Chapter

Biostimulant Properties of Marine Bioactive Extracts in Plants: Incrimination toward Sustainable Crop Production in Rice

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Abstract

Enhancing productivity through integrated and comprehensive nutrient management is pertinent to sustainable intensification of agricultural ecosystems. The utilization of marine bioactive stimulants has been gaining momentum and impetus in crop agricultural farming system due to their phytoelicitor activity. Liquids biostimulants derived from seaweed evoke defense responses in plants that contribute to resistance to abiotic stresses and challenges like high temperature, salinity, moisture stress, and cold. Seaweed extracts are immensely organic and suitable for growing crops that are both organic and environmentally friendly. Seaweeds provide an abundant source of natural growth substances that can be employed to enhance plant growth. Seaweeds are one of the most significant marine resources of the world, and derived compounds have been extensively used as amendments in crop production systems due to the presence of macronutrients such as Ca, K, and P and micronutrients like Fe, Cu, Zn, B, Mn, Co, and Mo, presence of several plant growth stimulating compounds including cytokinin, auxins, gibberellins, and betaines which are essential for plant growth and development. The purpose of the current chapter is to explore the functional and growth characteristics induced by seaweed extracts in addition to their modes and mechanisms of action in rice crops, which are responsible for elicitor and phytostimulatory activities and boost in grain production and nutrient usage efficiency.

Keywords: seaweed extract, macroalgae, liquid biostimulants, stress tolerance, sustainable agriculture, phytoelicitor compounds

1. Introduction

Abiotic and biotic stresses restrict the growth and productivity of crops. The global effects of negative climatic changes have manifested as desertification, escalate atmospheric CO_2, temperature, and soil salanization, and nutrient imbalances like mineral toxicity and deficiency have caused dramatic effects on agricultural production and the quality of crops. Abiotic stresses have reduced the growth, development, productivity, and quality of plants and local extinction of species. The global amount of cultivable land for agriculture is continuously shrinking due to adverse effects of climate change. Abiotic stresses may be prevented by optimizing plant growth conditions and through provision of water, plant growth regulators (PGRs – auxins, cytokinins, gibberellins, stringolactones, and brassinosteroids) and nutrients. Rice is one of the most significant food crops grown across the world. It is a primary staple food for more than 50% of the world's population, accounting for more than 20% of their daily caloric consumption from rice [1]. Rice is cultivated in 160 million ha area globally with an average yield of 4631 kg ha^{-1} [2].

Biostimulants are increasingly being incorporated into production system with the objective of altering physiological processes in plants to optimize plant productivity [3]. Biostimulants present a potentially novel approach for regulating and altering physiological processes in plants to stimulate growth, to mitigate stress limitations, and to boost yield. Biostimulant materials are natural products which contain no added chemicals or synthetic plant growth regulators and which have a beneficial effect on plant growth. Seaweed/sea plants are gaining considerable importance due to the distribution, renewable nature, and widespread application [4]. Organic biostimulants are compounds which increase plant growth and vigor through increased efficiency of nutrient and water uptake. Plant biostimulants are compounds when applied to plants, seeds, or growing substrates have the capacity to modify physiological processes of plants in a way that provides potential advantages to growth and stress response. Seaweed (macroalgae) is a multicellular macroscopic algae species which are subdivided into red, green, and brown algae due to their pigmentation according to phyla, Rhodophyta, Chlorophyta, and Phaeophyceae. Nine thousand species of macroalgae are broadly classified into three main groups, viz. Rhodophyta (red algae), Ochrophyta-Phaeophyceae (Brown algae), and Chlorophyta (green algae), based on pigments present. Sea plant biostimulants derived from natural raw resources are used in the ultrasmall and minute doses for modification of biochemical and physiological plant processes with the objective of more complete realization of genetic potential of their productivity due to changes in hormonal status, activation of metabolic processes, increase in nutrient efficiency, stimulation of growth, development, and strengthening of the potential to withstand the negative effects of various stress factors. Seaweed biostimulants are new class of inputs offering a potential alternative to traditional organic chemical inputs and can reduce the application of fertilizers to improve soil health and increase soil microbial activity [5]. Chemical analysis of seaweeds and their extracts have revealed the presence of a broad spectrum of plant growth regulators/phyto-hormones such as auxins, gibberellins, cytokinins, and betaines, enzymes, vitamins and hydrolyzed proteins, polysaccharides, nutrients, and trace elements (Fe, Cu, Zn, Co, Mo, Mn, and Ni) in varying amounts and biologically active alginic acids, polyphenols, and free amino acids which invigorate plant growth and alleviating several biotic and abiotic stresses [6]. Seaweeds often contain larger concentrations of Ca, K, Mg, Na, Cu, Fe, and Zn than terrestrial plants [5]. The biostimulant aids in fostering the development of beneficial soil microorganisms, developing tolerance to environmental stress and improving nutrient uptake from soil and enhancing antioxidant properties. Seaweed extract supplement improved significantly the content of nitrate nitrogen (N), available phosphorus (P), and available potassium (K) in rhizosphere soil in the tillering stage, and, finally, increased the rice yield and quality mildly in rice crop.

