaweeds. Trends Food Sci Technol 2011;22:315-26.
36. Ganesan AR, Tiwari U, Rajauria G. Seaweed nutraceuticals and their therapeutic role in disease prevention. Crit Rev Food Sci Nutr 2018;59:2733-51.
37. Zodape ST, Gupta A, Bhandari SC, Rawat US, Chaudhary DR, Eswaran K, *et al*. Foliar application of seaweed sap as biostimulant for enhancement of yieldand quality of tomato (*Lycopersicon esculentum* Mill.). J Sci Ind Res 2011;70:215-9.
38. Fitton JH, Stringer DN, Karpiniec SS. Therapies from fucoidan: An update. Mar Drugs 2015;13:5920-46.
39. Fernando IP, Kim M, Son KT, Jeong Y, Jeon YJ. Antioxidant activity of marine algal polyphenolic compounds. J Med Food 2020;23:1-14.
40. Li YX, Wijesekara I, Li Y, Kim SK. Phlorotannins as bioactive agents from brown algae. Process Biochem 2011;46:2219-24.
41. Jiao G, Yu G, Zhang J, Ewart HS. Chemical structures and bioactivities of sulfated polysaccharides from marine algae. Mar Drugs 2011;9:196-223.
42. Karadeniz F, Kim JA, Ahn BN, Kim SK. Functional properties of phlorotannins from *Ecklonia cava*. Food Chem Toxicol 2009;47:410-7.
43. Ermakova S, Sokolova R, Kim SM, Um BH, Isakov V, Zvyagintseva T. Fucoidans from brown algae as anticancer agents. Mar Drugs 2013;11:487-512.
44. Kim KT, Rioux LE, Turgeon SL. Alpha-amylase and alpha-glucosidase inhibition by alginates and fucoidans. Food Chem 2010;122:109-14.
45. Li B, Lu F, Wei X, Zhao R. Fucoidan: Structure and bioactivity. Molecules 2008;13:1671-95.
46. Prajapati VD, Maheriya PM, Jani GK, Solanki HK. Carrageenan: A natural seaweed polysaccharide and its applications. Carbohydr Polym 2014;105:97-112.
47. Deville C, Damas J, Forget P, Dandrifosse G, Peulen O. Laminarin in the dietary fibre concept. J Sci Food Agric 2007;87:1179-84.
48. O'Sullivan L, Murphy B, McLoughlin P, Duggan P, Lawlor PG, Gardiner GE. Prebiotics from marine macroalgae for human and animal health applications. Mar Drugs 2010;8:2038-64.
49. Zhao C, Gao L, Wang C, Liu B. Metabolic fate and antioxidant activity of marine polyphenols. Food Chem 2018;245:907-16.
50. Wang T, Jónsdóttir R, Ólafsdóttir G. Total phenolic compounds, radical scavenging and metal chelation of extracts from Icelandic seaweeds. Food Chem 2009;116:240-8.
51. Maruyama H, Tamauchi H, Hashimoto M, Nakano T. Antitumor activity and immune modulation by fucoidan. Int Immunopharmacol 2006;6:193-201.
52. Brownlee IA, Allen A, Pearson JP, Dettmar PW, Atherton MR, Onsoyen E. Alginate as a source of dietary fiber. Food Hydrocoll 2005;19:713-23.
53. Corona G, Coman MM, Spencer JP, Rowland I, Tzounis X. Absorption, metabolism, and biological activity of phlorotannins from brown seaweeds. J Agric Food Chem 2016;64:6476-86.
54. CPCRI. Coconut Cultivation and Nutrient Management Practices. Kasaragod, India: ICAR-Central Plantation Crops Research Institute; 2020.
55. 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;29:655.

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