Biostimulants are agents which at very low concentrations improve the basic biochemical processes in plants and soil and thereby improve the growth and development of plants and increase resistance to stress. The seaweed properties with most potential relevance to crop production involve elemental composition (e.g. primary plant nutrients, other nutrient elements, heavy metals, and salts) and organic compound composition (e.g. energy sources for microbial processes). Seaweed extracts improved the number and size of chloroplasts, the growth of chloroplast grana, and the concentration of chlorophyll in leaves due to the presence of beneficial amounts of cytokinins, auxins, betaines, and inorganic salts [7]. The most commonly used seaweed as a biostimulant is an alga, obtained from North Atlantic Ocean and known as *Ascophyllum nodosum*, rich in polysaccharides (alginate, fucoidan, and laminarin), minerals, and vitamins [8]. The goal of the chapter is to provide comprehensive analysis of the current situation in the field of biostimulants and to develop a science-based theoretical foundation for the conceptualization, classification, and practical application of sea plant biostimulants. The structure of the chapter is based on the consideration of biostimulants in terms of the action on different regulatory and functional system of plants (signaling, metabolism, uptake, and transport system) using both conceptual and methodological approaches.

2. Different types of seaweed/plants and its distribution

The seaweeds are distributed horizontally in different zonations, viz. supra-tidal (supra-littoral), intertidal (littoral) and subtidal (sub-littoral) regions of the seas and oceans. Green seaweeds are most commonly found in the intertidal zone (**Table 1**). Common green seaweeds are species of *Ulva* (sea lettuce), *Enteromorpha* (green string lettuce), *Chaetomorpha*, *Codium*, and *Caulerpa*. Brown seaweeds inhabit in the tidal or upper subtidal zone. Common brown seaweeds are species of *Sargassum*, *Laminaria*, *Turbinaria*, and *Dictyota*. Red seaweeds grow in subtidal waters. Common red seaweeds are species of *Gracilaria*, *Gelidiella*, *Eucheuma*, *Ceramium*, and *Acanthophora*. The blue green algae grow in supra-tidal region mostly as colonies, and sometimes they occur as epiphytes on other algae. Common blue green algae are species of *Lyngbya*, *Spirulina*, and *Oscillatora*. Seaweeds, which are multicellular, microscopic plants that are found coastal locations, are an integral component of coastal marine ecosystems. Marine algae or seaweeds are classified into three taxonomic groups that have diverse pigment composition: Rhodophyta (red algae), Chlorophyta (green algae), and Ochrophyta (brown algae). The Indian Ocean is host to 865 species of seaweed belonging to 216 genera and 68 families [9]. Brown algae (Phaeophyceae) are the largest prevalent type of seaweed that are habitat to water of temperate region where more than 2000 species are found. Green algae (Chlorophytta) can be found in marine or freshwater habitats, and some even thrive in moist soils where more than 1800 species are found. Green algae come in three forms: unicellular, colonial, or multicellular. Sea lettuce (*Ulva lactuca*) is a type of green algae commonly found in tidal pools. Red seaweed (Rodophyta) is the largest group of algae in the plant kingdom which account more than 7200 species

Class	Order	Family	*Species*
Rhodophyceae (Red algae)	Ceramiales	Ceramiaceae	*Spyridia filamentosa Ceramium planum*
		Rhodomelaceae	*Amansia glomerata Laurencia papillosa Acanthophora spicifera Laurencia johnstonii Laurencia obtusa*
	Corallinales	Lithophyllaceae	*Amphiroa rigida Amphiroa gracilis*
		Mastoporaceae	*Mastophora rosea Mastophora pacifica Mastophora multistrata*
		Corallinaceae	*Corallina elongate Janie rubens Lithothamnium calcareum*
	Nemaliales	Galaxauraceae	*Galaxaura apiculata Galaxaura fastigiata Galaxaura filamentosa Actinotrichia fragilis*
		Acrochaetaceae	*Porphyra perforate*
	Cyanidiales	Cyanidiaceae	*Cyanidium caldarium*
	Gelidiales	Gelidiaceae	*Gelidium serrulatum*
	Gracilariales	Gracilariaceae	*Gracilaria edulis Gracilaria gracilis Gracilaria salicornia Gracilaria textorii Gracilaria verrucos Gracilaria dura*
	Gigartinales	Solieriaceae	*Eucheuma denticulatum Eucheuma spinosum Kappaphycus alvarezii Kappaphycus cottonii Sarcodiotheca chordalis*
		Cystocloniaceae	*Hypnea spinella Hypnea musciformis*
Phaeophyceae (Brown algae)	Dictyotales	Dictyotaceae	*Dictyota dichotoma Padina australis Padina pavonica*
	Ectocarpales	Scytosiphonaceae	*Hydroclathrus clathratus Hydroclathrus minutus*
	Fucales	Sargassaceae	*Sargassum cristaefolium Sargassum polycystum Cystoseira humilis*
		Fucaceae	*Ascophyllum nodosum Fucus gardneri Fucus spiralis Fucus vesiculosus*
		Alariaceae	*Alaria esculenta*
		Durvillaeaceae	*Durvillea Antarctica Durvillea protatorum*
	Laminariales	Lessoniaceae	*Ecklonia maxima Nereocystis luetkeana*
		Laminariaceae	*Laminaria digitata Macrocycstis pyrifera*

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Class	Order	Family	*Species*
Ulvophyceae (Green algae)	Bryopsidales	Caulerpaceae	*Caulerpa paspaloides Caulerpa lentillifera Caulerpa racemosa Caulerpa serrulata Caulerpa sertularioides*
		Halimedaceae	*Halimeda cuneata Halimeda cylindracea Halimeda discoidea Halimeda incrassata Halimeda macroloba Halimeda opuntia Halimeda tuna*
		Udoteaceae	*Udotea geppiorum*
		Dichotomosiphonaceae	*Avrainvillea erecta Avrainvillea lacerata*
		Codiaceae	*Codium ovale Codium bursa Codium liyengarii Codium tomentosum*
	Cladophorales	Cladophoraceae	*Chaetomorpha crassa Chaetomorpha spiralis Cladophora rupestris*
		Anadyomenaceae	*Anadyomene wrightii Microdictyon marinum*
		Siphonocladaceae	*Boergesenia forbesii Dictyosphaeria cavernosa*
		Valoniaceae	*Valonia aegagropila Valonia fastigiata*
	Dasycladales	Dasycladaceae	*Bornetella sphaerica Neomeris annulata*
	Ulvales	Ulvaceae	*Ulva prolifera Ulva armoricana Ulva fenestrate Ulva lactuca Ulva rigida Enteromorpha prolifera*
	Ulotrichales	Monostromataceae	*Monostroma grevillei*
		Ulotrichaceae	*Spongomorpha aeruginosa*
	Prasiolales	Prasiolaceae	*Prasiola calophylla*

Table 1.
List of important seaweed species.

found in shallow waters and withstand deep water and low light conditions. It has been reported that 59 species of seaweeds found in Indonesian coastal region, 15 of the species are capable of stimulating germination, development, growth, and production of rice and legume crops [10]. *Halimeda opuntia*, *Caulerpa racemosa*, *Gracilaria edulis*, and *Chaetomorpha crassa* grow widely and abundantly in stagnant water in the mangrove hinterlands of Indian and Pacific Ocean. The seaweeds easily grow, survive, and monopolize in stagnant water where the salinity and temperature greatly fluctuate. *Hypnea musciformis* is found in Atlantic, Pacific, and Indian Ocean and has the widest geographical distribution. *Mastophora rosea, Mastophora pacifica, and Mastophora multistrata* were found in bluish purple color and distributed in Pacific Ocean and Indian Ocean. *Sarcodiotheca chordalis* was reported in the Mediterranean Sea and Atlantic Ocean from Morocco to Southwest England. *Cheilosporum cultratum* and *Caulerpa lentillifera* have been newly found in near the islands of Indian Ocean. Totally 59 species of seaweeds were recorded from the Indian Ocean which included six species of Scytasiphonaceae and Gracilariaceae, five species of Ulvaceae, four species of Cladophoraceae and Halimedaceae, three species of Dictyotaceae, two species of Caulerpaceae, Rhodomelaceae, Corallinaceae, Florideophyceae, Sargassaceae, Cystocloniaceae Gelidiellaceae, and Oscillatoriaceae, and one species of Bangiophyceae, Lithophyllaceae, Codiaceae, Cystocloniaceae, Characea, Valoniaceae, Boodleaceae, Siphonocladaceae, Solieriaceae, Galaxauraceae, Liagoraceae, Sphacelariaceae, Monostromataceae, Ulvophyceae, and Lessoniaceae [11]. *Kappaphycus alvarezii* is a tropical seaweed being cultivated in southeast coastline of India since more than a decade for the extraction of thickening agent called kappa-carrageenan using traditional farming systems.

3. Significance of seaweed in agriculture

Liquid products based on marine algae were introduced in 1950 and now are successfully used worldwide. The seaweed concentrates are admistered to crops as root dips, soil drenches, and foliar sprays. Seaweed-derived biostimulant extracts used as foliar sprays have gained importance for multiple crops including various grasses, cereals, pulses, and vegetables [12]. Seaweed extract application as foliar spray is a common practice to boost production in many commercial crops. Seaweed extract enhances tolerance against environmental stresses and challenges and enhances nutrient uptake from soil by plants [13]. Foliar application of seaweed biostimulants offers a quicker method of supplying nutrients to higher plants alternate to soil application method [14]. This may as a result of active nutrient uptake through stomatal pores instead of cuticular uptake [15]. The mechanism by which seaweed biostimulants affect cellular metabolism is based on the physiological action of macro- and microelements, amino acids, vitamins, and substances. The seaweed biostimulant enhances meristematic growth, translocation of photosynthates, enzyme activation, cell elongation, and cell stability [16]. Seaweed extract enhances chlorophyll content by increasing the biogenesis of chloroplasts and reducing chlorophyll degradation, which was due to the upregulated genes associated with photosynthesis, cell metabolism, stress response, and S and N metabolism in *Brassica napus* L. [17]. The seaweed when applied to crops as foliar spray can accelerate the rate of cell division and elongation. Seaweed extract of the brown algae *Sargassum heterophyllum* contain cytokinin, while *Ascophyllum nodosum* contain the growth hormone Indole-3-acetic acid. Seaweed supplies macro- and micronutrients, has liming properties, and increases phosphorus availability, the phycocolloids improve soil structure, increases the water retention and cation-exchange capacities of soil, binds metals, boosts biological activity, and improves plant resistance to aggressive biotic and abiotic agents [18].

4. Seaweed extract on biochemical characters in crops

The bioactive compounds (not yet fully elucidated) present in *Ascophyllum nodosum* extracts when applied to stressed plants have reduced the deleterious effects of drought stress by regulating a series of sequential molecular, cellular, and physiological responses including the modulation of several genes, resulting in an

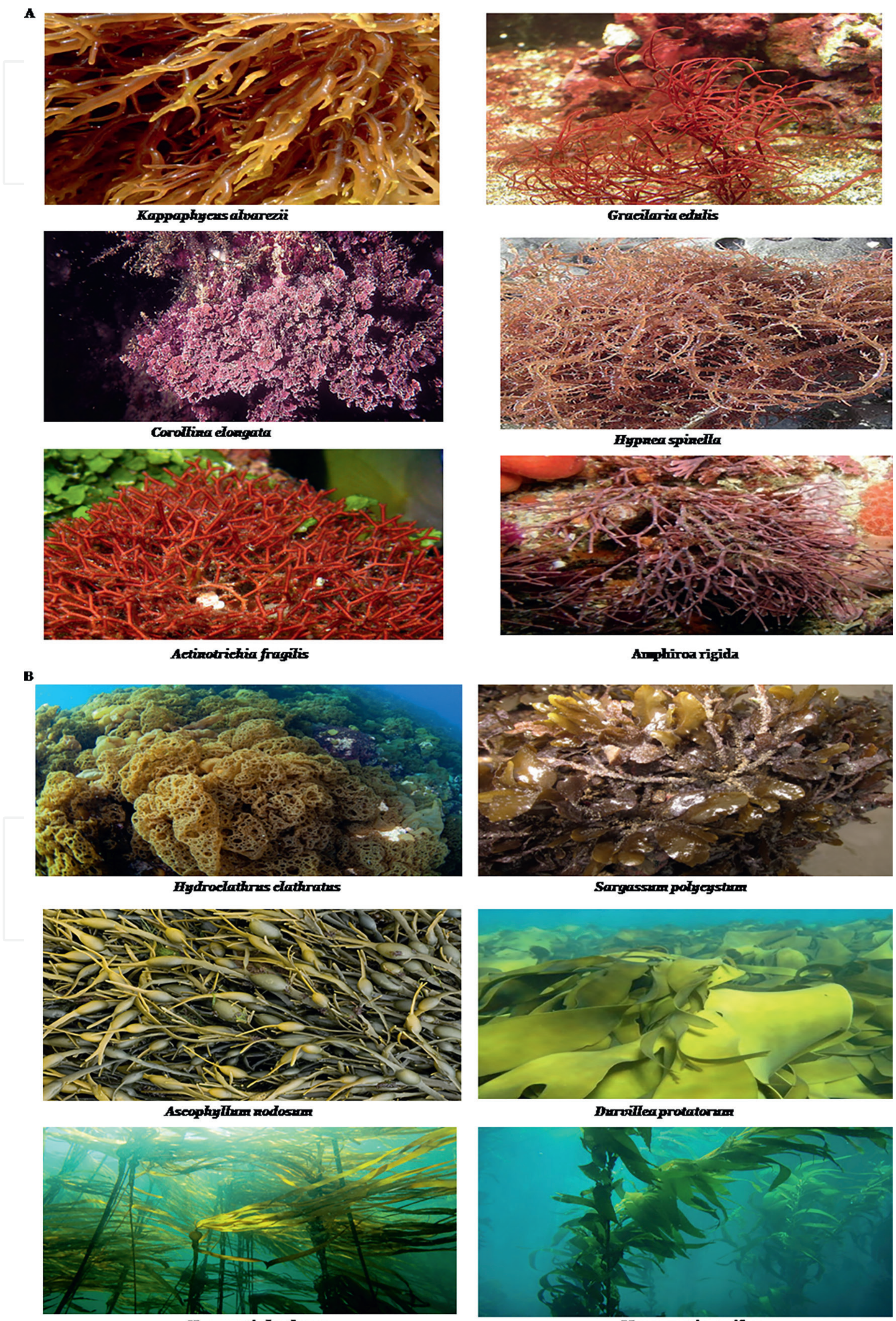
Parameters	*Ascophyllum nodosum*	*Laminaria digitata*
Type	Brown	Brown
Water (%)	70–80	73–92
Ash (%)	15–26	21–37
Alginic acid (%)	15–35	20–50
Laminaren (%)	0–15	0–20
Mannitol (%)	5–10	4–20
Fucoidan (%)	4–15	2–6
Carbohydrate (%)	10	1–3
Protein (%)	5–10	8–20
Fat (%)	2–8	1–3
Tannins (%)	2–12	1–2
Potassium (%)	2–3	1.3–3.8
Sodium (%)	3–4	0.9–2.2
Magnesium (%)	0.5–0.9	0.5–0.8
Iodine (%)	0.01–0.1	0.3–1.3

Table 2.
Chemical composition (in percentage) of the seaweeds Ascophylum nodosum and Laminaria digitata.

accumulation of various osmolytes, an improved antioxidant system, and enhanced gaseous exchange through stomatal regulation (**Table 2**). Priming wheat seeds with the extracts of *U. linza* or *C. officinalis* promoted almost physiological parameters like chlorophyll, carotenoids, sugars, proteins, and lipids. Seaweed extracts with high magnesium and mineral content tended to increase leaf total chlorophyll and carotenoids concentration [19]. The increased protein and sugar contents due to seaweed priming could be attributed to absorption of majority of the major elements in these extracts, particularly magnesium, which could have activated chlorophyll synthesis and, as a result, improved photosynthetic rates [20]. Foliar spray of seaweeds extract was effective in improving wheat performance by enhancing compatible osmolytes and antioxidant compounds and enhancing variation among non-coding chloroplast DNA (cpDNA) regions trnL intron and psbA-tnH as a response to water deficit.

5. Physiological effect of Seaweeds extracts application in mitigating abiotic stress

Application of seaweed extracts as natural regulators has had promising benefits, such as enhanced crop productivity and plant vigor to withstand adverse environmental influences. Plants, being sessile, are relentlessly challenged by a variety of environmental stresses that limit their growth and productivity. Due to the complex metabolic pathways involved in stress tolerance, limited success has been achieved in generating stress-tolerant crops through genetic engineering. Extract of *Ascophyllum Nodosum* application has shown to assist soybean plants endure severe drought conditions by regulating leaf temperature, turgor, and several stress-responsive genes [21]. Mild salinity stress causes physiological drought in plants, impairing cell–water relations, inhibiting cell expansion, and, consequently, reducing growth rate. Soil salinity is a global problem, affecting over 800 million hectares of land, resulting in massive impacts on agricultural productivity [22]. Long-term exposure



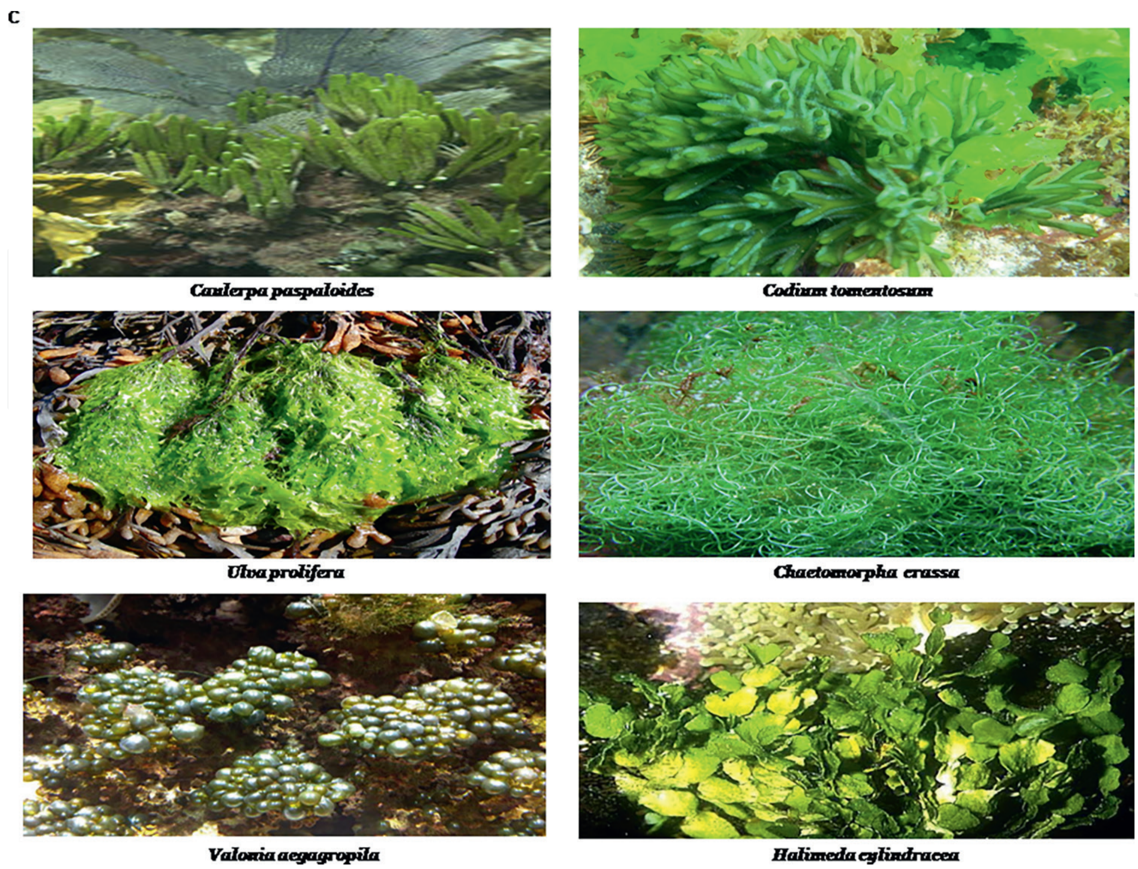


Figure 1.
Common seaweeds species in Ocean (A), Rhodophyceae (Red algae), (B) Phaeophyceae (Brown algae), and (C) Ulvophyceae (Green algae).

to high salinity causes ionic stress by disturbing the homeostasis of intracellular ions, which results in membrane dysfunction and attenuation of metabolic activity and secondary effects, inhibiting growth and inducing cell death [23]. Mild salinity stress induces physiological drought in plants, impairing cell–water relations, inhibiting cell expansion, and consequently, reducing growth rate. Salinity induces both ionic and osmotic stresses, thus reducing plant growth and productivity [24]. *Ulva prolifera* extract reduced the oxidative damage caused by drought not only by activating the antioxidative system but also by providing essential hormones and minerals for wheat growth [25]. Drought stress is one of the most severe abiotic stresses which have negative impact on plant growth, crop production, and numerous metabolic processes. Application of seaweed extract in mitigating water stress and adverse effects is highly important for plant production (**Figure 1**).

6. Effect of seaweed extract on crop development and yield

Seaweed extract (15 percent) was sprayed as foliar application to rice crop during vegetative and generative stages. The results shown that extracts of *Sargassum calophyllum*, *Sargassum polyceratum*, *Sargassum vulgare*, *Sargassu*m *aquifoliu*m, *Sargassum polycystum, Hydroclathrus clathratus, Hydroclathrus minutes, Ulva fasciata, Ulva ferticulata, Padina pavonica, Gracilaria edulis, Chaetomorpha crassa, Turbinaria ornata*, and *Turbinaria murayana* were able to promote growth of rice plants. *Hydroclathrus clathratus* extract enhanced crop growth and production of rice crop. This phenomenon may be due to the presence of active compounds and micro- and macronutrients in the extract of seaweeds which can stimulate plant growth (**Figure 2**). Various species of marine algae found in nature contain organic compounds which activities resemble the activity of cytokinins, auxins, and gibberellins. The organic compounds were able to stimulate growth as a result of enhancement of protein synthesis, cell division, and mobilization of nutrients needed to boost growth of rice crop [9].

Seaweed extract supplement of *Sargassum horneri* was applied at 5 percent to fertilizer (50 percent) as basal and top dressing increased the rice yield slightly and, especially, the amount of fertilizer applied was saved by 50% in rice crop [26]. Three foliar sprays of *Kappaphycus alvarizii* (K sap) and *Gracilaria edulis* (G sap) when applied at the doses of 2.5, 5.0, 7.5, and 15.0 percent (v/v) coupled with water spray as a control at different phases of the maize crop significantly enhanced grain yield significantly by 18.5 percent and 26.0 percent. The enhancement in yield was correlated to increase in the number of rows in cob, cob length, and 100 grain weight and improved in nutrient uptake [27]. The substantial increase in plant height, root nodules, root volume, number of branches at harvest, dry matter production, chlorophyll content of the leaves, grain yield, grain nitrogen percentage, and grain protein content was significantly recorded by soaking seed in 0.1% seaweed extract solution for 30 minutes + foliar application of seaweed extract (0.25%) twice on 25 DAS and 35 DAS in green gram (single spray). The existence of micro- and macronutrients, trace elements, humic acid, amino acids, plant growth hormones, vitamins, antibiotics, carbohydrates, metabolite boosters, and other organic compounds in seaweed extract significantly enhanced the growth, yield, and quality traits of green gram [28].

Spraying of *Kappaphycus alvarezii* sap (5.0%) in tomato crop significantly increased the root length, shoot length, and yield over (control) plants sprayed with water. The result was due to macro- and microelements as well as growth-promoting components like cytokinin present in seaweed. There was significant increase and

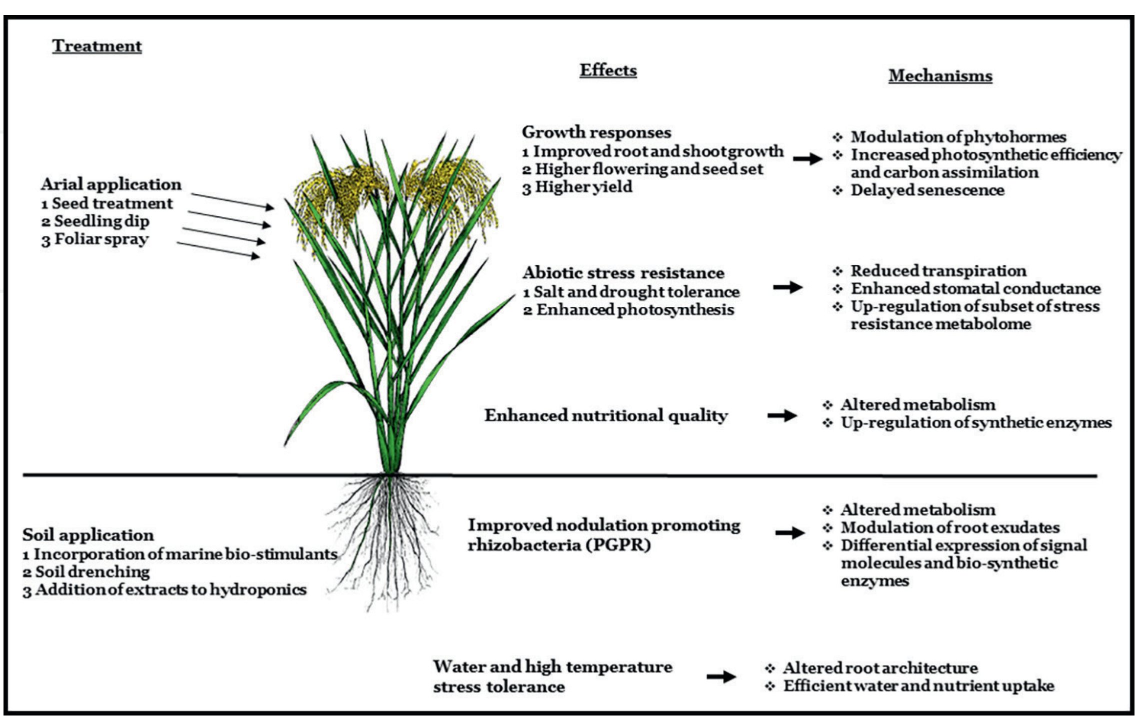


Figure 2.
Illustration of physiological effects of elicited seaweed biostimulants and possible mechanisms of bioactivity.

enhancement in chlorophyll and b content in leaves over control where *Kappaphycus alvarezii* was applied (5.0% sap). Enhanced leaf chlorophyll concentration of treated plants with seaweed biostimulant was due to the presence of betaines [29]. Spraying rice crop with seaweed extracts at rate of 2000 ppm led to a significant enhancement in the weight of 100 grains and produced the highest significant values of grains yield per plant under salt stress conditions. The superiority was due to the benefits of seaweed components providing a remarkable source of bioactive substances such as macro- and micronutrients, essential amino acids, fatty acids, vitamins, cytokinins, and auxins like growth-promoting substances influencing plant growth and production by altering cellular metabolism in treated plants. In rice, higher plant height, dry matter production, yield attributes such as number of grains per panicle, panicle length, thousand grain weight, number of productive tillers per m^2, grain yield, and straw yield were recorded when seaweed extract was applied to the soil at a rate of 12.5 kg/ha along with a foliar spray of seaweed liquid [30]. The application of liquid seaweed extracts improved plant growth and yield characteristics and enhanced soil quality in foxtail millet [31].

Seaweed liquid biostimulant of *Kappaphycus alvarezii* sap when applied as foliar application in rice crop boosted the crop growth characteristics such as plant height, number of leaves plant^{-1}, number of tillers plant^{-1}, and grain yield over recommended dose of fertilizers [32]. Increase in yield is due to higher number of panicles through improved canopy establishment, photosynthesis, translocation of assimilates, better interception of light, and markedly decrease in inter plant competition for soil nutrients and solar energy. Seaweed extracts applied on onion grown under water stress significantly enhanced N, P, and K uptake by 116, 113, and 93% compared to the unsprayed plants [33]. Agronomic characters and yield components of rice in algalized plots increased compared to the treatment with recommended dose of urea [34].

In vitro mass propagation using hypocotyls and leaf disk explants of brinjal (*Solanum melongena* L.) cultivar Pusa Purple Long, the influence of seaweed liquid extracts (SLEs) prepared from *Gracilaria salicornia*, *Padina gymnospora*, *Padina boergesenii*, and *Gelidiella acerosa* on plant growth was studied. The rate of shoot and root induction and the percentage of seed germination were both markedly improved by the use of seaweed liquid extract in MS medium. Plant growth can be promoted by seaweed extracts contain stimulating compounds. Seaweed extracts contain high endogenous levels of micro- and macronutrients, vitamins, cytokinins, auxins, amino acids, gibberellins, and organic acids to enhance the growth of crop plants [35].

Seaweed foliar spray sap of *Kappaphycus alvarezii* and *Gracilara edulis* at five percent and above concentration boosted grain yield attributes and yield of rice 5.4 to 19.4 percent higher as compared to recommended dose of fertilizers. Soaking of rice seeds in lower concentration (2.5 and 5%) of saps extracted from seaweed improved the germination and seedling vigor of rice [36]. *Padina gymnospora*, *Gracilaria edulis*, and *Ulva fasciata* aqueous extracts applied as a seaweed biofertilizer to promote seed germination of *Capsicum annuum* illustrated higher root and shoot length, mean germination time, germination index, germination percent, seedling vigor index, germination energy, total protein content, total phenol content, and antioxidant inhibition percentage [37]. Seaweed extract of *Sargassum denticulatum* (2 percent) foliar application enhanced all growth and yield parameters and more accumulation of the organic solutes in leaves of water-stressed plants. Application of seaweed biostimulant/extract enhanced seedling growth of wheat plants during growth period [38]. The influence of three red marine algae species (*Laurencia obtusa*, *Corallina elongata*, and *Jania rubens*) was assessed as biostimulant to enhance the growth of maize (*Zea mays* L.) plants. Application of mixture of *Laurencia obtusa* and *Corallina elongata* enhanced plant fresh and dry weight in maize crop [39]. Seaweed sap foliar application (*Kappaphycus alvarezii* and *Sargassum denticulatum*) at 10 percent at 20–40 DAS and 40–60 DAS revealed maximum accumulate growth rate (AGR), crop growth rate (CGR), and relative growth rate (RGR) over 5 percent and 7.5 percent along with foliar application water spray in maize. Seaweed extract mainly contains amino acids like betaines and sterols which enhance the photosynthetic activity, N metabolism, and protein synthesis which boost corn production and also the availability of growth regulators to extract especially auxins and cytokinins which are responsible for cell enlargement and inter-nodal elongation and thereby increase the vegetative growth [40]. Application of seaweed extract as foliar at 2 percent concentration enhanced all growth and yield parameters and more accumulation of the organic solutes in leaves of water-stressed crop plants. Low concentrations application of *Ascophyllum nodosum* extracts on the ground or on the foliage of rice caused an increase in chlorophyll content in the leaves. The decrease in chlorophyll degradation, which might be partially attributed to betaine from seaweed extract, resulted in an increase in chlorophyll content and photosynthetic rate [41].

Application of seaweed extract at the rates of 15% K sap or 15% G sap with 100% RDF at 35, 45, and 60 days after transplanting (three distinct intervals) over the required dose of fertilizer enhanced grain yield by 11.80 percent and 9.52 percent, respectively. The growth, yield attributes, grain yield, quality, and chlorophyll content of rice were significantly influenced with foliar spraying seaweed extract on the foliage. In accordance with the results, spraying seaweed extract at 15 percent K sap with 100 percent recommended dose of fertilizer resulted in substantially higher growth, yield attributes, and chlorophyll content over spraying seaweed extract at 15 percent G sap with 100 percent recommended dose of fertilizer. Yield enhancements in seaweed-treated plants are responsible to be associated with the hormonal components present in the extracts, especially cytokinins [42]. The most significant values of grain yield per plant were achieved after spraying wheat plants with seaweed extract at a concentration of 2000 ppm under salt stress conditions. The superiority was induced by the advantages of seaweed components, which function as a predominant source of bioactive compounds like macro- and micronutrients, essential fatty acids, amino acids, vitamins, cytokinins, and auxins, substances that affect cellular metabolism in treated plants and hence promote growth and productivity [43]. Application of seaweed biostimulant at a dose of 2 ml L^{-1} demonstrated positive impact on the growth, development, yield, and essential oil contents of coriander plant [44].

7. Effect of application of seaweed biostimulant on nutrient uptake

Rhizosphere microorganisms are conducive to soil nutrient cycling for plant growth. Rhizosphere microorganisms contribute to the release of organic acids, amino acids, carbohydrates, and secondary metabolism products in rice fields. Seaweed extracts have been reported to enhance tolerance to environment stress, boost the growth and yield of plants, and promote nutrients availability and nutrients uptake from the soil. Since seaweed extract is the source of organic matter and nutrients, so the utilization of seaweed extract as biofertilizer could balance the N, P, and K deficiencies in paddy soils. Root of rice is a hidden organ in soil that mediates critical functions, involving the uptake and storage of water and nutrients [45]. Rhizosphere microbes are critical for plant growth and biogeochemical cycles and are closely related to cultivated crop, fertilizer applications, and plant residue input [46]. *Sargassum horneri* extract, alginate, can chelate with major cations of Na^+ , Ca_2^+, Mg_2^+, and K^+ to form aggregate with richer nutrients, improve the crumb structure and capillary activity of soil pores, and, finally, boost soil microbial activity [47]. Therefore, seaweed extract supplement can potentially be a strategy of enhancing the amount of nitrogen, phosphorous, and potassium contents in soil. Application of seaweed extract on plant is capable of enhancing nutrient concentrations in the leaves, through implication of growth hormone in the process of nutrients absorption and movements in a plant, thus enhancing the weight of the rice plant. The utilization of seaweed-based extracts has reduced the levels of nitrogen, phosphorus, and potassium fertilizers and also induced the seed germination and growth parameters strongly than chemical fertilizers in rice crop [10]. *Ecklonia maxima* seaweed extract is most effective in neutral pH soil, and it can be used to promote plant growth under low pH and water stress conditions [47]. Application of algae mixture of *Corallina elongate, Laurencia obtusa,* and *Jania rubens* caused increase in phosphorus content and nitrogen content in maize plant [39]. Decomposed seaweed, as an organic matter, generally improved soil physico-chemical properties, water holding capacity, and microbial activity and also protected plant against unfavorable environmental conditions such as extreme temperatures and water stress [48].

Application of seaweed concentrate led to significantly increase of K, Mg, and Ca concentrations in the leaves of lettuce plants which received adequate supply of nutrients but had meager effect on nutrients-stressed plants. Moreover, the components, nitrogen, phosphorus, and magnesium, were significantly increased when seaweed extract applied through foliar application. Seaweed application in meager quantities has the effect on several metabolic processes and improves plant growth and development through enhancing of photosynthesis, endogenous hormones, nutrients uptake, and protein synthesis as well as with relatively improved ability for increasing available micronutrients in the soil [49]. Foliar applications of *Ascophyllum nodosum* seaweed extract reinvigorated the plants to utilize with soil mineral N and other available nutrients more efficiently which enhanced increased grain potassium uptake and increased in wheat plant yields by 25 percent [50]. Due to increased membrane permeability of roots, leaves, and stoma cells, as well as hormone-like activities of seaweed extract through their involvement in cell respiration, photosynthesis, and enzymatic processes, the application of seaweed extract boosted the uptake of copper. Application of 5 percent of *Kappaphycus alvarezii* sap enhanced the uptake of N, P K, S, Ca, K, and Mg in leaves of rice crop. Seaweed extract supplement could impact the bacterial community in tillering and heading stages in rice crop, and hence α-diversity of rhizosphere bacteria in the heading stage improved substantially [24]. In the rice environment, enhanced soil available nutrients of N (260 kg/ha), P (42 kg/ha), K (180 kg/ha), Ca (27.7 meq/100g), Mg (5.5 meq/100g), S (18.2 mg/kg), Zn (1.17 ppm), Fe (33.82 ppm), Cu(1.61 ppm), and Mn (18.97 ppm) were observed after applying seaweed extract to the soil at a rate of 25 kg [28]. *Ulva linza* and *Calendula officinalis* contain macronutrients such as N, P, K, Ca, Mg, and some trace elements, as well as growth regulators, amino acids, and antioxidants which are excellent natural fertilizers [51].

Elevation in uptake of K, Ca, Mg, and Cu with application of seaweed extract of *Kappaphycus alvarizii* was due to enhanced membrane permeability of roots, leaves and stoma cells, and hormone-like activities of seaweed extract through their implication in cell respiration, photosynthesis, and enzymatic reactions [27]. Application of seaweed at the rate of 15 percent *Kappaphycus alvarezii* in black gram in sandy loam soil of the red and lateritic belt of West Bengal resulted in higher availability and absorption of inorganic elements like Ca, Na, K, Mg, N, Zn, and Cu [52].

8. Conclusion

Abiotic stress such as drought, high soil salinity, and temperature affect and limit crop productivity worldwide. Biostimulant seaweed application reduces the need for fertilizers and enhances nutritive efficiency, abiotic stress tolerance, grain yield, and plant quality traits. Application of minimal concentration of seaweed extract as a priming agent enhances plant growth, physiological attributes, and molecular traits. Application of seaweed extracts of *Kappaphycus alvarezii*, *Ascophyllum nodosum*, *Sargassum calophyllum*, *Sargassum aquifolium*, *Sargassum polycistum*, *Hydroclathrus clathratus*, *Turbinaria ornata*, and *Turbinaria murayana* are able to stimulate vegetative growth and increase yield of rice plants. The use of seaweed biostimulants in low quantities has effect on several metabolic processes and improves plant growth and development through the increase of photosynthesis, endogenous hormones, nutrients uptake, and protein synthesis as well as with relatively higher capacity for increasing available micronutrients in the soil. In order to boost crop growth parameters like plant height, leaf area index, dry matter production, and SPAD reading (chlorophyll content), as well as yield parameters like the number of grains per panicle, panicle length, and number of products, seaweed extract *Kappaphycus alvarezii* was applied to rice crop (Oryza sativa L.) at a rate of 12.5 kg/ha in the soil and 0.5% twice at the tillering and panicle initiation stages. The rice yield was also increased by 18–20% over the recommended fertilizer dosage. However, the application of seaweed extract in soil at the rate of 25 kg/ha improved the available nutrients like N, P, K, Ca, Mg, and S and micronutrients. Hence, seaweed has a substantially greater potential to boost bioavailable macro- and micronutrients to the rice crop.

Conflict of interest

The authors declare no conflict of interest.

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